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

2021 Annual Report—First Year of a three Year Project (2020 corn growing season)

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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 discussed the results from the first 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 as 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 in order to reduce the impact of agriculture on the environment but at the same time, requires robust and evolving research based scientific knowledge, specifically in the fields like irrigation that has not been explored much in Minnesota. An 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 researches 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 principle 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, 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. 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 was 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. 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) 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 (R2) 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: $\mathrm{K_c} = \frac{\mathrm{ET_a}}{\mathrm{ET_{ref}}}$. Since we just have one year of data, 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.

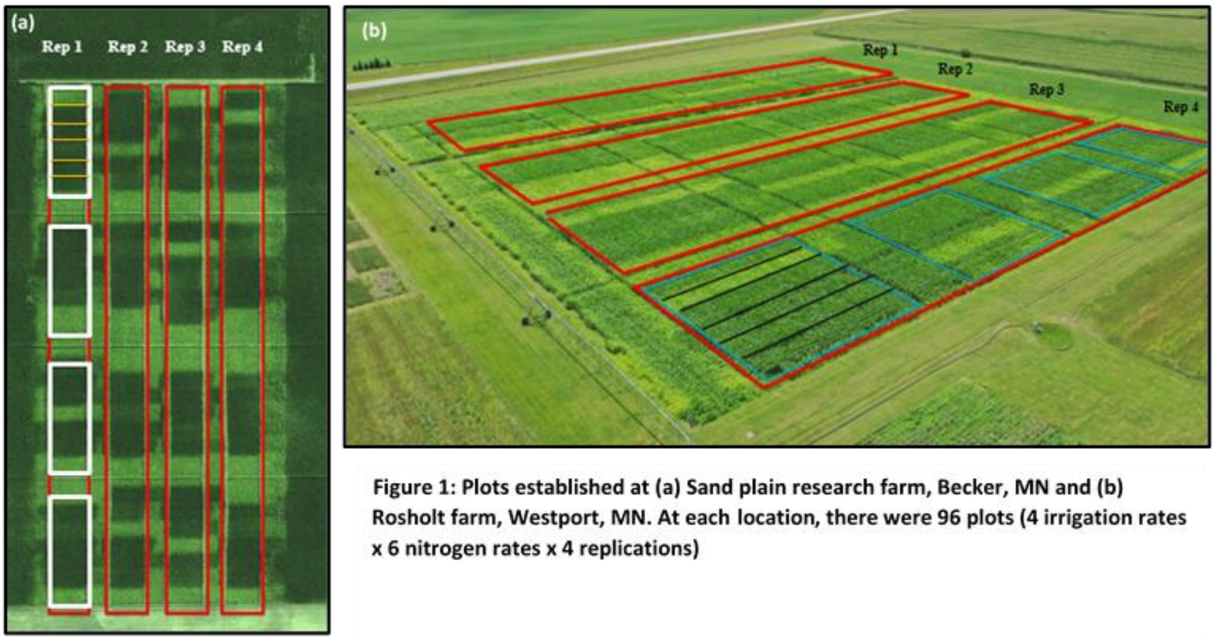

Figure 1: Plots established at (a) Sand plain research farm, Becker, MN and (b) Rosholt farm, Westport, MN. At each location, there were 96 plots (4 irrigation rates x 6 nitrogen rates x 4 replications)

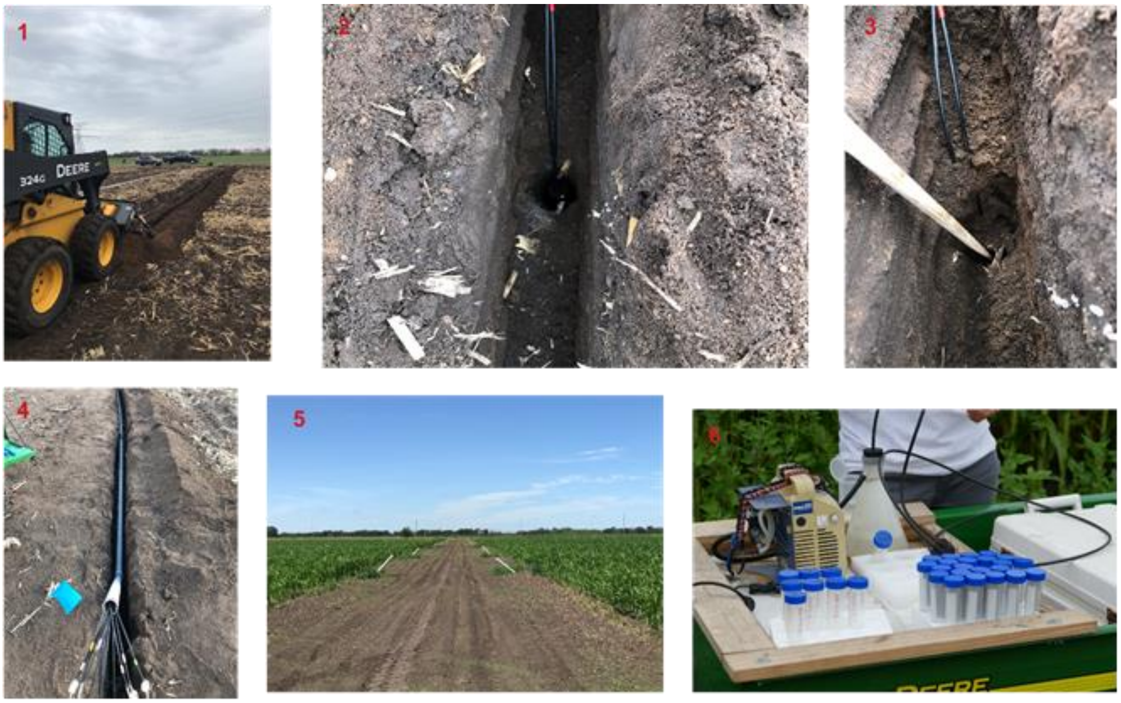

Figure 2: Permanent suction cup lysimeter installation. 1. Digging 2 feet deep trenches, 2. Dug a 2 feet deep hole inside the trench so that the bottom of the lysimeter is at 4 feet and then lowered the lysimeter in, 3. Packed the soil around the lysimeter so that there is no preferential flow, 4. Connected 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 first year of the study

The average growing season precipitation was 16 inches and 18 inches at SPRF and Westport site respectively. The average growing season (planting to harvesting) temperature was 18oC at SPRF whereas at Westport, average temperature was 16oC. The 100% irrigation applied was 7 inches at SPRF and 3.2 inches at the Westport site.

The grain yields that were measured for all N treatments under 100% irrigation, 75% irrigation, 50% irrigation, and rainfed conditions for the 2020 growing season at SPRF and Westport, MN are presented in tables 1 and 2, respectively. Greater grain yield response existed at Becker than at Westport in 2020. This could be due to higher growing season temperature and lower rainfall at Becker than at Westport. It is likely that the irrigation water was able to prevent crop water stress and allowed near-maximum transpiration rates to occur because high temperatures can stimulate N mineralization and consequently increase photosynthesis and transpiration. Due to this phenomenon there might be greater carbon assimilation, which most likely resulted in greater yield at Becker. The maximum grain yield result obtained at SPRF was 220 bu/ac under the 75% irrigation and 280 lb N/ac treatment. The lowest grain yield was also observed under 75% irrigated condition, however, it occurred at the lowest N treatment (0lb N/ac). In 2020, we did not find any significant effect of irrigation on grain yield however, effect of nitrogen on grain yield was significant. There was no interaction effect of irrigation and nitrogen on grain yield. At all irrigation level, no difference in grain yield was observed between 280 lb N/ac and 350 lb N/ac. Figures 5 and 6 shows 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. At Becker, there was no significant grain yield difference between 50%, 75% and 100% irrigation at any level of N application which suggests that limited irrigation can be effectively used to conserve water with minimal to no effect on grain yield. However, a significant grain yield difference was observed between rainfed treatment and all other irrigated treatments but only at 210 lb N/ac. The similar results were obtained for Westport site, except there was no difference between irrigated and rainfed treatment too. This could be due to the fact that there was sufficient rainfall at the Westport site that even rainfed treatment has enough moisture to avoid any crop water stress that could impact yield.

Table 1. Grain yield, actual evapotranspiration (ETc), and crop water use efficiency (CWUE) for 0, 70, 140, 210, 280 and 350 lb N/ac treatments under 100% irrigation, 75% irrigation, 50% irrigation and rainfed settings for the 2020 growing season at SPRF, MN.

Becker	Irrigation	Nitrogen (lb/ac)	ETc (inches)*	Grain yield (bu/ac)¥	CWUE (bu/ac-in)
	100%	0	18.1abc	59.7g	3.3
		70	18.5ab	144.7f	7.8
		140	19.6a	191.2bcd	9.8
		210	19.1ab	217.3a	11.4
		280	18.8ab	215.3a	11.5
		350	19.0ab	214.8a	11.3
	75%	0	17.7abcd	**56.3g**	3.2
		70	17.9abcd	139.4f	7.8
		140	18.1abc	182.9dc	10.1
		210	17.9abc	205.9abc	11.5
		280	17.9abcd	**219.6a**	12.3
		350	19.4a	214.6a	11.1
	50%	0	15.5cde	61.6g	4.0
		70	16.5bcde	142.5f	8.6
		140	17.8abcd	189.3bdc	10.6
		210	17.6abcd	203.0abc	11.5
		280	18.1abc	210.8ab	11.7
		350	17.6abcd	216.5a	12.3
	Rainfed	0	14.0cde	63.4g	4.5
		70	15.2cde	157.3ef	10.4
		140	15.4cde	173.7ed	11.3
		210	15.3cde	175.9ed	11.5
		280	15.6de	202.8abc	13.0
		350	15.7e	202.5abc	12.9

*ETc followed by same letter are not significantly different from each other
¥Grain yield followed by same letter is not significantly different from each other

Table 2. Grain yield, actual evapotranspiration (ETc), and crop water use efficiency (CWUE) for 0, 70, 140, 210, 280 and 350 lb N/ac treatments under 100% irrigation, 75% irrigation, 50% irrigation and rainfed settings for the 2020 growing season at Westport, MN.

Westport	Irrigation	Nitrogen (lb/ac)	ETc (inches)*	Grain yield (bu/ac)¥	CWUE (bu/ac-in)
	100%	0	14.3bcde	69.2f	4.8
		70	14.5bcde	142.4ed	9.8
		140	14.0bcdef	174.6abc	12.5

	210	14.1bcdef	173.7abc	12.3
	280	15.3abc	190.2a	12.4
	350	14.3bcde	173.0abc	12.1
75%	0	13.0defghi	70.4f	5.4
	70	13.8bcdefg	135.6e	9.8
	140	14.0bcdef	162.1dc	11.6
	210	16.6a	186.0ab	11.2
	280	14.5abcde	179.4abc	12.3
	350	15.7ab	180.6abc	11.5
50%	0	14.4bcde	84.9f	5.9
	70	13.6bcdefg	140.0ed	10.3
	140	13.2cdefgh	175.2abc	13.3
	210	14.3bcde	180.7abc	12.6
	280	15.0abcd	172.1abc	11.5
	350	14.9abcd	181.7abc	12.2
Rainfed	0	11.5fghi	63.1f	5.5
	70	11.1ghi	127.8e	11.5
	140	12.8efghi	159.9dc	12.5
	210	11.8ghi	167.8abc	14.2
	280	12.5ehi	168.4abc	13.5
	350	12.1hi	165.9bc	13.7

*ETc followed by same letter are not significantly different from each other
¥Grain yield followed by same letter is not significantly different from each other

The responses of grain yield to ETc (crop water production function) for 100% irrigation, 75% irrigation, 50% irrigation and rainfed treatments are presented in figures 3 and 4 for SPRF and Westport, respectively. Average values of grain yield and ETc were taken for the irrigation and N treatments to reduce any potential differences in yield caused by variation in soil physical and chemical properties within the research area, following Rudnick and Irmak (2014). A positive linear relationship was observed for all irrigation treatments. We observed stronger relationships with higher R2 for rainfed and 50% irrigation treatment as compared to 75% and 100% treatment at SPRF. These relationships are relationships are stronger at Becker site as compared to the Westport site. Variation in linear slopes between sites can be due to the differences in seasonal precipitation and distribution, soil characteristics and other climatic conditions. Higher ETc values were observed at SPRF than at Westport due to higher evaporative conditions and earlier leaf area development in response to warmer conditions at Becker than at Westport which is also reflected in yield results. Statistically we did not find any significant effect of nitrogen application amount and interaction of irrigation and nitrogen on ETc, however, effect of irrigation rate on ETc was significant.

We also calculated the EONR for each irrigation treatment at both sites. Similar results were obtained at both sites with maximum EONR and maximum yield at EONR at 75% irrigation (Table 3). At both sites the minimum EONR was obtained at 100% irrigation with only 1 to 2 bu/ac decrease in grain yield as compared to 75% irrigation. These results indicate that with an increase in 20 lb N/ac in 75% irrigation treatment as compared to 100% irrigation, the yield increase was only 1 bu/ac which indicates that 100% irrigation is more economically efficient system. However, nitrate leaching is another factor that needs to be considered before deciding the efficiency of the management system.

The cumulative nitrate leaching from each treatment is shown in figures 7 and 8 for SPRF and Westport site, respectively. At both sites, higher N rates (210 to 350 lb N/ac) had greater N leaching at all irrigation levels.

At SPRF, except 75% irrigation treatment, maximum leaching was observed under 350 lb N/ac treatment. On average, 100% irrigation had lower N leaching as compared to all other irrigated treatments indicating that there was enough water from irrigation that allowed higher ETc thus higher nitrogen uptake and lower leaching. Where as in limited irrigation treatments, with lower water in the soil profile crop was not able to uptake nitrogen at higher N rates and with rainfall or irrigation that nitrogen in the soil profile was drained below the root zone.

The situation was opposite at the Westport site. The 100% irrigation on average had the highest N leaching. This could be due to the fact that at 100% irrigation, soil profile was full or at field capacity and with very high rainfall at this site, there was no room for extra moisture from rain to stay thus most of it was lost to dep percolation along with nitrogen in the soil profile. However, at limited irrigation treatments there was enough room for rainfall in the soil profile. These results echo with the N uptake data at harvest (Figures 9 and 10). At high N rates (280 lb n/ac), 100% irrigation at Becker had higher N uptake whereas at Westport site, N uptake at 100% irrigation was lower than other irrigated treatments.

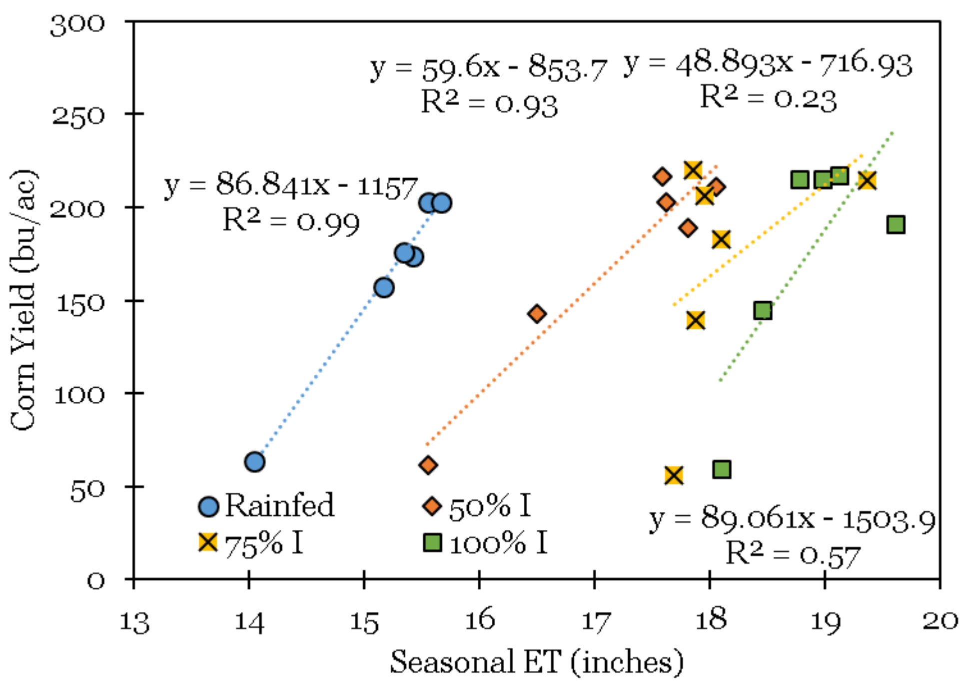

Figure 3. Grain yield response to actual evapotranspiration under different irrigation treatments at SPRF, MN

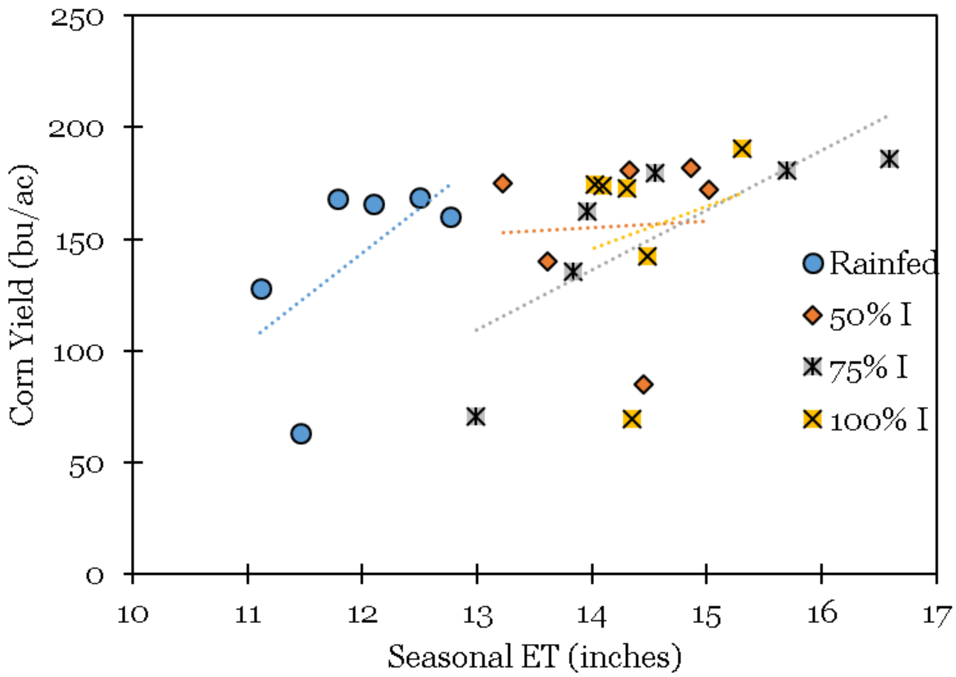

Figure 4. Grain yield response to actual evapotranspiration under different irrigation treatments at Westport, MN

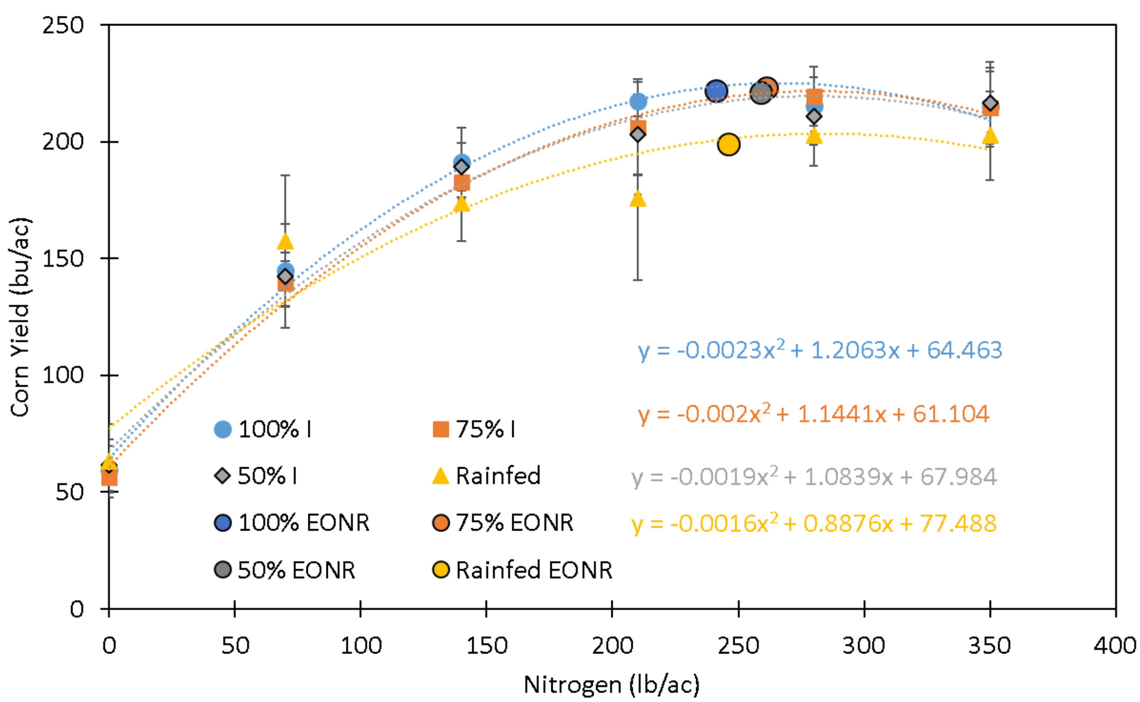

Figure 5. Grain yield response to nitrogen application under different irrigation treatments at SPRF, MN

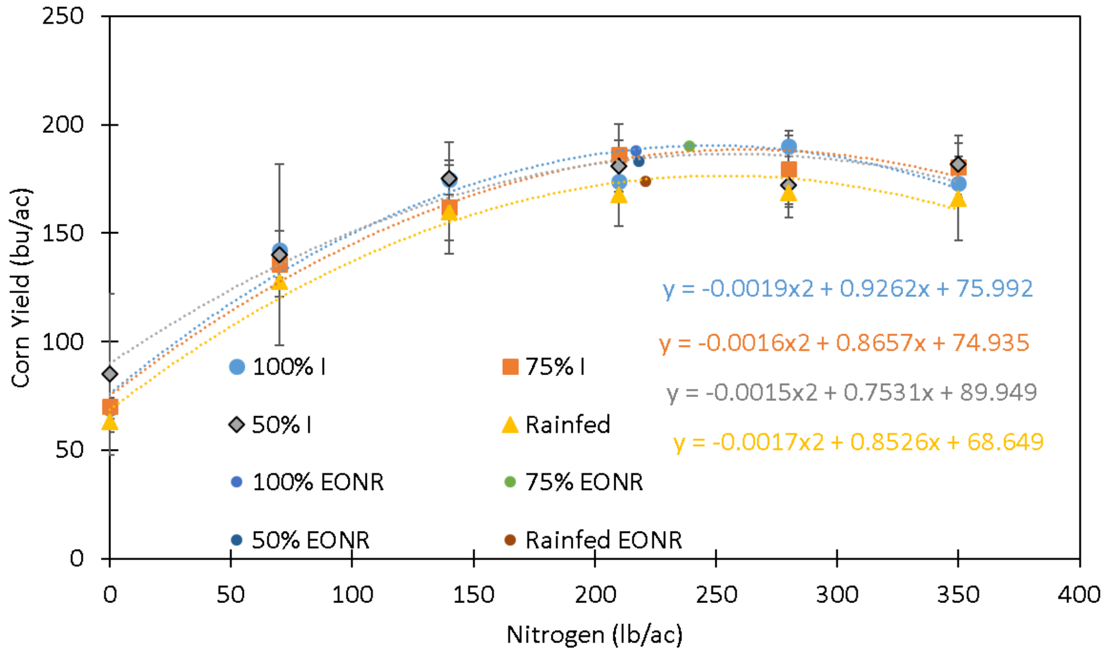

Figure 6. Grain yield response to nitrogen application under different irrigation treatments at Westport, MN

Table 3. Economic optimum N rate (EONR) of corn as affected by irrigation level in 2020 at SPRF and Westport farm sites. N fertilizer/price grain ration (0.1)

Site	Irrigation	Fraction	Irrigation (in)	R^2	EONR (lb N/ac)	Yield at EONR	AE at EONR (bu grain/lb N applied))
Becker	Rainfed	0.4	2.75	0.91	246	199	0.49
	50%	0.7	4.8	0.98	259	221	0.59
	75%	0.9	5.825	0.99	261	223	0.62
	100%	1.0	6.85	0.99	241	222	0.63
Westport	Rainfed	0.4	1.4	0.97	221	174	0.48
	50%	0.6	1.8	0.95	218	183	0.43
	75%	0.8	2.5	0.98	239	190	0.48
	100%	1.0	3.2	0.96	217	188	0.51

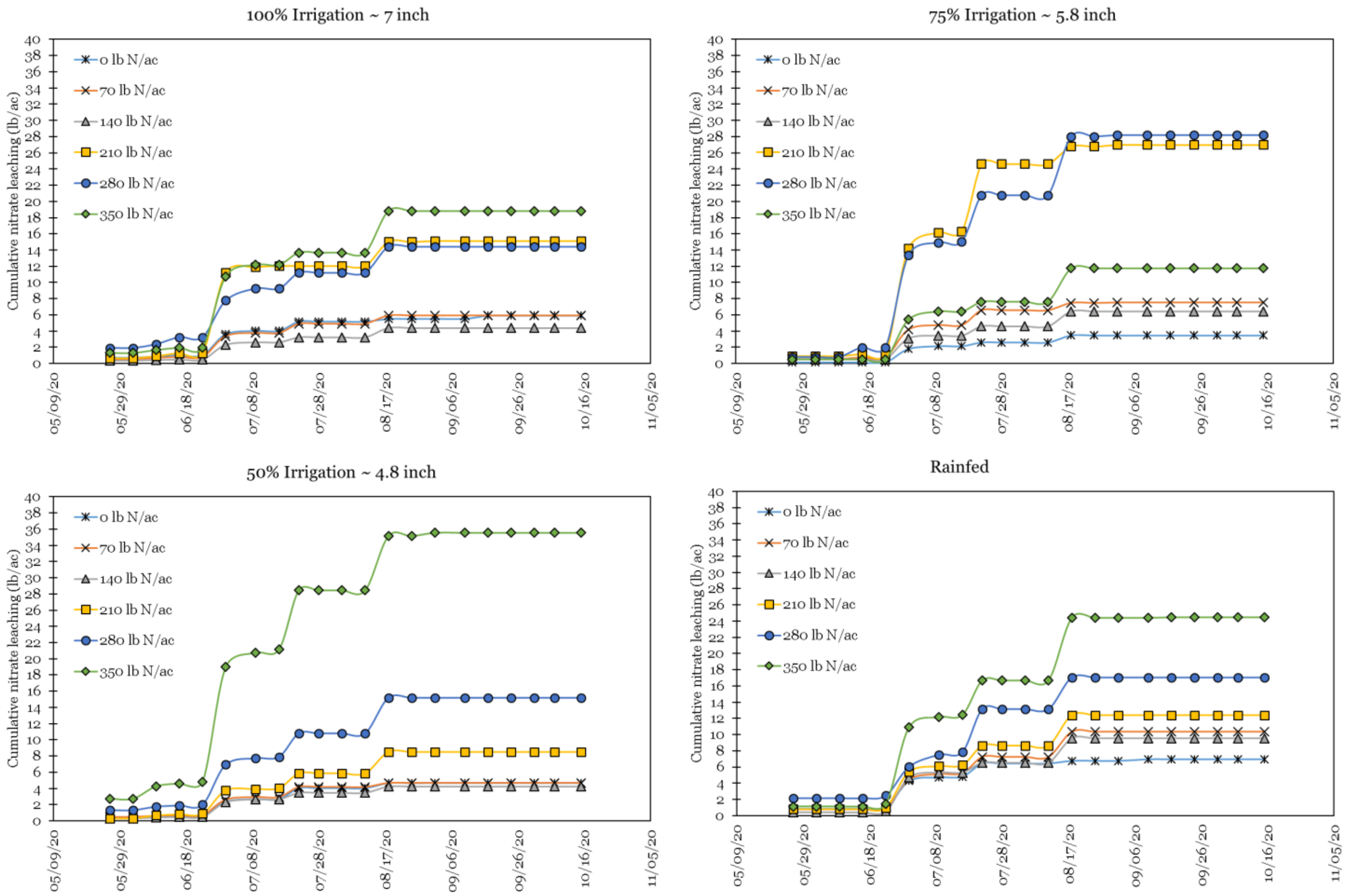

Figure 7. Cumulative Nitrate-N leaching under different irrigation treatments at different nitrate rates for SPRF, MN

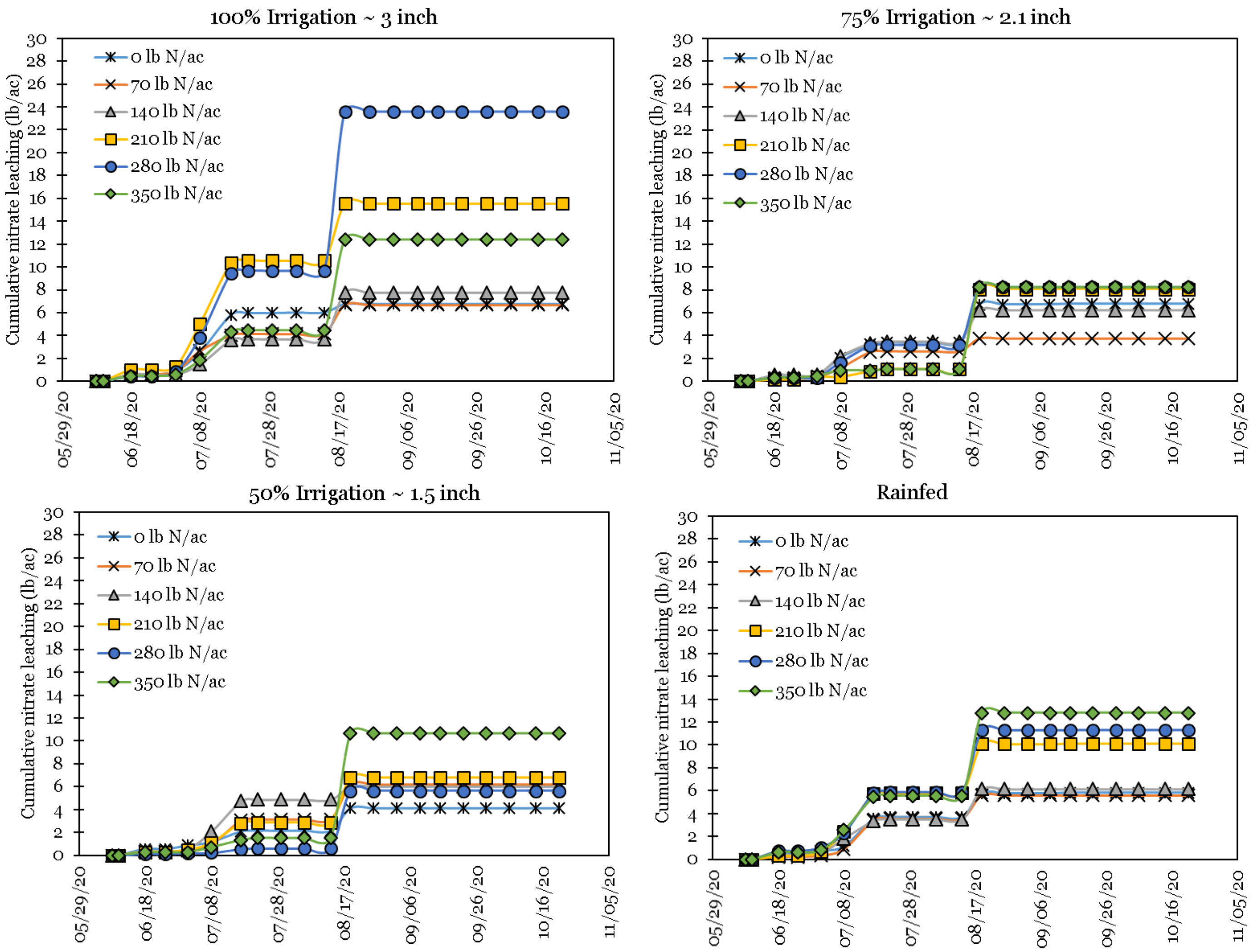

Figure 8. Cumulative Nitrate-N leaching under different irrigation treatments at different nitrate rates for Westport, MN

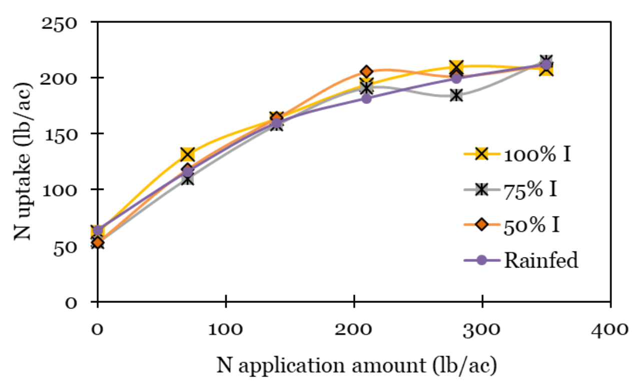

Figure 9. Nitrogen uptake at R6 growth stage at SPRF, MN

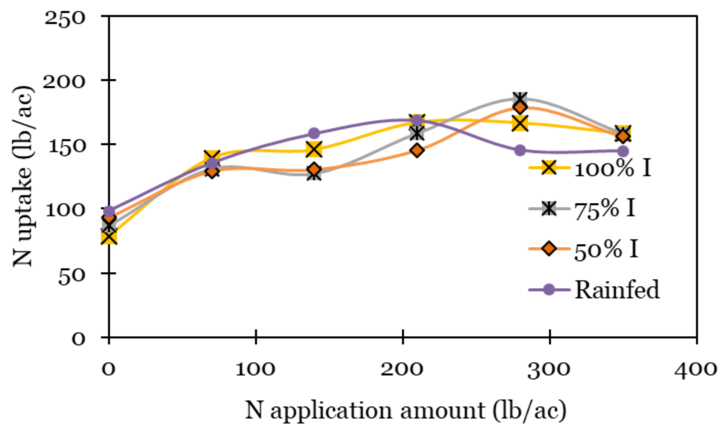

Figure 10. Nitrogen uptake at R6 growth stage at Westport, MN