

Effect of variable rate irrigation and nitrogen fertilizer rates on crop productivity and water quality

Final Report: 2021-2024

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Summary

Under deficit irrigation, nitrogen (N) fertilizer strategies must be carefully adjusted to sustain profitable crop production while minimizing environmental impacts. In Minnesota, however, the combined influence of irrigation and nitrogen (IxN) management on corn yield, evapotranspiration, and nitrate leaching has not been extensively quantified under real-world conditions. Current N recommendations in the state are largely based on either fully irrigated (100% I) or rainfed systems, leaving a gap in guidance for producers adopting deficit irrigation strategies, which are increasingly promoted due to water resource limitations and concerns over groundwater nitrate contamination. This 5-year study was designed to address a key question: Can reductions in irrigation be paired with optimized nitrogen rates to maintain yield while minimizing nitrate leaching? Furthermore, what are the best IxN combinations for balancing economic returns, environmental protection, and system resilience under variable Minnesota weather? Through replicated field trials at two sites (Becker and Westport), this research established foundational, field-tested relationships between yield, ET, water input, nitrogen uptake, and nitrate leaching across a matrix of irrigation and nitrogen rates. Key findings show that full yield potential can be achieved using moderate irrigation (I2, 75% I) combined with nitrogen rates of 210–250 lb/ac (N4–N5). These combinations consistently produced high yields, high water use efficiency, and minimal nitrate loss, demonstrating that more input does not always mean more output.

Background

In Minnesota, the interest in deficit/limited and variable rate irrigation management to address/reduce water quality and quantity problems has been increasing amongst farmers, agricultural professionals and key stakeholders. However, it's challenging to understand how much reduction in irrigation rate is compared to full irrigation and what amount of nitrogen (N) fertilizer is optimum, under that reduced irrigation rate, for sustainable crop production. Consequently, when farmers use deficit irrigation amounts in combination with recommended N rates that are developed under well-watered conditions, plants cannot utilize all the N applied and thus the remaining can be lost in the environment.

Water quality and quantity issues in irrigated regions of the state have led to scrutiny of groundwater by the government, leading to the development of new regulatory approaches and groundwater policies. One such regulation is the Groundwater Protection Rule developed by the Minnesota Department of Agriculture (MDA) that would regulate the N fertilizer use in the areas that are vulnerable to groundwater contamination. Such rules are important to reduce the impact of agriculture on the environment but at the same time, require robust and evolving research based scientific knowledge, specifically in the fields like irrigation that have not been explored much in Minnesota. Innovative research, that integrates N fertilizer and irrigation or crop water use,

needs to be developed to back up these programs and rules with scientific research-based knowledge and also help growers in efficient farm management.

Several research have investigated the combined effect of irrigation and N on crop production, nitrate leaching, and water use efficiency, and found that N and water are codependent management factors that cannot be evaluated independently (Al-Kaisi and Yin, 2003; Pandey et al., 2000a; Pang et al. 1997). In these studies researchers found that crop water productivity (yield/water use) vary with varying rates of N and irrigation and that under deficit irrigation, N must be correspondingly adjusted to optimize economic crop production. However, most of this knowledge is based on research conducted in more arid regions where precipitation and the water balance of cropping systems are substantially different from those in Minnesota. To the best of our knowledge, very limited research has been done to investigate the N and irrigation interaction effect on nitrate leaching in corn cropping systems in Minnesota. One such research is Maharjan et al. (2014) who compared the effects of different N treatments for fully irrigated and minimum-irrigated corn in Becker, MN. They found greater yield-based nitrate leaching and lower grain yields in minimum-irrigated plots than fully irrigated plots. However, in their study, they used only one N rate (180 kg N/ha) under two irrigation levels with different types and timing of N fertilization.

Our overarching goal is to build capacity to provide government agencies, stakeholders and producers with scientific research-based irrigation and N management data, and information on fundamental relationships that help develop policy/rules, make better on-farm management decisions, and help advancing the sensor-based (proximal and remote sensing) irrigation and N management research. Since corn is one of the principal crops irrigated in Minnesota, our research will focus on continuous corn cropping systems under sprinkler irrigation.

Materials and Methods

Field plot experiments were conducted at the Sand Plain Research Farm (SPRF) in Becker, MN (45° 20' N, 93° 51' W) and Herman Rosholt farm (45° 42' 49.07" N; 95° 10' 29.39" W), in Westport, Minnesota (both sites are in vulnerable groundwater areas) from 2020-2024. Four (4) irrigation treatments and six (6) N rate treatments were evaluated and replicated four (4) times (Figure 1). The irrigation treatments were full irrigation (FI), i.e., imposing no water stress on the crop, 75% of FI, 50% of FI and rainfed conditions. The N application rates were 0, 70, 140, 210, 280 and 350 lb/ac. Irrigation was applied using a GPS guided variable rate linear move irrigation system at both locations. The plot layouts are shown in Figure 1. Urea- N fertilizer was applied to the plots in two splits, with 30% at V2, and 70% at V9 growth stages. The experimental design was a split-plot design with irrigation treatments as the main plot and N-rates as the sub-plot.

Above-ground plant biomass and N uptake were measured by taking plant samples from each plot at V8, R1 and R6 development stages to evaluate the effect of irrigation levels on N uptake under different nitrogen rates. Grain yield and grain N content were measured for total N balance and N use efficiency calculations by combine-harvesting the middle two rows of each plot.

Weekly nitrate-N concentrations below the root zone at 1.2 m depth were monitored with two lysimeters in each plot. We have installed 192 permanent suction cup lysimeters at each location.

A neutron moisture gauge was used to monitor soil moisture status for each plot in 1 ft intervals down to 4 ft soil depth to estimate crop evapotranspiration and drainage at different N rates under full irrigation, limited irrigations and rainfed conditions. A general soil water balance approach followed by FAO-56 was used to calculate crop evapotranspiration (ET_c) and drainage. Crop water use efficiency (CWUE), which is the ratio of yield (Y, bu/ac) to crop water use (ET_c, in) was estimated for each treatment. The dates of important cultural and management practices is given in Table 1.

To evaluate the effects of irrigation rate (I), and nitrogen rate (N), on evapotranspiration (ET), nitrogen leaching, crop nitrogen uptake, crop water use efficiency (CWUE), and grain yield, a split-plot analysis of variance (ANOVA) was conducted. Irrigation rate was treated as the whole-plot factor and nitrogen rate as the subplot factor.

A linear model incorporating all main effects and their interactions (I * N) was fit to the data, and Type II ANOVA tables were generated using the car package in R. The significance of main effects (I, N) and two-way interactions (I×N) was assessed at $\alpha = 0.05$ and 0.1. Where significant main effects were detected, Tukey’s Honest Significant Difference (HSD) post-hoc tests were performed to compare treatment means. The results of statistical analysis is shown in Table 2.

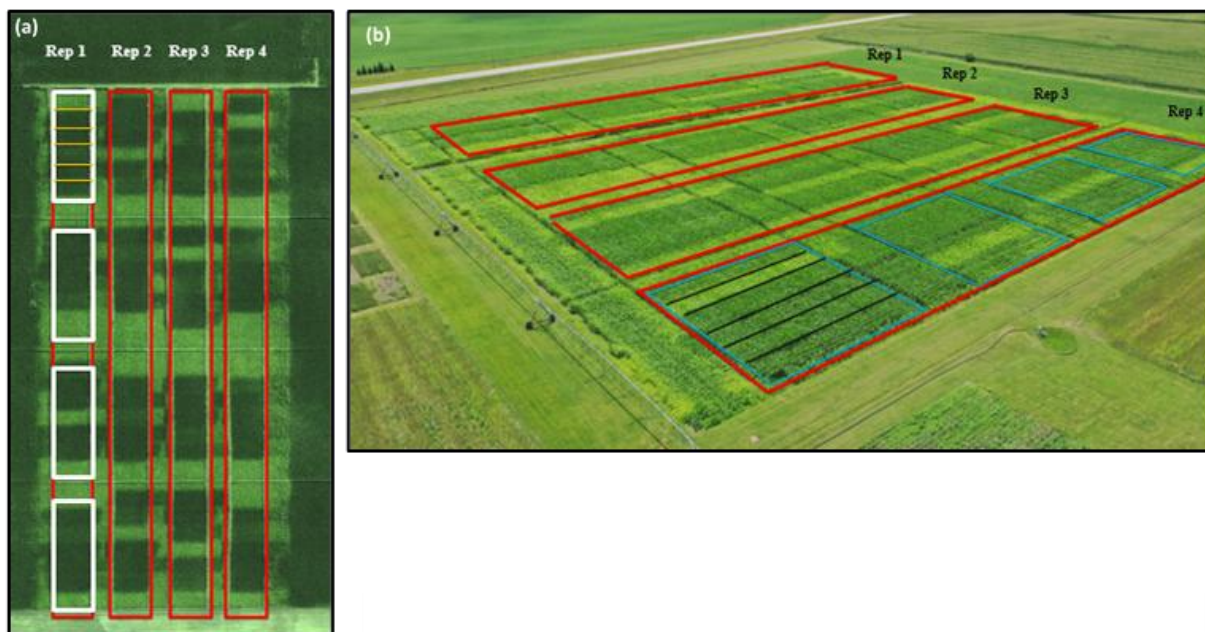


Figure 1. Plot layouts at (a) Sand Plain Research Farm, Becker, MN and (b) Rosholt Farm, Westport, MN.

Table 1. Different agronomic and cultural management activities and associated dates at Becker and Westport, MN

Activity	Becker					Westport				
	2020	2021	2022	2023	2024	2020	2021	2022	2023	2024
Planting	13-May	7-May	16-May	4-May	1-May	22-May	18-May	23-May	11-May	24-May
V2 N application	3-Jun	28-May	8-Jun	24-May	31-May	11-Jun	9-Jun	14-Jun	1-Jun	25-Jun
V8 N application	30-Jun	25-Jun	28-Jun	15-Jun	26-Jun	8-Jul	28-Jun	6-Jul	22-Jun	9-Jul
V8 Plant sampling	26-Jun	25-Jun	28-Jun	23-Jun	3-Jul	30-Jun	29-Jun	6-Jul	22-Jun	12-Jul
R1 Plant Sampling	27-Jul	23-Jul	27-Jul	19-Jul	22-Jul	3-Aug	29-Jul	3-Aug	31-Jul	6-Aug
R6 Plant sampling	21-Sep	27-Sep	6-Oct	7-Sep	23-Sep	23-Sep	5-Oct	5-Oct	28-Sep	9-Oct
Harvesting	21-Oct	22-Oct	31-Oct	3-Nov	16-Oct	28-Oct	3-Nov	18-Oct	17-Oct	24-Oct
Post harvest soil sampling	26-Oct	16-Nov	8-Nov	3-Nov	21-Oct	28-Oct	15-Nov	31-Oct	10-Nov	7-Nov

Results

Irrigation and Precipitation

Cumulative growing season precipitation (Planting to harvest) varied considerably by year and location, influencing irrigation requirements and crop water dynamics (Figures 1, 2, 3 and 4). Westport generally received higher rainfall than Becker in the earlier years (2020–2021), while Becker received substantially more rainfall in 2023 and especially in 2024. Specifically, Westport precipitation ranged from 10.6 inches in 2022 to a high of 20.1 inches in 2021, while Becker ranged from 11.9 inches in 2021 to 22.8 inches in 2024. The year 2024 was the wettest for Becker, with rainfall exceeding 22 inches which is well above the five-year average, due to frequent and well-distributed events through June and July. In contrast, 2022 was the driest year at Westport with just 10.6 inches, whereas 2021 saw a relatively wet season at Westport and one of the driest at Becker, emphasizing the interannual and site-specific variability in precipitation patterns. Though 2021 was generally classified as a drought year, Westport received unusually high rainfall in August and September, which elevated the total seasonal precipitation; however, rainfall was very limited during June and July, the critical period for crop water demand. In most years, the majority of rainfall occurred between late May and mid-August, which coincides with the peak crop water demand during vegetative growth, flowering, and grain fill.

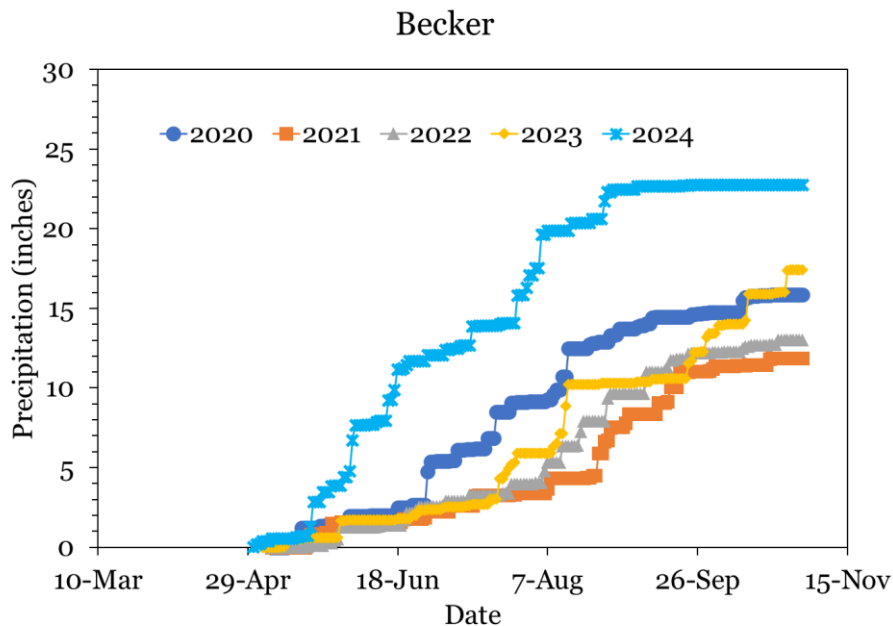


Figure 2. Cumulative precipitation in 2020, 2020, 2022, 2023 and 2024 corn growing seasons (planting to harvest) at Becker.

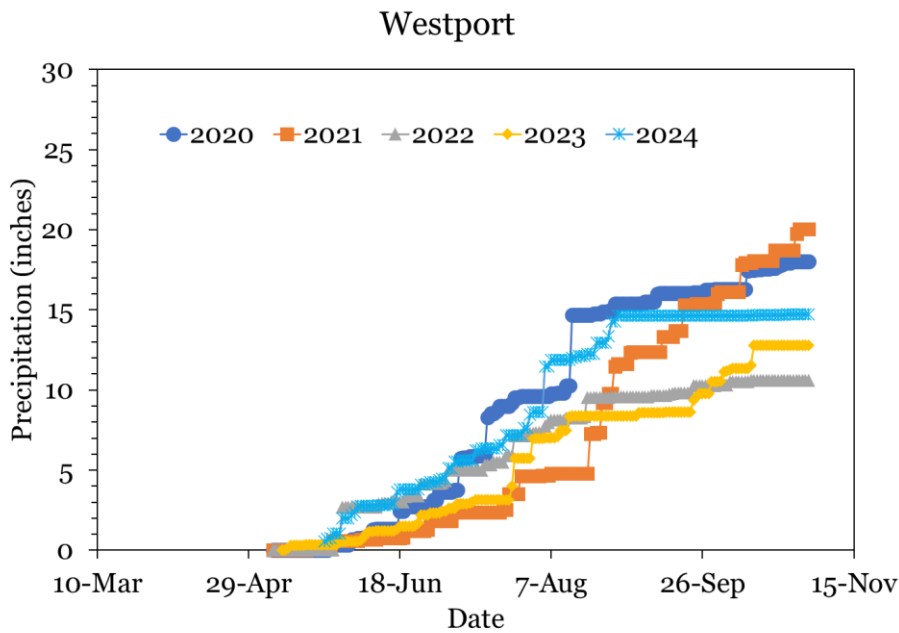


Figure 3. Cumulative precipitation in 2020, 2020, 2022, 2023 and 2024 corn growing seasons (planting to harvest) at Becker.

The inverse relationship between seasonal rainfall and applied irrigation was clearly evident across both sites (Figures 3 and 4). When growing season precipitation was high and well-timed, especially during June to August, irrigation requirements dropped substantially. This is particularly apparent in 2024 at Becker, where I1 (full irrigation) plots received less than 5 inches of supplemental irrigation, compared to over 12 inches in 2021 when rainfall was more erratic and clustered in early or late season periods. Similarly, at Westport, 2020 and 2024, which experienced abundant and timely rainfall especially during June-August, saw minimal irrigation inputs across all irrigation treatments, with I3 and I4 plots receiving as little as 1–2 inches of supplemental water. In contrast, in 2021 and 2023, where mid-season rainfall deficits occurred, irrigation volumes increased, particularly in the I1 and I2 treatments which aimed to meet full or near-full crop evapotranspiration (ET) demand. In drier years (e.g., 2021-2023), higher irrigation levels provided essential moisture during critical growth periods, maintaining yield and ET. Conversely, in wetter years like 2020 and 2024, even rainfed treatments (I4) produced high yields due to well-distributed rainfall, minimizing the yield gap between I4 and I1.

These findings underscore the importance of dynamic, responsive irrigation scheduling that accounts not only for total seasonal precipitation but also its temporal alignment with crop water demand. Simply put, more total rainfall did not always equate to less irrigation, but timely rainfall between June and August sharply reduced irrigation needs and improved water use efficiency.

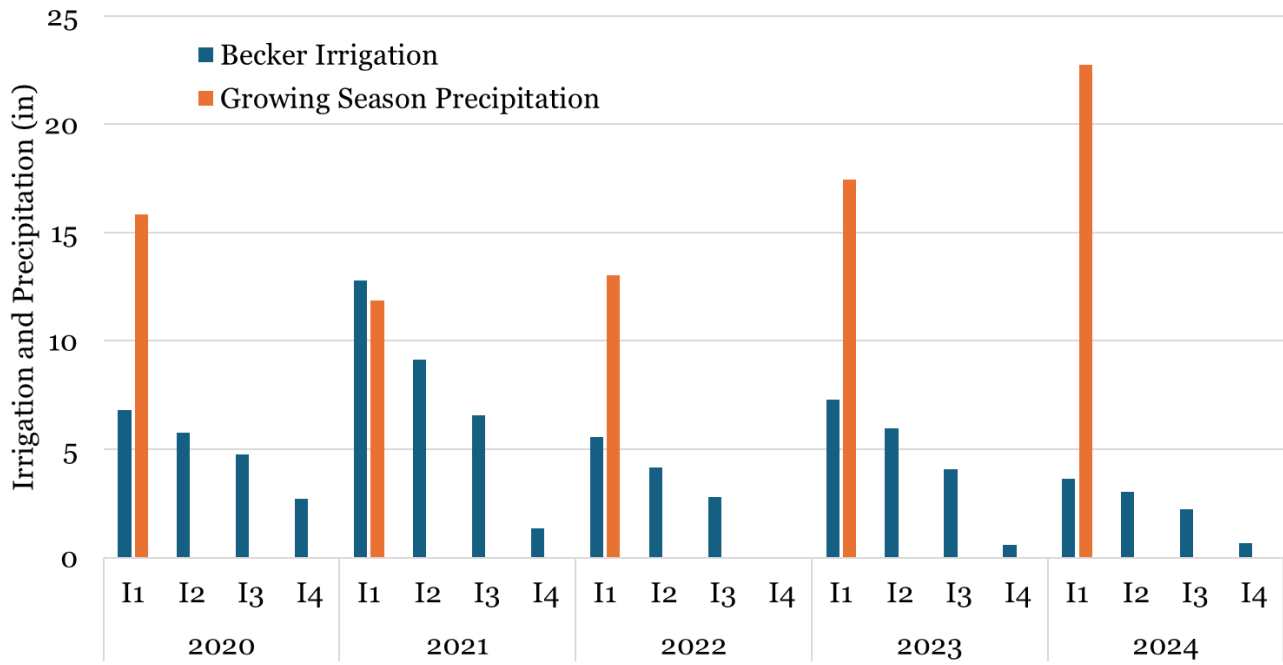


Figure 4. Irrigation amounts at I1, I2, I3, I4 irrigation levels in 2020, 2020, 2022, 2023 and 2024 corn growing seasons (planting to harvest) along with total growing season precipitation (orange bar) at Becker, MN. (I1 is the highest irrigation and I4 is no irrigation)

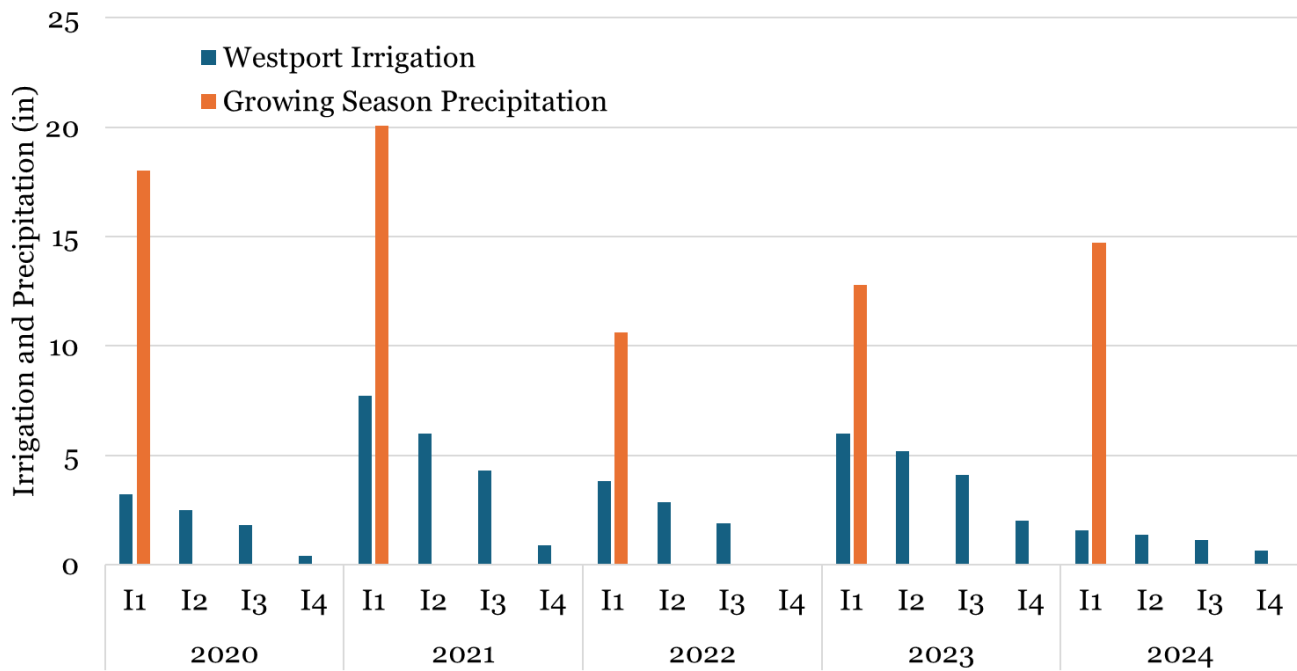


Figure 5. Irrigation amounts at I1, I2, I3, I4 irrigation levels in 2020, 2020, 2022, 2023 and 2024 corn growing seasons (planting to harvest) along with total growing season precipitation (orange bar) at Westport, MN. (I1 is the highest irrigation and I4 is no irrigation)

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Table 2. ANOVA table of significance of main effects (I, N) and two-way interactions (I×N) at $\alpha = 0.05$ and 0.1 for Becker and Westport for all data from 2020 to 2024..

Site	Parameter	ET (in)	Leaching (lb/ac)	N Uptake (lb/ac)	CWUE (bu/ac-in)	Yield (bu/ac)
Becker	I	**	*	**	**	**
	N	**	**	**	**	**
	I×N	NS	NS	NS	**	**
Westport	I	**	NS	**	**	**
	N	**	**	**	**	**
	I×N	NS	NS	NS	NS	**

** Significant at α 0.05
* Significant at α 0.1
NS not significant

Treatment Effect on Yield

At Becker, grain yield showed a strong positive response to both increasing irrigation and nitrogen rates (Figure 6, Table 3). Under fully irrigated conditions (I1), yield increased steadily with nitrogen application, reaching a maximum at N5 (280 lb/ac) with an average yield of 224.0 bu/ac. Further increasing nitrogen to N6 (350 lb/ac) did not significantly improve yield, indicating a plateau in the response curve beyond N5. Under rainfed conditions (I4), yields were substantially lower across all N levels, with the lowest yield of 44.85 bu/ac observed in I4–N1, and a maximum of 100.6 bu/ac in I4–N5. The yield gap between rainfed and fully irrigated treatments increased as nitrogen rate increased, and plateaued after N4 (210 lb N/ac), emphasizing the importance of irrigation for realizing nitrogen use efficiency and importance of optimum rate for reducing nitrate leaching. Intermediate irrigation treatments (I2 and I3) also exhibited strong yield responses to nitrogen. For example, in I2, yield increased from 144.0 bu/ac (N2) to 202.2 bu/ac (N6), with diminishing returns evident beyond N4. Similarly, I3–N4 and I3–N5 produced over 170 bu/ac, only ~20–30 bu/ac less than the fully irrigated treatments. This suggests that moderate deficit irrigation (I2 or I3), when combined with sufficient nitrogen (N4–N5), can approach the productivity of full irrigation with more efficient water use.

At Westport, yield also increased with both irrigation and nitrogen, though the response to irrigation was less dramatic than at Becker (Figure 7, Table 4). This was likely due to more frequent and timely rainfall at Westport, especially during sensitive growth stages in some years. Under full irrigation (I1), yield rose from 74.4 bu/ac (N1) to a maximum of 206.9 bu/ac (N5), beyond which no statistically significant yield gain was observed. The yield response to nitrogen was more consistent than to irrigation, with all treatments plateauing between N5 and N6. Interestingly, rainfed yields (I4) were higher at Westport than Becker, ranging from 63.5 bu/ac (N1) to 143.5 bu/ac (N4). This reflects the relatively reliable in-season rainfall at Westport, especially in 2020 and 2024, which reduced reliance on irrigation. Similar to Becker, the yield difference between I1 and I4 increased with an increase in nitrogen until N5 and then decreased after that, however, the difference was smaller at Westport than at Becker, indicating greater resilience under rainfed conditions at Westport site.

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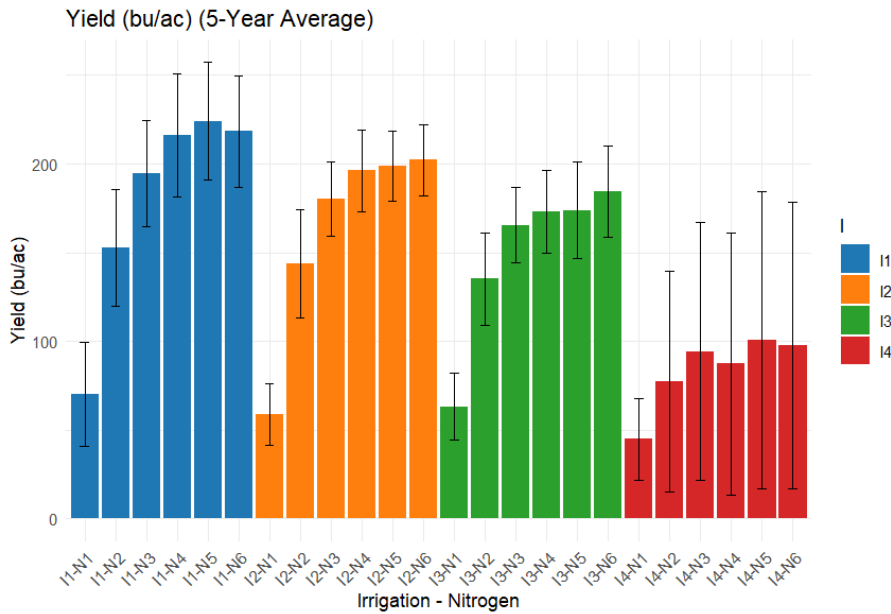


Figure 6. Average Corn grain yield under each irrigation-Nitrogen treatment at Becker, MN.

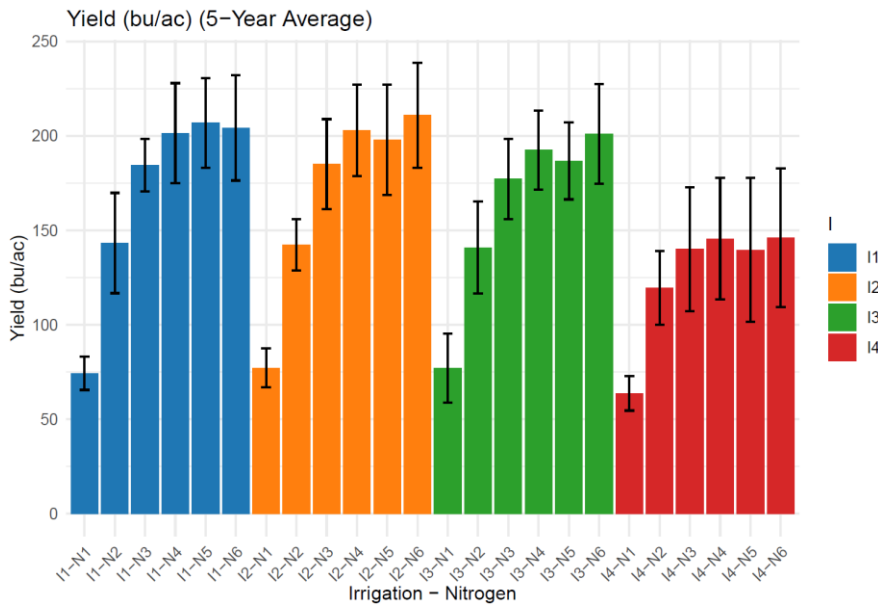


Figure 7. Average Corn grain yield under each irrigation-Nitrogen treatment at Westport, MN.

One of the most practical findings from this study was the consistent performance of the I2 treatment (75% of estimated ET) across both locations. At Becker, I2 produced average yields of ~163 bu/ac, only ~9% less than I1 (full irrigation), while requiring 2 inches less irrigation water per season (Figures 4 and 5). At Westport, the yield difference between I1 and I2 was even smaller less than 1 bu/ac on average due to higher in-season rainfall mitigating the need for full irrigation. This pattern demonstrates that I2 offers an optimal balance between productivity and resource conservation. Compared to I1, it delivers comparable yields with reduced irrigation inputs, making it a compelling target for deficit irrigation strategies in water-limited or regulated contexts. Especially in years with moderate rainfall or in systems with good soil water-holding capacity, I2 can achieve high yields and reducing energy and labor associated with excessive irrigation.

Overall, Becker yields were more irrigation-sensitive, with a steep drop under rainfed (I4) conditions where as Westport yields were more rainfall-buffered, resulting in higher I4 yields and narrower gaps between I1 and I4. In both locations, nitrogen response plateaued beyond N4–N5, with no benefit from N6. The interaction of irrigation × nitrogen was evident meaning adequate irrigation enhanced nitrogen responsiveness, while under water-limited conditions, the full benefit of higher nitrogen rates was not realized.

These findings highlight the importance of aligning irrigation strategy with nitrogen input levels. In years or regions with reliable rainfall, moderate irrigation may suffice when coupled with optimal N. In drier conditions like Becker, however, irrigation plays a critical role in realizing the full yield potential of applied nitrogen.

Treatment Effect on Evapotranspiration (ETc)

Evapotranspiration (ETc) at Becker was significantly influenced by irrigation treatment, with clear increases from I4 (rainfed) to I1 (fully irrigated) (Figure 8, Table 3). Average ETc under I1 treatments ranged from 15.4 to 17.5 inches, depending on nitrogen level, while I4 treatments produced ETc values ranging from 12.5 to 13.6 inches. Nitrogen also played a notable role in modulating ETc across all irrigation levels. At each irrigation level, ET generally increased with nitrogen rate, with the lowest ETc values consistently observed at N1 and the highest at N3–N6. This reflects greater canopy development and transpiration demand under high-N conditions. For instance, under I3, ETc increased from 14.89 inches (N2) to 16.05 inches (N5). These trends suggest that both water and nitrogen availability synergistically influenced actual crop water use. Crops under limited irrigation but sufficient nitrogen (e.g., I3–N4) achieved comparable ETc to those under full irrigation but moderate N (e.g., I1–N2), highlighting the importance of integrated nutrient–water management.

At Westport, average ET values were slightly lower than at Becker, reflecting cooler temperatures, more rainfall, and reduced irrigation volumes overall (Figure 9, Table 4). ETc under I1 ranged from 11.8 to 14 inches, while I4 treatments remained in the 10.3–12.0 inch range. The smaller spread across irrigation treatments compared to Becker is consistent with more consistent rainfall during peak growth stages, especially in years like 2020 and 2024. Nevertheless, the same general trend persisted that ETc increased with both irrigation and nitrogen with no significant difference between I1 and I2. ETc increased from 11.30 inches (N1) to 13 inches (N5), indicating higher biomass accumulation and transpiration driven by greater nitrogen uptake and canopy expansion, however, ETc decreased from N5 to N6 indicating that further canopy expansion would not increase ET or yield. The differences between irrigation levels (I1 and I4) were narrower at Westport (~1.6 inches) than at Becker (~3.2 inches), suggesting a greater reliance on rainfall and reduced irrigation effect at Westport.

Across both sites, Irrigation had a stronger impact on ETc than nitrogen, especially at Becker where irrigation volumes were higher and rainfall was less reliable. However, nitrogen amplified ETc by stimulating canopy growth and transpiration demand. The highest ETc values at all irrigation levels were consistently observed between N4–N6, indicating that under high nitrogen, the crop approached its maximum evapotranspirative potential. Importantly, the results demonstrate that ETc can be partially sustained under limited irrigation (I2) if nitrogen levels are adequate. This insight is valuable for developing deficit irrigation strategies that balance productivity with water conservation.

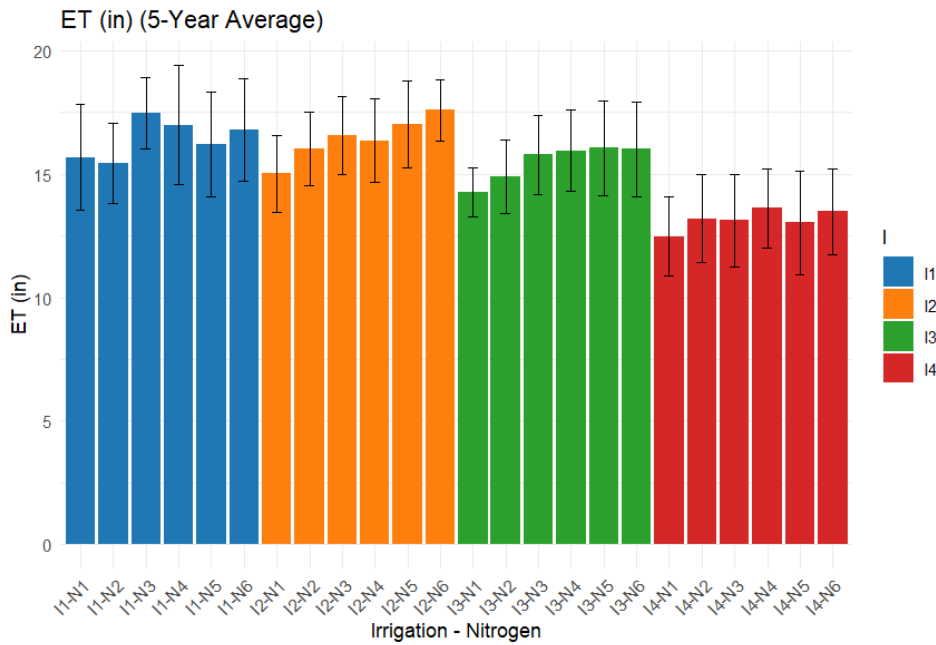


Figure 8. Average crop evapotranspiration (ETc) under each irrigation-Nitrogen treatment at Becker, MN.

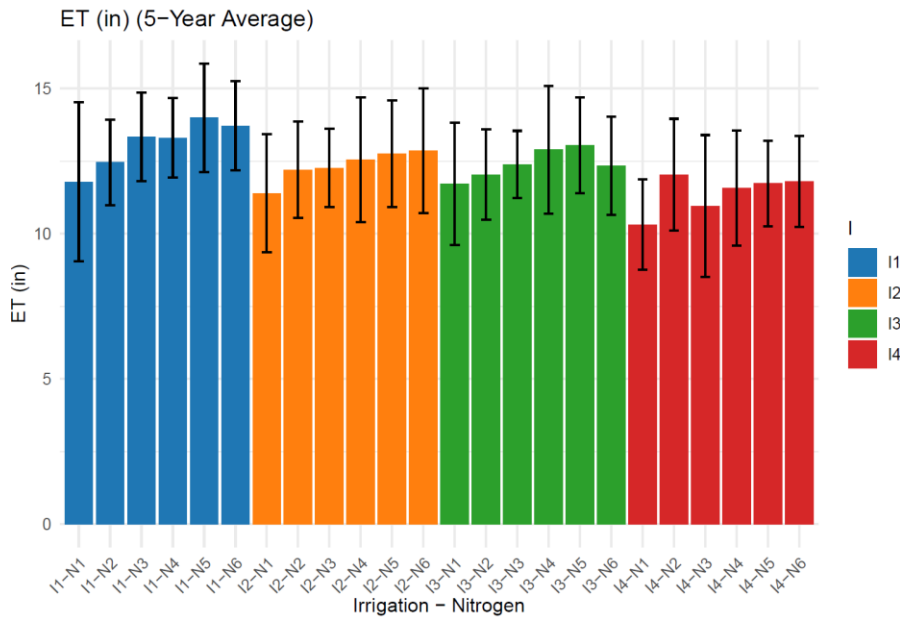


Figure 9. Average crop evapotranspiration (ETc) under each irrigation-Nitrogen treatment at Becker, MN.

The relationship between evapotranspiration (ETc) and yield was also studied (Figure 10) and it was notably stronger at the Becker site compared to Westport. Quadratic functions provided the best fit for both locations; however, the coefficient of determination (R^2) was substantially higher at Becker ($R^2 = 0.58$) than at Westport ($R^2 = 0.16$). This suggests that yield variability at Becker was more closely associated with seasonal ETc patterns, while at Westport, yield was less dependent on ETc fluctuations. Based on the fitted production functions, the estimated optimal ETc for maximum yield was approximately 18.4 inches at Becker and 17.9 inches at Westport. Although the optimal ETc values were relatively similar across sites, the strength of the

ETc–yield dependency differed markedly. At Becker, achieving near-optimal ET was critical for maximizing yield, as reduced ETc corresponded to significant yield declines. In contrast, at Westport, yield penalties associated with lower ETc were modest, indicating a reduced dependency of yield on ETc.

One plausible explanation for this difference is the rainfall distribution and soil moisture dynamics at the two sites. At Westport, timely and well-distributed rainfall events likely minimized soil water deficits even under lower irrigation treatments. As a result, crop stress due to water limitation was reduced, leading to relatively stable yields across irrigation levels. In contrast, Becker likely experienced periods of greater soil moisture deficits under reduced irrigation, making supplemental water (and thus total ET) a more critical driver of yield outcomes. These findings are consistent with previous studies (Irmak et al., 2014; Payero et al., 2006), which have shown that the strength of ET–yield relationships is site-specific and highly sensitive to rainfall timing, soil properties, and crop water demand. Under conditions where rainfall is insufficient or poorly timed, irrigation becomes a major contributor to total ETc, leading to a tighter coupling between ETc and yield. Conversely, under minimally stressed conditions, crop yields may reach near-maximum levels without requiring high ETc, diminishing the apparent dependency between these variables. Overall, these results underscore the importance of considering site-specific water dynamics when interpreting ETc–yield relationships and designing irrigation management strategies.

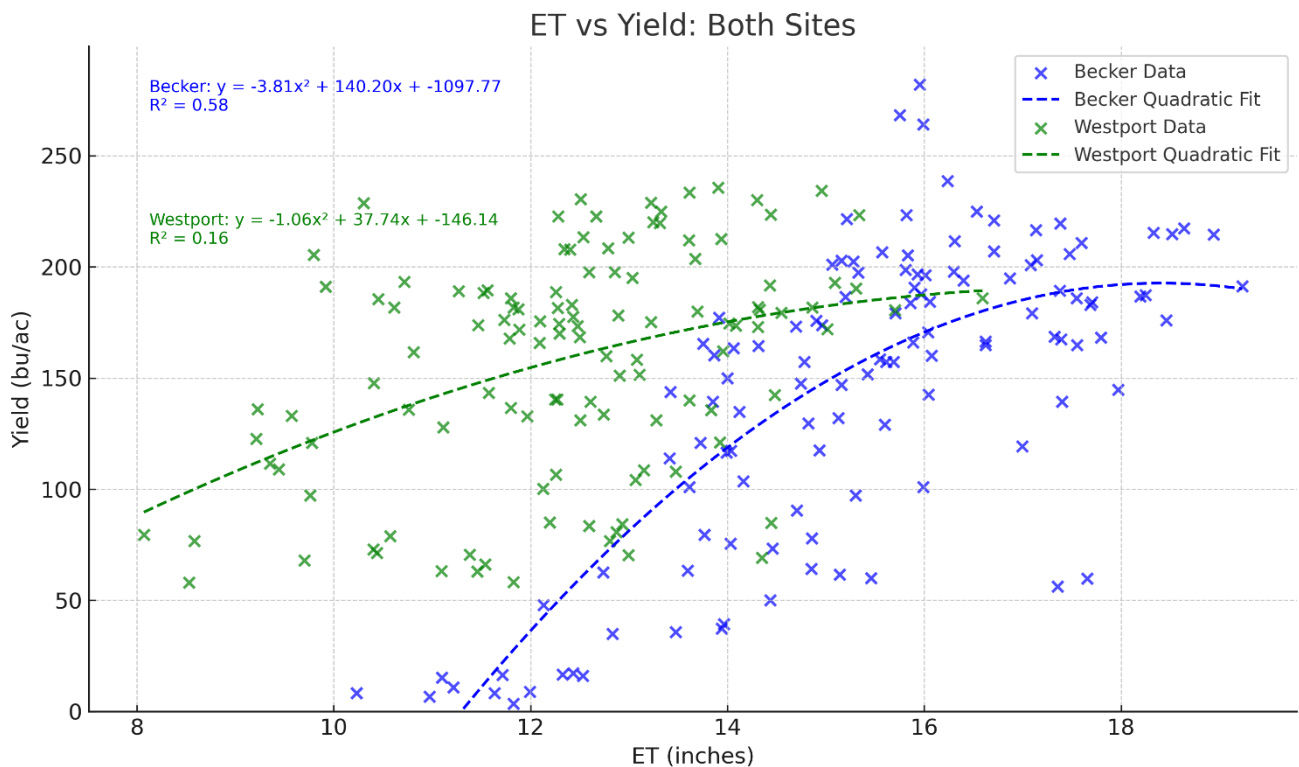


Figure 10. Corn yield and Etc relationship at Becker and Westport, MN

Table 3. Grain yield, actual evapotranspiration (ETc), nitrate leaching, R6, Grain and Total N uptake, and crop water use efficiency (CWUE) for 0, 70, 140, 210, 280 and 350 lb ac⁻¹ nitrogen treatments under fully irrigated (I1), limited irrigation (I2 and I3), and rainfed settings (I4) for 2020-2024 combined data at Becker, MN.

I	N	Yield (bu/ac)	ET (in)	Leaching (lb/ac)	R6 N uptake (lb/ac)	Grain N uptake (lb/ac)	Total N uptake (lb/ac)	CWUE (bu/ac-in)
I1	N1	70.07	15.67	5.97	21.86	58.81	80.67	4.42
I1	N2	152.78	15.42	5.36	35.12	104.78	139.90	9.92
I1	N3	194.78	17.46	4.30	40.80	127.36	168.16	11.11
I1	N4	216.07	16.98	8.36	60.70	151.61	212.31	12.79
I1	N5	224.04	16.20	9.60	72.53	158.65	231.19	14.16
I1	N6	218.33	16.78	12.07	79.69	161.47	241.16	13.33
Avg. of all N		179.35 a	16.42 a	7.61 a	51.78 b	127.11 a	178.90 a	10.96 a
I2	N1	59.00	15.01	3.78	20.12	64.94	85.06	3.90
I2	N2	144.00	16.03	3.84	33.76	97.54	131.30	9.14
I2	N3	180.41	16.57	3.70	43.03	130.99	174.02	10.90
I2	N4	196.30	16.35	8.25	57.17	151.02	208.19	12.29
I2	N5	198.61	17.02	9.00	70.70	147.94	218.64	12.08
I2	N6	202.22	17.58	6.48	75.37	163.20	238.58	11.61
Avg. of all N		163.42 ab	16.42 a	5.84 ab	50.02 b	125.94 a	175.96 ab	9.99 a
I3	N1	63.32	14.25	2.67	20.01	55.37	75.39	4.39
I3	N2	135.11	14.89	3.28	34.11	103.61	137.72	8.86
I3	N3	165.49	15.78	2.65	47.70	131.41	179.11	10.74
I3	N4	172.98	15.95	2.78	63.32	130.12	193.44	11.03
I3	N5	173.94	16.05	4.34	71.94	142.83	214.78	10.91
I3	N6	184.40	16.00	8.91	84.35	155.82	240.17	11.77
Avg. of all N		149.21 b	15.49 b	4.11 b	53.57 b	119.86 a	173.43 ab	9.61 a
I4	N1	44.85	12.48	3.00	32.09	52.19	84.28	3.63
I4	N2	77.20	13.19	3.20	55.48	68.33	123.81	5.46
I4	N3	94.38	13.12	3.57	73.71	83.94	157.65	6.43
I4	N4	87.31	13.61	4.34	89.52	79.24	168.76	5.51
I4	N5	100.57	13.03	7.44	101.36	95.17	196.53	6.99
I4	N6	97.80	13.48	7.15	104.97	85.02	189.99	6.69
Avg. of all N		83.68 c	13.15 c	4.78 b	76.19 a	77.31 b	153.50 b	5.78 b
Average of all irrigations	N1	59.31 c	14.35 b	3.86 b	23.52 d	57.82 d	81.35 e	4.08 c
	N2	127.27 b	14.88 ab	3.92 b	39.62 c	93.56 c	133.18 d	8.35 b
	N3	158.77 a	15.73 a	3.55 b	51.31 c	118.43 b	169.73 c	9.80 ab
	N4	168.16 a	15.72 a	5.93 ab	67.68 b	128.00 ab	195.67 b	10.40 a
	N5	174.29 a	15.57 a	7.59 a	79.13 ab	136.15 ab	215.28 ab	11.04 a
	N6	175.69 a	15.96 a	8.65 a	86.09 a	141.38 a	227.48 a	10.85 a

For a given variable, the mean value with the same letter are not significantly different.

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Table 4. Grain yield, actual evapotranspiration (ETc), nitrate leaching, R6, Grain and Total N uptake, and crop water use efficiency (CWUE) for 0, 70, 140, 210, 280 and 350 lb ac⁻¹ nitrogen treatments under fully irrigated (I1), limited irrigation (I2 and I3), and rainfed settings (I4) for 2020-2024 combined data at Westport, MN.

I	N	Yield (bu/ac)	ET (in)	Leaching (lb/ac)	R6 N uptake (lb/ac)	Grain N uptake (lb/ac)	Total N uptake (lb/ac)	CWUE (bu/ac-in)
I1	N1	74.36	11.79	7.01	23.80	52.21	76.01	7.09
I1	N2	143.28	12.46	5.43	36.57	90.48	127.05	12.20
I1	N3	184.52	13.33	8.15	45.43	123.50	168.93	13.85
I1	N4	201.46	13.30	14.34	58.67	146.86	205.53	15.35
I1	N5	206.92	13.99	17.43	63.31	149.01	212.33	15.14
I1	N6	204.23	13.71	22.92	70.27	151.03	221.30	15.17
Avg. of all N		169.13 a	13.10 a	12.55 a	49.67 a	118.85 a	168.52 a	13.13 a
I2	N1	77.22	11.40	7.50	29.24	52.90	82.14	6.93
I2	N2	142.26	12.20	5.93	39.24	92.36	131.60	11.81
I2	N3	185.00	12.27	8.44	47.44	119.93	167.37	15.27
I2	N4	202.92	12.55	17.12	58.80	139.64	198.44	16.97
I2	N5	197.96	12.75	16.70	66.01	146.58	212.60	16.02
I2	N6	210.91	12.86	20.29	69.71	155.95	225.65	17.17
Avg. of all N		169.34 a	12.34 ab	12.66 a	51.74 a	117.90 a	169.63 a	14.03 a
I3	N1	77.06	11.72	7.02	26.10	65.99	92.10	6.93
I3	N2	140.89	12.03	5.49	38.00	90.72	128.72	12.05
I3	N3	177.26	12.39	8.99	43.84	122.14	165.97	14.85
I3	N4	192.48	12.90	10.10	55.51	142.01	197.52	15.75
I3	N5	186.80	13.05	13.75	64.18	146.23	210.41	14.54
I3	N6	201.10	12.34	20.19	68.85	142.92	211.77	16.85
Avg. of all N		162.60 a	12.40 b	10.92 a	49.41 a	118.33 a	167.75 a	13.50 a
I4	N1	63.50	10.31	4.46	29.09	43.16	72.25	6.54
I4	N2	118.88	12.03	5.93	40.38	88.69	129.07	10.01
I4	N3	137.60	10.96	11.14	48.60	119.60	168.20	13.49
I4	N4	143.52	11.57	14.80	62.48	127.13	189.61	12.79
I4	N5	137.42	11.73	23.94	63.18	124.69	187.88	11.73
I4	N6	143.91	11.80	27.20	63.26	128.13	191.39	12.51
Avg. of all N		124.14 b	11.40 c	14.58 a	51.16 a	105.23 a	156.40 a	11.18 b
Average of all irrigations	N1	73.03 d	11.30 b	6.50 d	27.06 e	53.57 d	80.62 a	6.87 c
	N2	136.33 c	12.18 ab	5.69 d	38.54 d	90.56 c	129.11 d	11.52 b
	N3	171.10 b	12.24 ab	9.18 cd	46.33 c	121.29 b	167.62 c	14.36 a
	N4	185.10 ab	12.58 a	14.09 bc	58.86 b	138.91 a	197.77 b	15.21 a
	N5	182.27 ab	12.88 a	17.95 ab	64.17 ab	141.63 a	205.80 ab	14.36 a
	N6	190.04 a	12.68 a	22.65 a	68.02 a	144.51 a	212.53 a	15.43 a

For a given variable, the mean value with the same letter are not significantly different.

Analysis of the total water (precipitation plus irrigation) versus evapotranspiration (ETc) relationship across all study years was also performed and is shown in Figure 11. The relationship revealed that maximum ETc occurred at approximately 22.7 inches of total water at Becker and 23.0 inches at Westport. Quadratic functions provided the best fit for both locations, consistent with prior studies demonstrating that crop ETc often responds nonlinearly to increasing water availability (Irmak et al., 2014; Howell et al., 1998). These results suggest that a total water input in the range of 22–23 inches optimizes crop water use and minimizes non-beneficial water losses under the soil, climatic, and crop management conditions encountered in this study.

Importantly, the observed optimum total water levels were not consistently achieved across all irrigation treatments and years, reflecting limitations due to precipitation variability and irrigation system capacity. This finding highlights a critical management implication: irrigation strategies should target achieving total seasonal water availability near the ETc optimum to maximize water productivity, particularly in years with lower in-season rainfall. Providing less than optimal total water can constrain ETc and ultimately reduce yield potential, while excessive irrigation beyond the ETc plateau may contribute to deep percolation losses without proportional yield gains (Klocke et al., 2004; Geerts and Raes, 2009).

Incorporating these findings into irrigation scheduling could help optimize system design and management recommendations. Specifically, targeting approximately 22–23 inches of combined irrigation and rainfall could serve as a benchmark for full-season water management in similar agroecosystems, helping growers balance yield goals with water conservation priorities under variable precipitation scenarios.

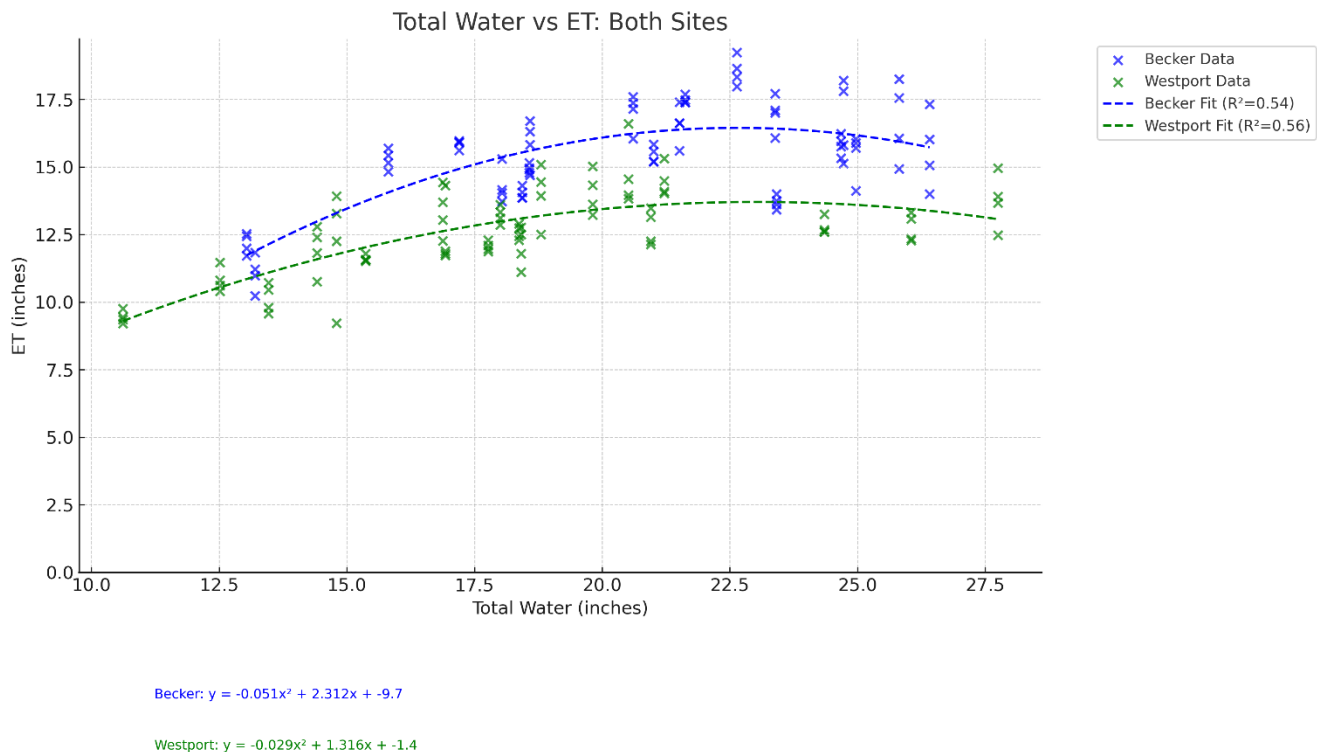


Figure 11. Total water (precipitation plus irrigation) versus evapotranspiration (ETc) relationship for Becker and Westport, MN.

Treatment Effect on Nitrogen Uptake

Nitrogen uptake was shown at three levels- R6 uptake (total aboveground N at physiological maturity), grain N uptake, and total N uptake (sum of grain and stover N) (Table 3 and 4). These metrics provide insight into nitrogen use efficiency and crop demand across irrigation and nitrogen treatments. Figures 12 and 13 shows R6 and grain N uptake at Becker, respectively and Figure 14 and 15 shows R6 and grain N uptake at Westport, respectively.

At Becker, all three nitrogen uptake metrics increased significantly with increase in nitrogen rate with a very slight increase after N5 (280 lb/ac) (Table 3). R6 N uptake increased from 21.9 lb/ac in I1–N1 to a maximum of 79.7 lb/ac in I1–N6. The pattern held across all irrigation levels, with moderate gains beyond N4 and a plateau at N6. Grain N uptake followed a similar trajectory, rising from 58.8 lb/ac (I1–N1) to 161.5 lb/ac (I1–N6). This indicates strong partitioning of nitrogen into reproductive tissues under high N availability, particularly in well-irrigated treatments. The stover N was lower than grain N under irrigated treatments where as under rainfed treatment stover N was greater than grain N indicating a stress-induced disruption in nitrogen remobilization and grain filling under water-limited conditions. In well-watered environments, plants efficiently translocate nitrogen from vegetative tissues to developing grain during reproductive stages. However, under drought or rainfed conditions, limited water availability can impair photosynthesis, protein synthesis, and kernel development which reduce sink strength in the grain.

Total N uptake (grain + stover) showed the highest values under fully irrigated, high-N treatments, peaking at 241.2 lb/ac in I1–N6, but with minimal increases beyond N5, suggesting inefficient N use at the highest rate.

Irrigation had a strong effect on all N uptake parameters. Fully irrigated plots (I1) consistently had higher N uptake values than rainfed plots (I4) however no significant difference between I1, I2, and I3 was observed. For instance, total N uptake in I1–N5 was 231.2 lb/ac, compared to 196.5 lb/ac in I4–N5, despite the same N application rate. This highlights the importance of water availability in facilitating nitrogen uptake and transport in the plant.

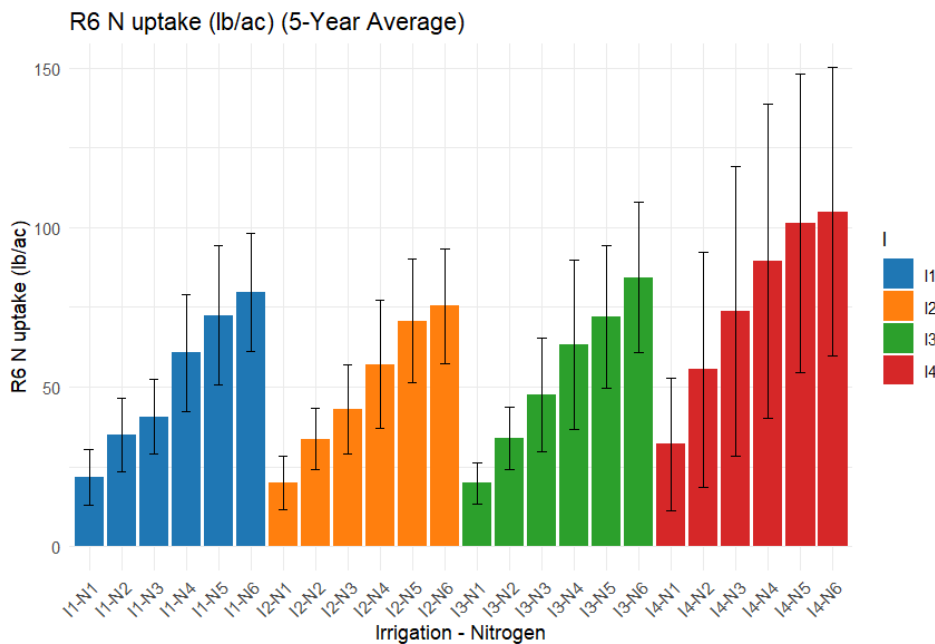


Figure 12. Nitrogen uptake at R6 corn growth stage under different irrigation and nitrogen treatments at Becker, MN.

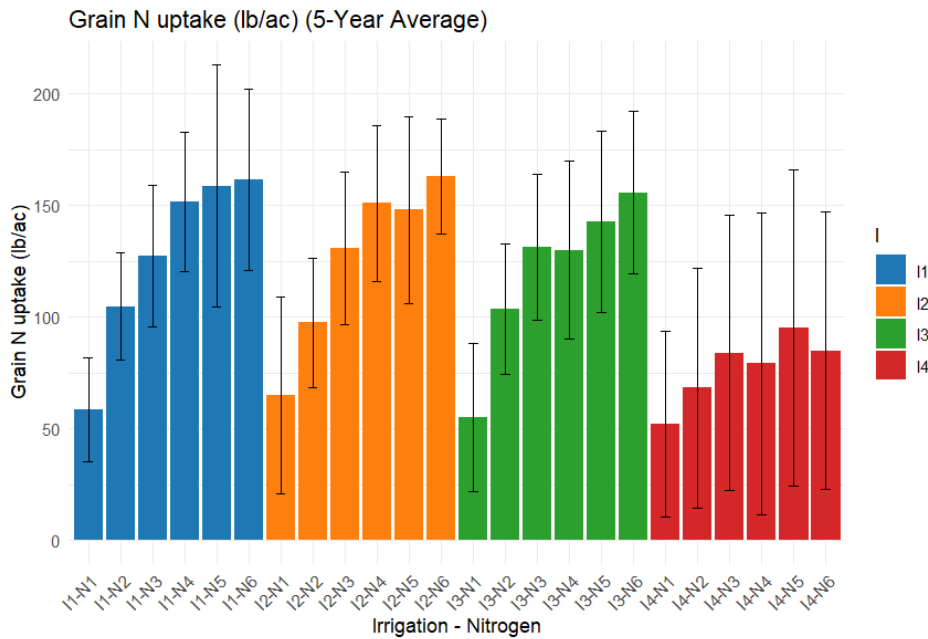


Figure 13. Grain nitrogen uptake under different irrigation and nitrogen treatments at Becker, MN.

At Westport, nitrogen uptake values mirrored trends seen at Becker, with significant increases across N treatments and moderate effects of irrigation (Figures 14 and 15, and Table 4). R6 N uptake ranged from 23.8 lb/ac (I1–N1) to 70.3 lb/ac (I1–N6) under full irrigation, showing a consistent rise with N input. Interestingly, even under reduced irrigation (I3), total N uptake remained high at Westport when sufficient N was available. For instance, I3–N5 and I3–N6 produced total N uptake values over 210 lb/ac, indicating that Westport's rainfall patterns helped sustain N uptake despite lower irrigation volumes. Grain N uptake increased sharply from 52.2 lb/ac (I1–N1) to 151.0 lb/ac (I1–N6), demonstrating a similar pattern of efficient nitrogen partitioning as observed at Becker. Total N uptake peaked at 225.6 lb/ac (I2–N6), comparable to the maximum seen at Becker, though the response to increasing N was more gradual.

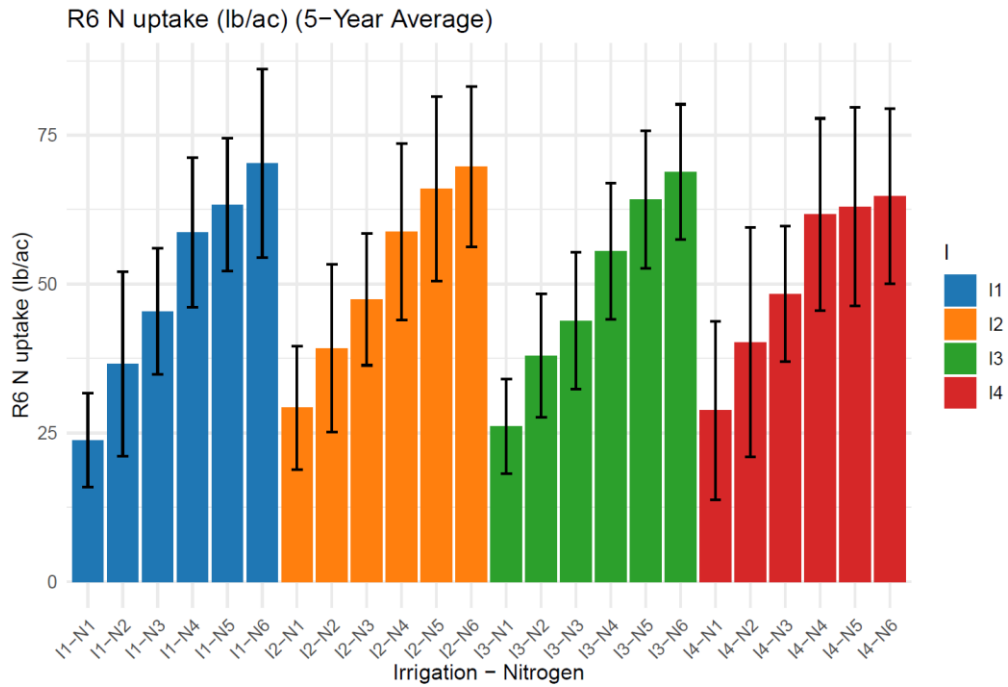


Figure 14. Nitrogen uptake at R6 corn growth stage under different irrigation and nitrogen treatments at Westport, MN.

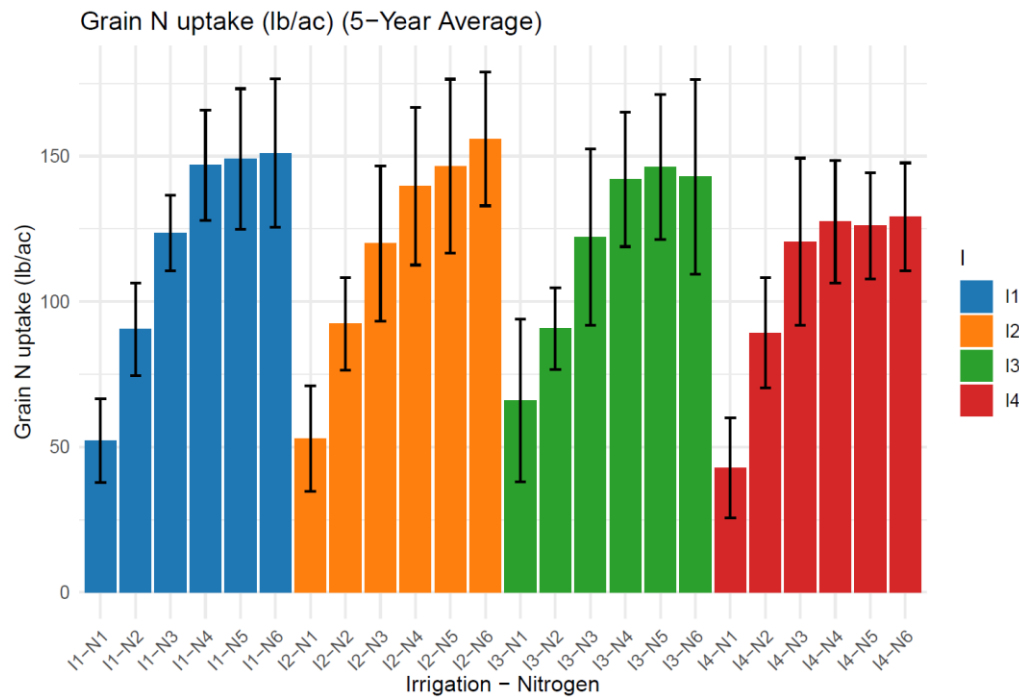


Figure 15. Grain nitrogen uptake under different irrigation and nitrogen treatments at Westport, MN.

Treatment Effect on Nitrate Leaching

Nitrate leaching was strongly influenced by both irrigation and nitrogen rates, with the highest losses observed in treatments combining high N inputs and excessive water supply (Tables 3 & 4 and Figures 16 and 17). At Becker, leaching ranged from 3 lb/ac (I4–N1) to over 12 lb/ac (I1–N6), showing a clear increase with both irrigation level and N rate. A slight different pattern was observed at Westport, with highest N leaching under rainfed setting (I4) and N6. The leaching values at Westport are slightly greater than Becker. We did not find a significant difference in leaching between irrigation treatments at Westport where as at Becker, I1 had a significantly higher leaching than I3 and I4. Rainfed (I4) and deficit irrigation (I3) treatments consistently had the lowest leaching losses, especially under low to moderate N inputs (N1–N3) at Becker. This confirms that water movement through the soil profile, driven largely by irrigation, plays a critical role in nitrate transport beyond the root zone. The impact of nitrogen rate on leaching was significant at both sites with higher N rate (N5–N6) had significantly higher leaching losses as compared to N1–N3. We observed a similar trend in yield where after N4 the increase in yield was very slow or negligible indicating that there are increased leaching losses that impacted yield at higher N rates.

Evapotranspiration (ETc) also contributed to this dynamic. Treatments with higher ETc (e.g., I1–N4 or N5) had greater plant water and nutrient demand, supporting higher N uptake and yield. However, in cases like I1–N6, ETc decreased, while leaching spiked, indicating that the additional water primarily promoted leaching rather than productive transpiration. This highlights the need for fine-tuned irrigation and N synchrony to minimize unproductive water and nutrient losses.

Westport consistently exhibited higher nitrate leaching than Becker, especially under full irrigation and high nitrogen treatments. This pattern is likely driven by greater total rainfall and, more importantly, poorly timed precipitation events, particularly in years like 2021, when large rainfall amounts occurred in August and September, after peak crop N demand had passed. Such late-season rainfall can lead to substantial nitrate flushing, especially when residual soil N remains high. In contrast, Becker received less rainfall overall and experienced more controlled leaching losses, as irrigation was the primary water input and could be better timed with crop demand. For example, in I1–N6, Westport leaching exceeded 75 lb/ac, while Becker remained closer to 55–60 lb/ac. These results highlight how unpredictable rainfall at Westport increased the potential for nitrate losses, even under similar irrigation and fertilization regimes.

These results emphasize the need for site-specific, weather-informed irrigation and nitrogen management. Applying more than 200–250 lb N/ac or irrigating beyond 75% of crop ETc led to disproportionate increases in leaching without meaningful yield gains. The combination of deficit irrigation (I2) and moderate nitrogen (N4–N5) emerged as the most efficient strategy for maintaining high yields while minimizing environmental losses.

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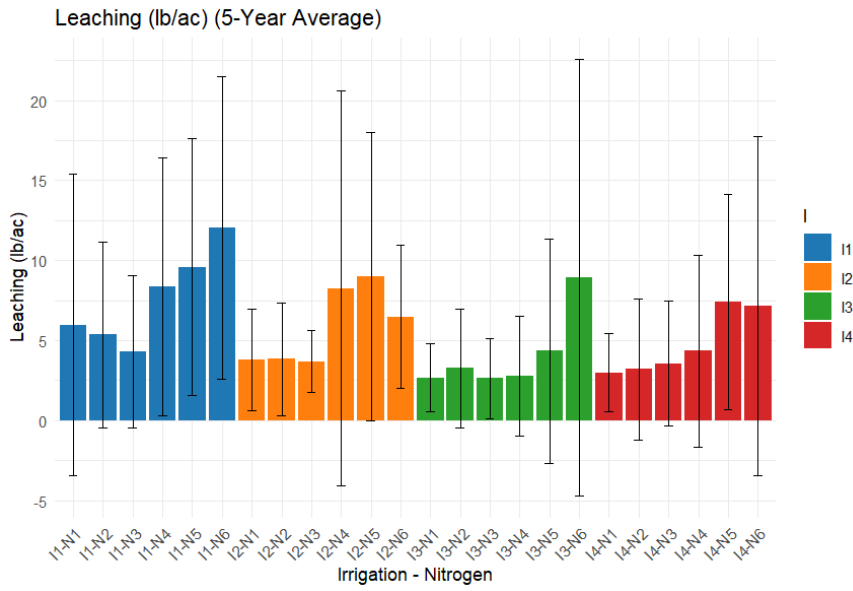


Figure 16. Nitrate leaching losses under different irrigation and nitrogen treatments at Becker, MN.

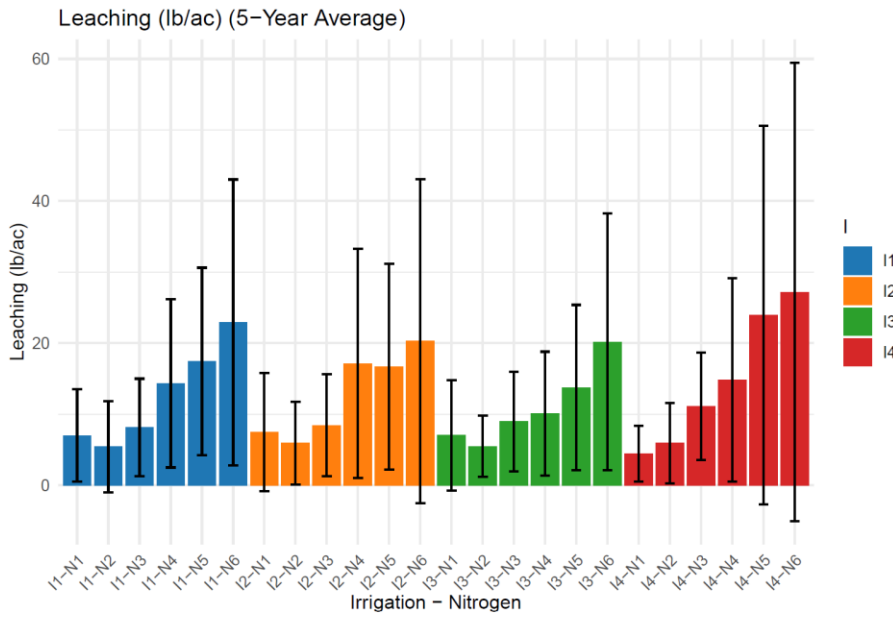


Figure 17. Nitrate leaching losses under different irrigation and nitrogen treatments at Becker, MN.

Conclusions

This 5-year study across two sites in Minnesota- Becker and Westport, provides robust functional insights into how irrigation and nitrogen management strategies impact corn productivity, evapotranspiration (ET_c), nitrogen uptake, and environmental losses under variable irrigation and nitrogen rates. By quantifying yield responses and resource use patterns across a gradient of irrigation and nitrogen inputs, this work offers clear, actionable thresholds for optimizing both yield and sustainability.

Grain yield showed consistent curvilinear responses to nitrogen, with a plateau around 210–250 lb N/ac (N4–N5), beyond which gains diminished. Yield also increased with irrigation, especially at Becker, where full irrigation (I1) significantly outperformed rainfed treatment. However, moderate irrigation (I2) delivered yields nearly equivalent to I1, suggesting that 75% irrigation treatment is a strategic middle ground for balancing productivity and water use. At Westport, where rainfall timing and distribution played a larger role, rainfed and deficit irrigation plots performed relatively well, reinforcing the value of rainfall buffering in humid climates.

Evapotranspiration increased with both irrigation and nitrogen, but plateaued beyond ~23 inches of total water (precipitation and irrigation) input. Maximum yield was associated with ET_c values near 18 inches, though in many years, that threshold was difficult to achieve without substantial irrigation, especially at Becker. Nitrogen uptake and partitioning also improved with irrigation, highlighting the critical role of water in enabling effective nutrient assimilation. However, under rainfed conditions, stover N often exceeded grain N, indicating impaired remobilization and reduced nitrogen use efficiency.

Nitrate leaching was strongly driven by both irrigation and nitrogen rate, with the highest losses observed under high N and full irrigation at Becker. Notably, Westport experienced higher leaching than Becker, primarily due to poorly timed rainfall, particularly in August and September, which exceeded crop N demand and flushed residual soil nitrate. In contrast, Becker's more irrigation-controlled system enabled better synchronization of water and nitrogen with crop needs.

Taken together, these findings highlight the importance of site-specific, seasonally responsive IxN strategies. Across both locations, the combination of moderate irrigation (I2) and N4–N5 nitrogen rates consistently delivered high yield, high water productivity, and low environmental loss. These functional thresholds can inform practical guidelines for growers, while also supporting regulatory frameworks focused on nitrogen efficiency and water conservation in the Upper Midwest.

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