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

2024 Annual Report—Fourth Year of a five-Year Project (2023 corn growing season results)

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Summary

Under reduced irrigation rates, nitrogen (N) fertilizer must be correspondingly adjusted to optimize economic crop production. However, in Minnesota, the combined effects of irrigation and N management on corn yield and nitrate leaching have not been extensively investigated. As one example, the current N recommendations in Minnesota are based on 100% irrigation or rainfed conditions. However, with increasing pressure on water resources and declining water quality, deficit/limited irrigation management practices are being promoted and used, which alters the N uptake by the crop. Will reduction in irrigation rates (using deficit irrigation management) reduce the N fertilizer requirement and thus nitrate leaching? What is the best irrigation and nitrogen management combination practice that will maintain optimum crop yields while reducing nitrate leaching? These are the questions that irrigators and key agricultural stakeholders have, and we do not have the answers to. So our goal is to develop research-based irrigation and N management data, information and fundamental relationships that will help farmers to make better on-farm management decisions, government agencies to develop policy/rules, and researchers to advance the sensor-based (proximal and remote sensing) irrigation and N management research. This report discusses the results from the third growing season of this study.

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.

Major objectives of this study are to: 1) evaluate variable irrigation and N rate interaction effects on corn yield, nitrate-N leaching, crop evapotranspiration, crop water productivity, and water- and N-use efficiency; 2) develop corn evapotranspiration crop coefficient (Kc) curves for efficient irrigation management, and, 3) develop proximal and UAV remote sensing-based non-destructive in-season corn water and N status diagnosis methods and in-season variable rate N and irrigation management strategies.

Methods

Field plot experiments were conducted at the Sand Plain Research Farm (SPRF) in Becker, MN (45º 20' N, 93º 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). 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, 125% of FI, 65% 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. 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 (Figure 2).

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 (ETa) and drainage. Crop water use efficiency (CWUE), which is the ratio of yield (Y, kg/m2) to crop water use (ETa, mm) and irrigation water use efficiency (IWUE) which is the ratio of (yield – rainfed yield)/irrigation water applied was estimated for each treatment.

Economic optimum N rate (EONR) was calculated using the regional N rate guideline approach with an N fertilizer to corn price ratio reflecting mean market prices.

Analysis of variance (ANOVA) was conducted using Proc Mixed in SAS. Fisher's Protected Least Significant Difference Test at a 95% confidence interval will be used to identify significant differences among mean grain yield and ETa of different treatments. The regression procedure will be used to test the heterogeneity of regression slopes of Irrigation and ETa on N fertilizer rates. The coefficient of determination (R^2) and standard deviation (SD) will also be used to assess potential treatment differences.

Crop coefficient (Kc) values are the ratio of soil water balance determined ETa and ETref from the Penman-Monteith equation: $K_c = \frac{ET_a}{ET_{ref}}$. Since we do not have the complete dataset for three years, we have not developed these relationships yet. ETa will be calculated for each treatment as described in Task 1C. Daily reference evapotranspiration (ETref) will be calculated using the Penman-Monteith equation. The weather variable for calculating ETref will be obtained from the weather station at the research sites. Crop coefficients will be calculated for each treatment on a weekly basis. Crop coefficient curves as a function of cumulative growing degree days (GDD) will be developed for each irrigation and nitrogen combination treatments.

Sensing data was collected from each plot and related to soil moisture measured using neutron probe. The Crop Circle Phenom proximal sensor has three spectral bands and sensing capability to measure air temperature, crop canopy temperature, humidity, and LAI, relative chlorophyll content and photosynthetically active radiation (PAR) etc. This instrument was used to collect weekly measurements until V12. A UAV remote sensing system with an optical camera of 6 wavebands and FLIR thermal camera was used to monitor corn N and water status across the growing season. These data will be used together with ground truthing data to develop non-destructive N and water status diagnosis methods.

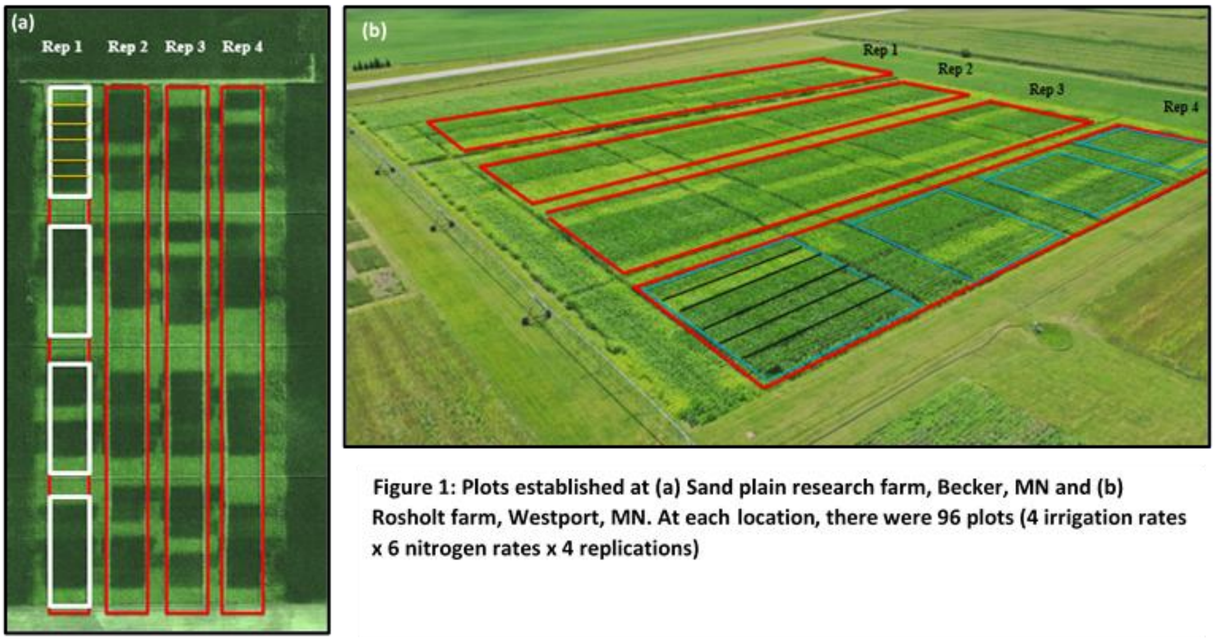


Figure 1: Plots established at (a) Sand plain research farm, Becker, MN and (b) Rosholt farm, Westport, MN. At each location, there were 96 plots (4 irrigation rates x 6 nitrogen rates x 4 replications)

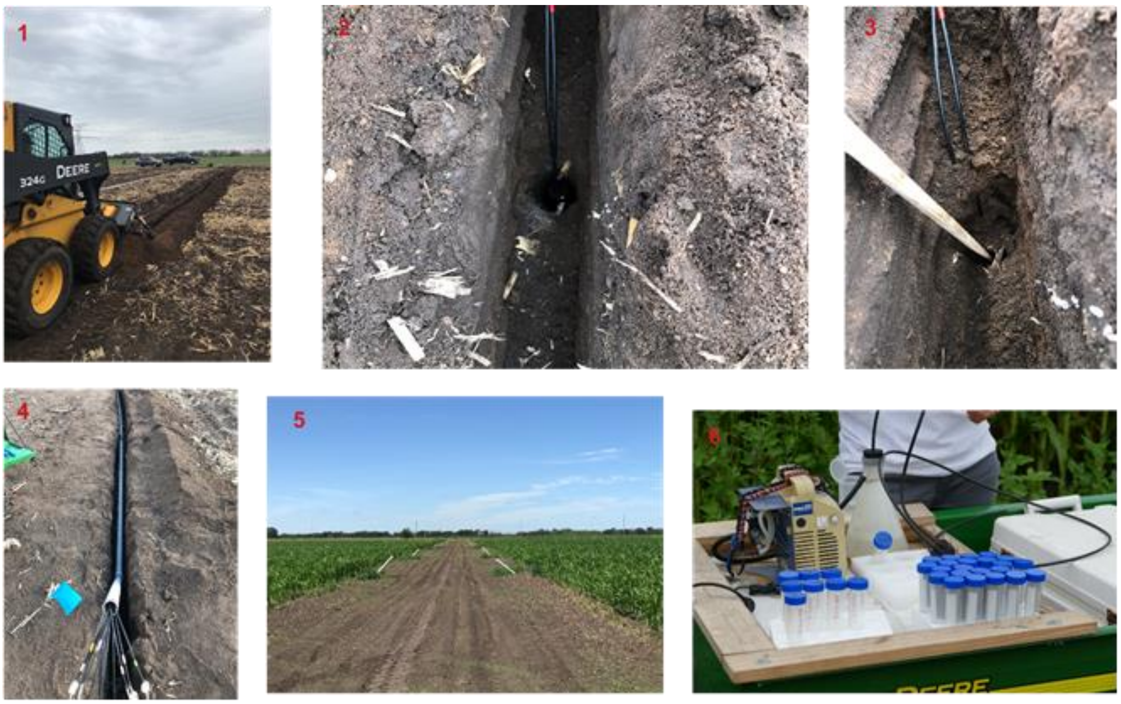


Figure 2: Permanent suction cup lysimeter installation. 1. Digging 2 feet deep trenches, 2. Dug a 2 feet deep hole inside the trench so that the bottom of the lysimeter is at 4 feet and then lowered the lysimeter in, 3. Packed the soil around the lysimeter so that there is no preferential flow, 4. Connected 6 lysimeters together and brought them out from one outlet, 5. Final picture of lysimeter outlets, 6. Intern collecting the water samples from the lysimeters.

Results from the fourth year of the study

The average growing season precipitation in 2023 was 17 inches and 13 inches at SPRF and Westport sites, respectively. The average growing season (planting to harvesting) temperature was 64ºF at SPRF and 65ºF at Westport. The 100% irrigation applied was 6 inches at SPRF and 5.2 inches at the Westport site.

The grain yields that were measured for all N treatments under 125% irrigation, 100% irrigation, 65% irrigation, and rainfed conditions for the 2023 growing season at SPRF and Westport, MN are presented in table 1. The maximum grain yield result obtained at SPRF was 201 bu/ac under the 125% irrigation at 280 lb N/ac treatment. The lowest grain yield was observed under rainfed conditions. At Rosholt farm, maximum grain yield of 228 bu/ac was observed under 100% irrigation at 350 lb N/ac and lowest yield was observed under rainfed treatment. In 2023, we observed a non-significant irrigation and nitrogen interaction effect on grain yield at Becker where as main effects of irrigation and nitrogen were significant. At Becker, no significant grain yield difference was observed between irrigation treatments, however, rainfed yield was significantly lower than irrigated treatments. At all levels of irrigation, grain yield increases with an increase in N application amount and then plateues or become stable at a certain N amount (table 1, and figures 3 and 4). No significant grain yield difference was observed between 140, 210, 280 and 350 lb N/ac treatments. At Westport, irrigation and nitrogen interaction was significant at $p<0.002$ (Table 2). Similar to Becker, no significant grain yield difference was observed between irrigation treatments, however rainfed plots had significantly lower yield as compared to irrigated treatments. At Westport, we observed a slight decline in yield at 280lb N/ac at all irrigation levels and a slight bump at 350lb N/ac. Overall, we see a similar response of yield N (figure 4) as at becker, where yield stabilizes at a higher N rate. Figures 3 and 4 show the grain yield response to nitrogen application under different irrigation treatments. A quadratic relationship was observed between grain yield and N application amounts for all irrigation levels at both sites.

The yield results of 2023 indicate that even in the dry years like 2023, there is a potential in using limited irrigation such as 65% irrigation as an irrigation management strategy to save water while producing a comparable yield.

At both sites, the effect of irrigation and nitrogen was also significant on evapotranspiration (ET) where as the effect of nitrogen and irrigation interaction was not significant. At both sites, ET was not significantly different between irrigated treatments and ET in rainfed treatment was significantly lower than irrigated treatments. For nitrogen treatment, the highest ET was observed for 210 lb/ac treatment at Becker and for 280lb/ac treatment at Westport. Overall, no significant difference in ET was observed beween 140, 210, 280 and 350 lb N/ac (Tables 1 and 2).

The effect of irrigation and nitrogen treatments on nitrate leaching was also observed in this study (Tables 1 and 2). We found a non-significant effect of irrigation on nitrate leaching, suggesting that precipitation is the major driver for nitrate leaching. Though not significant, at both sites we found highest leaching in 125% and 100% irrigation as compared to other treatments. The lowest leaching at both sites was observed in 65% irrigation treatment, even lower than rainfed plots indicating the need of optimum water for nitrogen uptake. A significant effect of N application amount on nitrate leaching was observed at both sites. Signifcantly higher leaching losses were observed at 350 lb N/ac as compared to lower N rates (Tables 1 and 2).

All the results preseneted in this report indicate the potential of reduced or deficit irrigation management in Minnesota as a management strategy which would help reduce the environmental pollution while maintaining our crop yields.

Table 1. Grain yield, Evapotranspiration (ET) and nitrate leaching for 0, 70, 140, 210, 280 and 350 lb N/ac treatments under I1=125% irrigation, I2=100% irrigation, I3=65% irrigation and rainfed settings for the 2023 growing season at SPRF, MN.

	N1	N2	N3	N4	N5	N6	Mean
Yield (bu/ac)							
I1	58.7	132.2	163.8	179.6	200.7	192.0	154.5a
I2	50.4	124.7	159.0	188.1	191.1	179.6	148.8a
I3	68.1	128.3	165.1	166.1	162.5	187.3	146.2a
I4	66.1	94.1	109.2	82.4	107.4	110.2	94.9b
Mean	60.8c	119.8b	149.3a	154.0a	165.4a	167.3a	
ET (in)							
I1	15.5	15.1	17.8	18.2	15.8	16.4	16.5a
I2	14.4	17.0	16.1	17.1	17.7	18.5	16.8a
I3	14.9	15.6	16.6	17.4	16.6	17.5	16.4a
I4	12.7	14.2	13.7	15.3	14.0	13.4	13.9b
	14.4c	15.5bc	16.1ab	17.0a	16.0ab	16.5ab	
Nitrate Leaching (lb/ac)							
I1	1.9	2.5	2.5	4.0	7.1	10.1	4.7a
I2	1.6	2.4	2.9	2.5	4.6	5.5	3.2ab
I3	1.1	1.4	1.3	1.2	1.5	6.4	2.1b
I4	2.2	1.6	2.3	1.9	4.0	4.4	2.7ab
	1.7c	1.9bc	2.2bc	2.4bc	4.3ab	6.6a	

Table 2. Grain yield, Evapotranspiration (ET) and nitrate leaching *for 0, 70, 140, 210, 280 and 350 lb N/ac treatments under* I1=*125% irrigation,* I2=100*% irrigation,* I3=65*% irrigation and rainfed settings for the 2023 growing season at Westport, MN.*

	N1	N2	N3	N4	N5	N6	Mean
Yield (bu/ac)							
I1	80.8	138.7	192.0	212.2	227.0	215.4	177.7a
I2	78.1	147.9	186.4	222.5	210.5	228.2	178.9a
I3	77.2	140.9	189.7	202.9	191.8	212.9	169.3a
I4	68.1	122.6	134.3	141.4	130.2	158.7	125.9b
Mean	76.0e	137.5d	175.6c	194.7ab	189.9b	203.8a	
ET (in)							
I1	10.6	12.5	15.1	13.9	14.4	15.3	13.6a
I2	12.9	13.1	12.9	13.3	13.6	13.2	13.2a
I3	12.8	12.3	13.7	13.0	14.4	13.0	13.2a
I4	9.7	13.9	9.2	12.2	13.3	12.9	11.9b
	11.5b	13.0ab	12.7ab	13.1a	13.9a	13.6a	
Nitrate Leaching (lb/ac)							
I1	2.3	1.5	2.6	6.0	8.5	8.2	4.9a
I2	3.8	2.4	3.3	8.1	4.1	11.2	5.5a
I3	1.9	3.2	2.7	3.3	6.0	7.3	4.1a
I4	1.6	1.5	6.4	5.4	5.9	8.8	4.9a
	2.4c	2.1c	3.8bc	5.7b	6.1ab	8.9a	

The responses of grain yield to irrigation (irrigation production function) for different nitrogen treatments are presented table 1 and figure 5 for SPRF and Westport. A quadratic relationship of irrigation and grain yield was observed for all nitrogen treatments. Higher N treatments typically experienced a greater increase in grain yield with increasing irrigation water than lower N treatments. At both sites, grain yield increased significantly with an increase in irrigation, however, plateaus or starts decreasing at higher levels of irrigation with an exception of 280 lb N/ac treatment at both sites. As expected, the lower N treatments imposed N deficiency on the crop resulting in greater variability in grain yield vs. irrigation amount relationship. However, at higher N rates, there was no N deficiency on the crop, therefore the grain yield vs irrigation amount relationships were stronger.

Detailed results, nitrogen leaching, uptake data and analysis and remote sensing analysis will be presented in the final report.

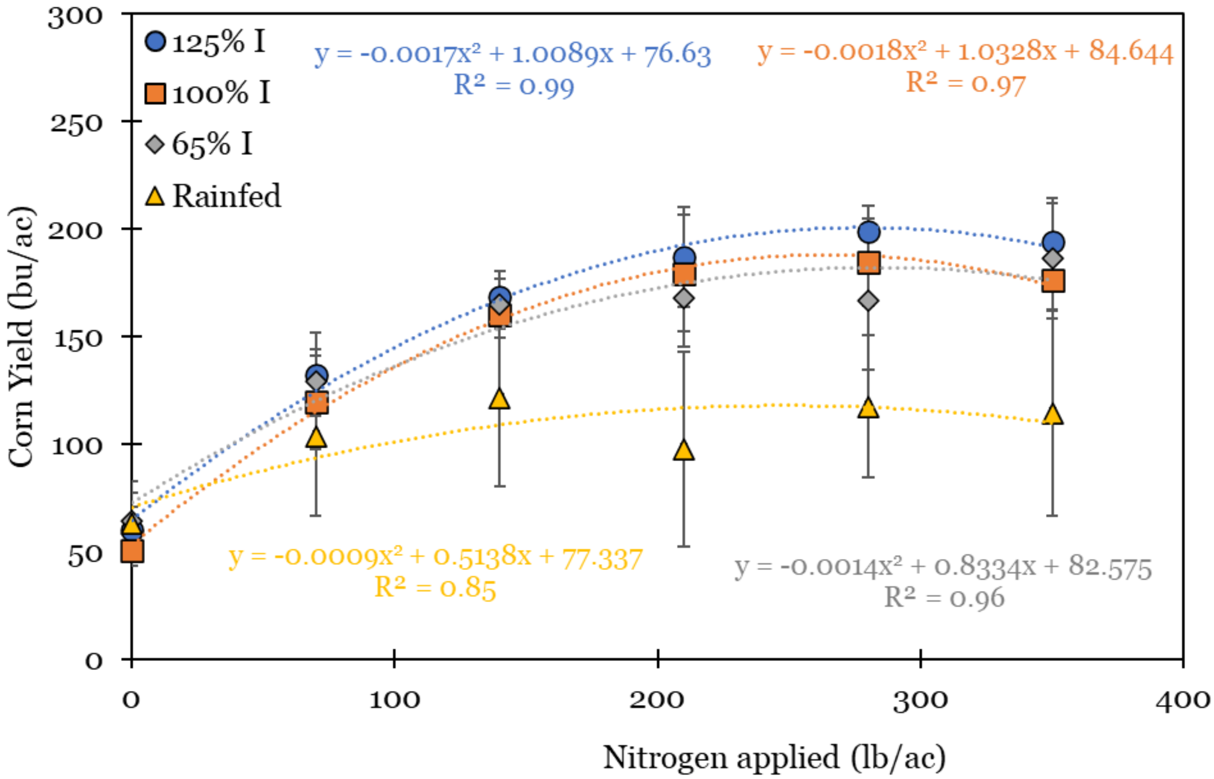


Figure 3. Grain yield response to nitrogen application under different irrigation treatments at SPRF, MN.

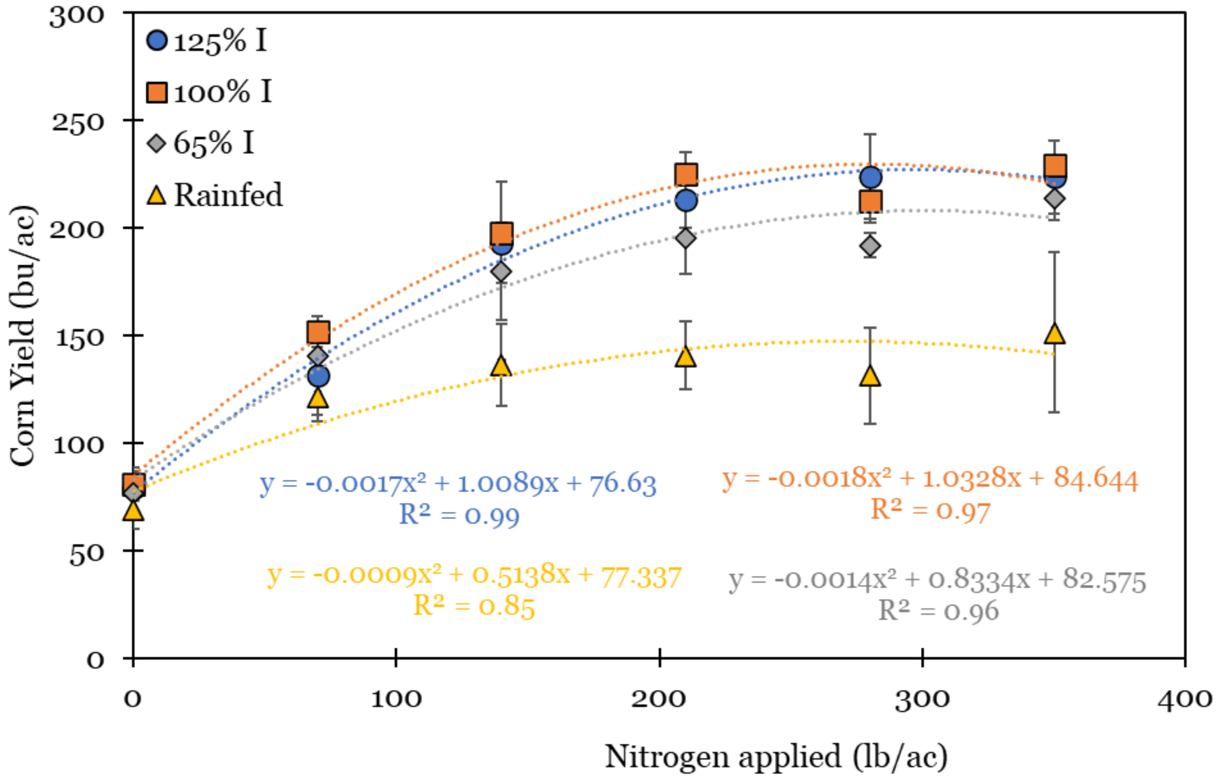
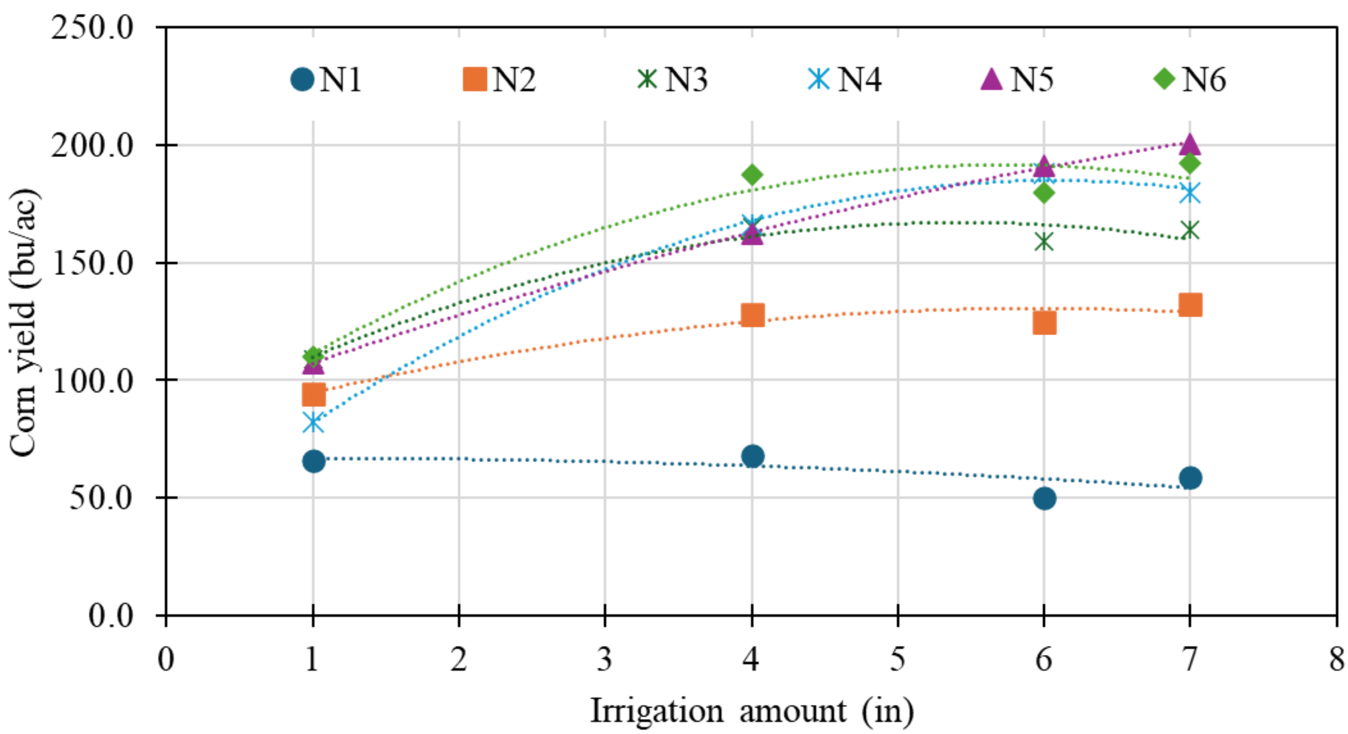


Figure 4. Grain yield response to nitrogen application under different irrigation treatments at Westport, MN.



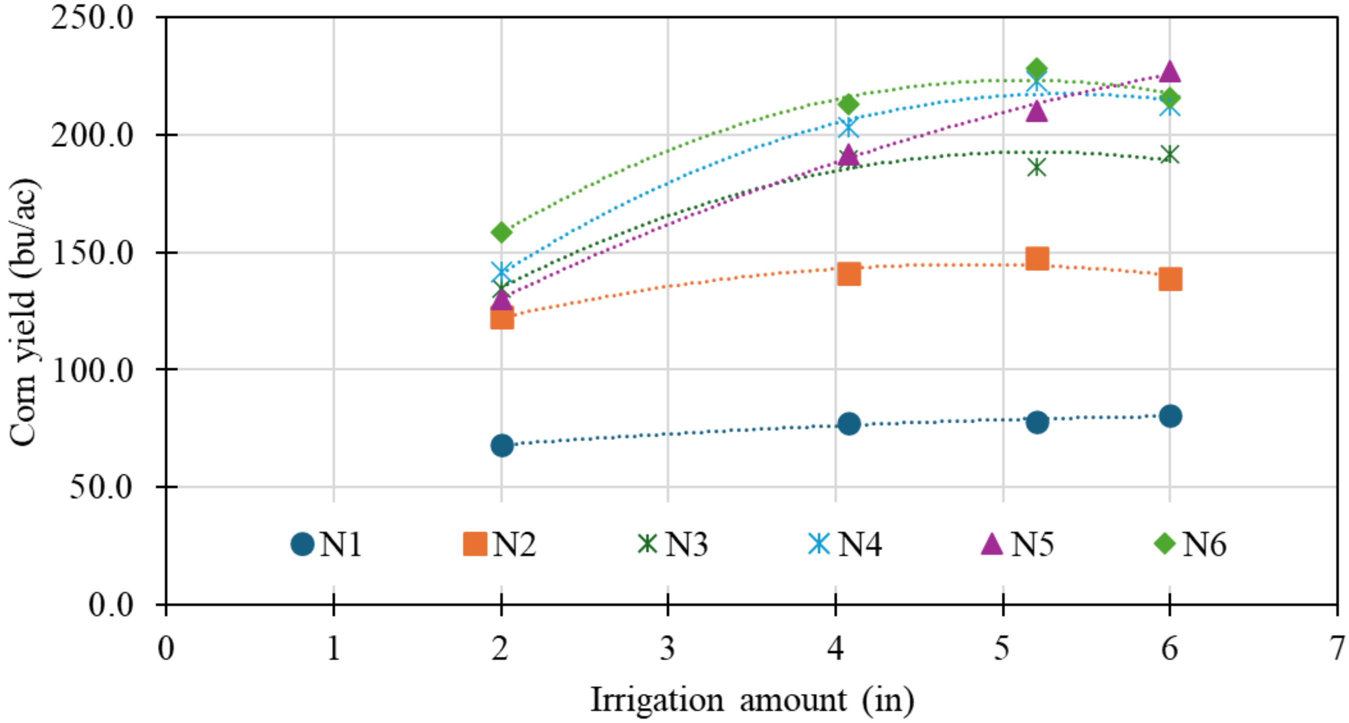


Figure 5. Grain yield response to irrigation at different nitrogen rates (top-SPRF and bottom-Rosholt farm)