Evaluation of Deficit Irrigation Strategies for Corn

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Abstract. *Competition for water is increasing while a growing world population requires more food production. It is critical to develop and implement efficient deficit irrigation strategies, and to predict the impacts of deficit irrigation on yield. South Dakota State University Management Software was used to simulate center pivot irrigation and corn yield at seven locations across the Great Plains with historical weather data. Thirty irrigation strategies were evaluated across three soil water holding capacities and three pumping rates. Yield ratio was calculated based on a normalized transpiration ratio. Strategies with high water use efficiencies performed well across all treatments and locations. The recommended maximum yield strategy is 30-60-30 (strategies were defined by the minimum available soil water (%) for early, middle, and late season). Recommended deficit strategies are 15-50-0, 0-30-0, and 0-15-0 for minimal, moderate, and severe water restrictions. Annual variation in yield is greatest when water is most limited.*

Keywords. Deficit irrigation, corn, center pivot irrigation, irrigation modeling, irrigation management, water conservation.

Introduction

Competition for water is increasing while a growing world population requires more food production. One study predicts that in the year 2050, there will be an annual water shortage of 640 billion cubic meters (Spears, 2003). Some irrigators are already faced with limited water supplies. Drought in western South Dakota has reduced water supplies for several irrigation projects, and low water flows in the Missouri River have restricted irrigation from the reservoirs in the system. Since irrigation is the largest consumptive use of water in many places, accounting for 65% of the fresh water use in the 22 western states (calculated from USGS, 2000), proper irrigation water management is critical to make the best use of the water available.

As competition for irrigation water supplies becomes greater, it will be necessary for irrigators to optimize the use of the water available to them and reduce the risk of large yield losses. The benefits of scientific irrigation scheduling have been documented (Stegman, 1986; Steele et al., 1994; Steele et al., 1999). Corn yield response to limited irrigation has also been studied (Klocke et al., 2004; Klocke et al., 2007, Lamm et al., 2008). However, specific deficit strategies have not been developed for use with center pivot management software. English et al. (2002) calls for “more detailed models of the relationships between applied water, crop production, and irrigation efficiency.”

Center pivot irrigation became popular in the 1960s, and now accounts for nearly 75% of sprinkler irrigation in the United States (Werner, 2000). Center pivots provide a high-efficiency and low-labor alternative to surface irrigation. South Dakota State University (SDSU) Management Software was developed by Oswald (2006) to account for the complexities of center pivot irrigation while simulating irrigation water use and estimating yields for various crops. Heeren (2008) modified the software with an improved ET routine and yield model.

Using the SDSU Management Software, the objectives of this research were, 1) to develop a method for evaluating deficit irrigation strategies; 2) to recommend deficit and full irrigation strategies for various locations, soil types, and system capacities; and 3) to increase understanding of yield-water relationships in these situations.

Methods

SDSU Management Software, developed by Oswald (2006) and modified by Heeren (2008), was used to simulate center pivot irrigation and corn yield. Simulations were performed on seven locations across the Great Plains, for 16 to 24 years of historical weather data for each location, 30 irrigation strategies, three soil types, and three pumping rates. A total of 40,000 simulations were performed. Output files included data for ET, soil water levels, irrigation amounts, and yield.

The SDSU Management Software was set up to simulate a center pivot irrigator with an effective length of 418 meters (1370 feet) , covering 55 hectares (135 acres). The maximum speed was set to one full revolution in 12 hours. Irrigation application efficiency was assumed to be 90%. Evapotranspiration was calculated with the tall reference Penman-Monteith equation (Allen et al., 2005) and dual crop coefficients for corn (Allen et al., 2007). The yield ratio was calculated with a normalized transpiration ratio (Steduto et al., 2006).

The locations and their associated planting dates for corn are shown in Table 1. All simulations ended on September 30th. Years of available weather data (downloaded from the High Plains Regional Climate Center, 2007) are also shown.

Table 1. Locations where simulations were performed.

Location	Planting Date	Season Length (days)	Years
Akron, CO	April 1st	180	1983 – 2006
Brookings, SD	April 15th	165	1983 – 2006
Nisland, SD	April 15th	165	1988 – 2006
Oakes, ND	May 1st	150	1990 – 2006
Ord, NE	April 1st	180	1983 – 2006
Rock Port, MO	April 1st	180	1991 – 2006
St. John*, KS	April 1st	180	1985 - 2006

*weather station at the Sandyland field station.

Pumping rates included 37.9, 50.5 and 63.1 L/s (600, 800, and 1000 GPM). Three soil types were selected to represent a range of soils. Soil types included available water holding capacity (WHC) values of 37.9, 50.5, and 63.1 mm/m (1, 1.5, and 2 in/ft), as defined in Equation 1.

$$WHC = (\theta_{FC} – \theta_{WP}) * 1000 \qquad (1)$$

Here, WHC is in mm/m, θ_{WP} is the volumetric water content at the wilting point, and θ_{FC} is the volumetric water content at field capacity. For irrigation scheduling purposes, it is helpful to define soil water content as a percentage, with zero being the soil moisture at the wilting point and 100% being the soil moisture at field capacity. This plant available water (AW) is the amount of water available to the crop and is calculated by Equation 2.

$$AW = (\theta – \theta_{WP}) / (\theta_{FC} – \theta_{WP}) * 100 \qquad (2)$$

Here, AW is the available water (%), and θ is the actual volumetric water content. An irrigation strategy offers a guideline for making irrigation decisions. A method was needed to numerically describe an irrigation strategy so that strategies could be changed and tested easily. An irrigation strategy was defined by the minimum available water (MAW) as it varies throughout the season. This concept is similar to the maximum allowable depletion (MAD), with MAW = 100 – MAD. Irrigation events were triggered when the soil directly in front of the pivot dried to the MAW.

Thirty strategies were defined for the simulations. These were inputs for the SDSU Management Software, which ran center pivot simulations for each strategy. The general shape of most of the strategies required higher AW levels mid-season and lower AW levels early and late-season. This is based on the observed effects of stress timing, showing that corn is more sensitive to water stress during flowering than the vegetative and yield formation phases of development (Doorenbos and Kassam, 1979).

Each strategy was defined by timing parameters (defining the early and middle stages of the season) and correlating MAW parameters. A strategy can be conveniently labeled by the MAW values for early, middle, and late season. Many strategies have similar timing parameters, although “30-60-30 extended” has a longer peak than normal. Based on the parameters, the MAW for any point in the season can be determined, as illustrated in Figure 1.

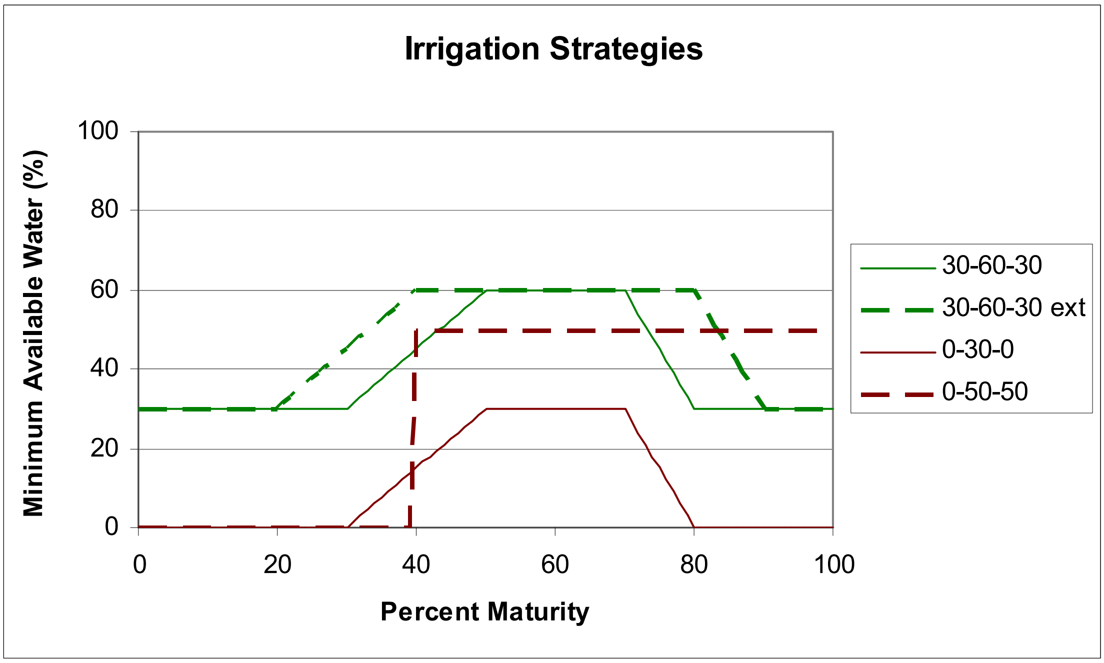

Figure 1. Selected irrigation strategies. Percent maturity expresses the ratio of days after planting to total days in the growing season.

The center pivot SDSU Management Software divides a circular field into 60 sections, each a 6° pie shape with its own water balance. Initial AW was set to 80% at the beginning of each season for each location. (This assumption was tested against a 20% initial AW at a dry site. While seasonal irrigation changed slightly, the shape of the yield-irrigation graph remained the same.)

The SDSU Management Software was modified to graph the mean, mean +/- one standard deviation, and the maximum/minimum AW for the 60 soil water balances. Figure 2 illustrates the variability in AW throughout a corn field for a particular season at Rock Port, MO. To account for this spatially variability, yield was calculated for three equidistant locations within the field and the results were averaged for each simulation.

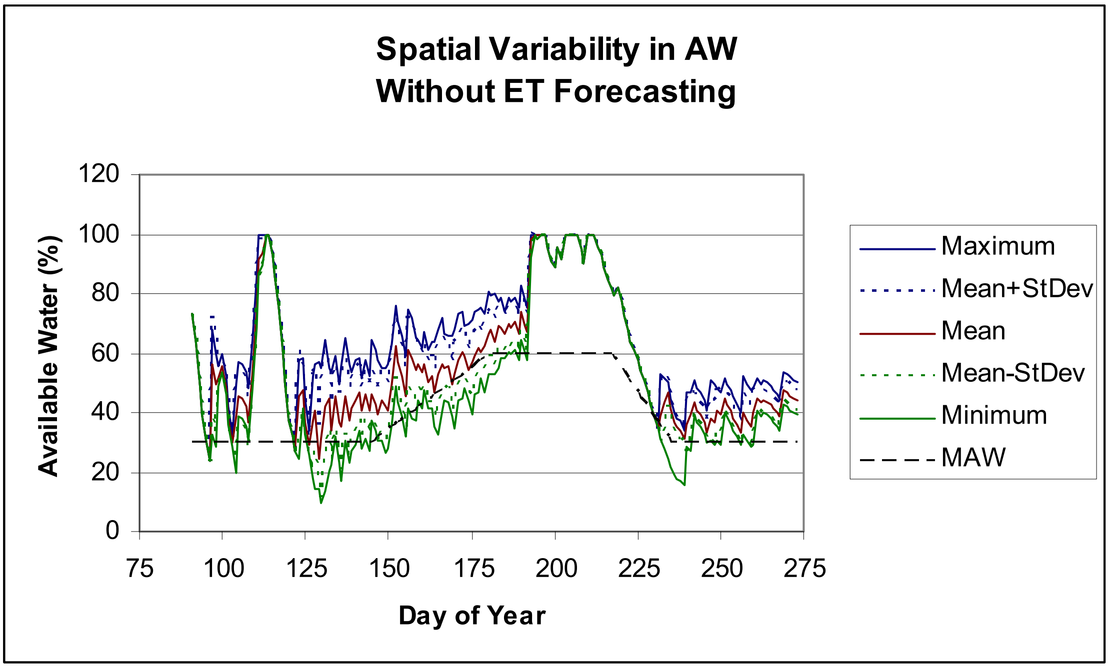

Figure 2. Example of spatial variability in AW without ET forecasting. Rock Port, MO, 1992 (driest year in dataset: 370 mm seasonal precipitation), 125 mm/m WHC, 63.1 L/s pumping rate, 30-60-30 irrigation strategy.

It was noted that ET forecasting, originally included in the SDSU Management Software, was not necessary for good irrigation management. While the drier portions of the field are often below the MAW line, high enough MAW values can be selected to achieve a desired result. The mean AW is maintained above the MAW line, if the system is able to keep up with ET demand.

Results

Water Relationships

For each site, the yield ratio is generally proportional to transpiration (Figure 3). Crops at sites with greater evaporative demand have a smaller increase in yield for each unit increase in transpiration.

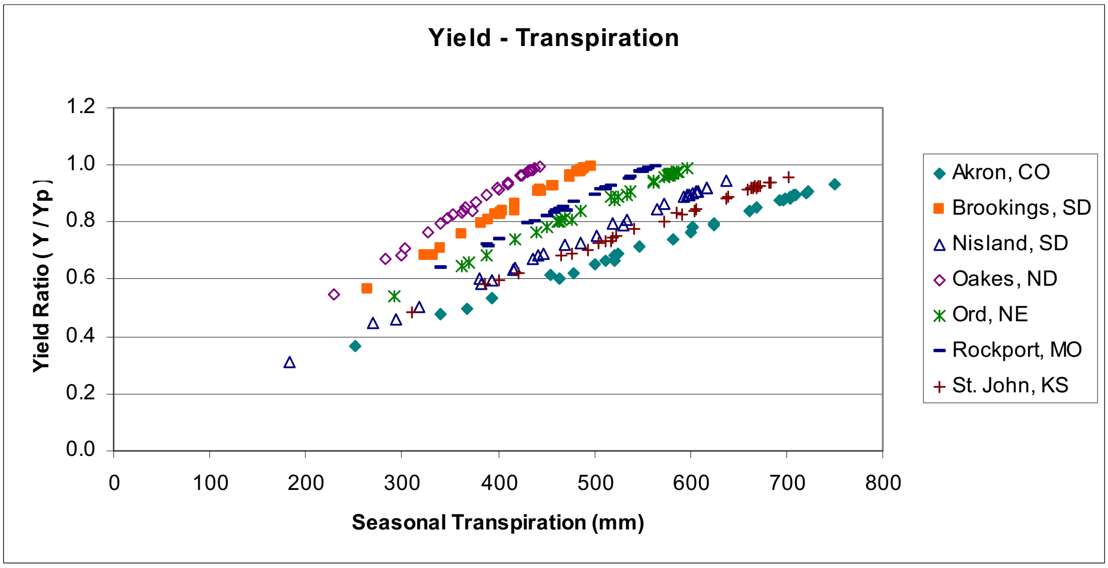

Figure 3. Yield-transpiration relationship for each site. Each point represents an irrigation strategy. Data is averaged across all WHCs, pumping rates, and years.

Yield ratio was also plotted against seasonal irrigation values in order to evaluate irrigation strategies. Figure 4 shows the summary of the results, with all 30 strategies represented for each location.

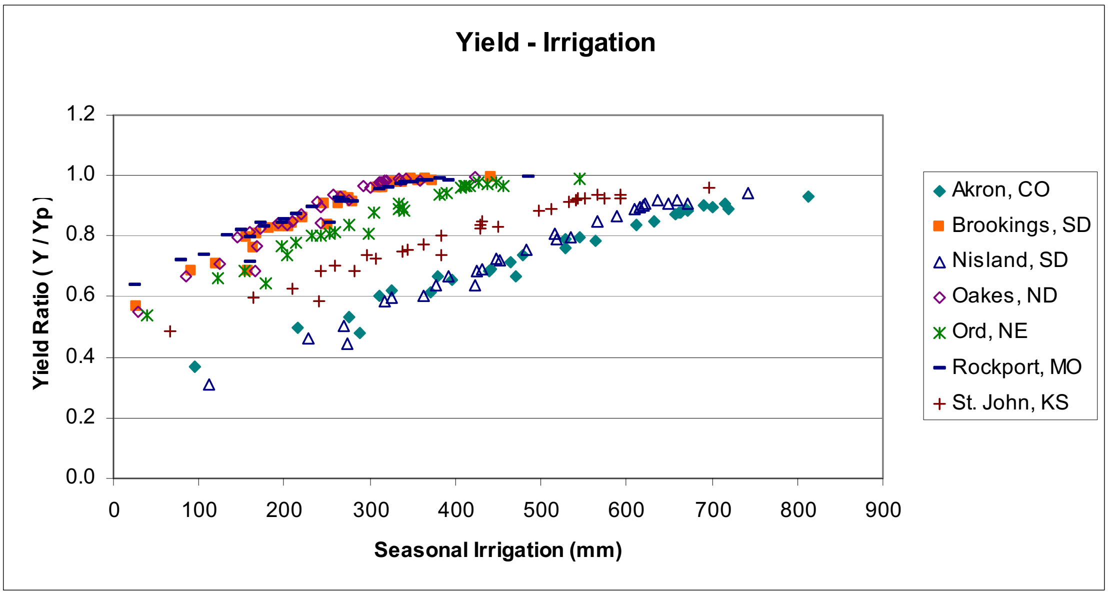

Figure 4. Yield-irrigation relationship for each site. All WHCs, pumping rates, and years. Net seasonal irrigation is used, based on a 90% application efficiency.

Sites with lower rainfall and higher ET demand showed greater yield loss for deficit irrigation strategies and required more water for high yields. The yield-irrigation relationship is relatively linear for each location until maximum yield is approached.

Figure 5 illustrates the differences among three yield-water relationships. The yield-transpiration line was nearly linear. Evaporation introduced more variability, which was shown in the yield-ET relationship. The precipitation plus irrigation was substantially different from ET. This difference was likely due to runoff and deep percolation losses. The amount of water loss generally increased with the amount of irrigation applied, and some strategies had more loss than other strategies with similar yields.

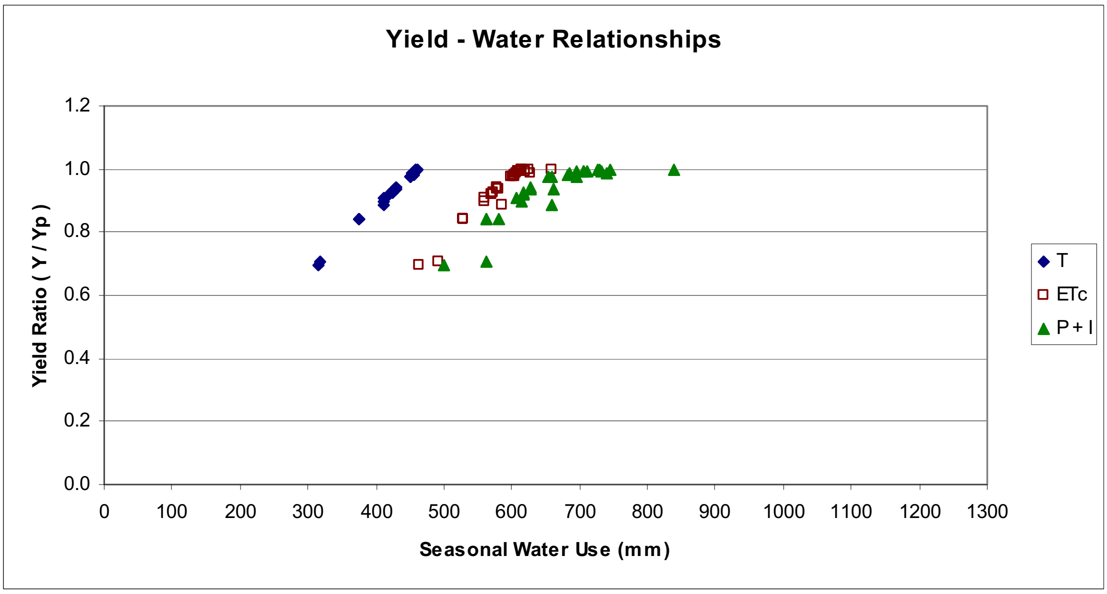

Figure 5. Yield-transpiration, yield-actual crop evapotranspiration, and yield-precipitation/irrigation relationships. Oakes, ND, 2005, 83 mm/m WHC, 63.1 L/s pumping rate.

Besides total seasonal precipitation, the timing of the precipitation is also important when considering crop water stress. Figure 6 shows climagraphs comparing average monthly reference ET to rainfall during the growing season for each location (based on weather data used for this project). While the curve for precipitation follows the ET curve for Rock Port, MO; Nisland, SD, and Akron, CO, reach peak rainfall two months before peak monthly ET. Climate trends can indicate the potential for mid to late-season water stress for a given location.

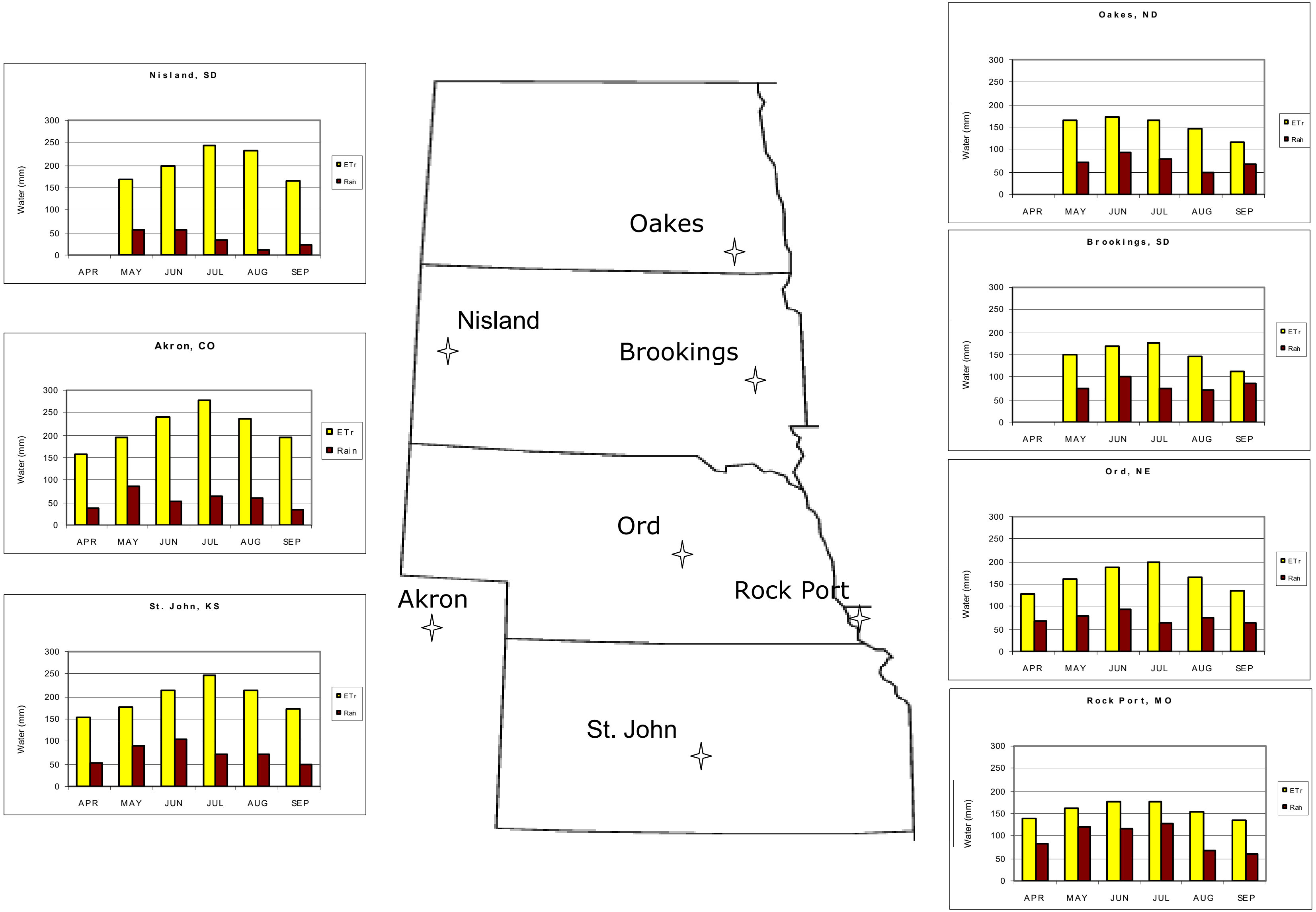

Figure 6. Climagraphs showing average monthly reference ET and rainfall (mm) for each location.

Recommended Strategies

The yield-irrigation relationship is the most relevant of the yield-water relationships for evaluating irrigation strategies. An example yield-irrigation graph is show in Figure 7, with strategies of interest labeled.

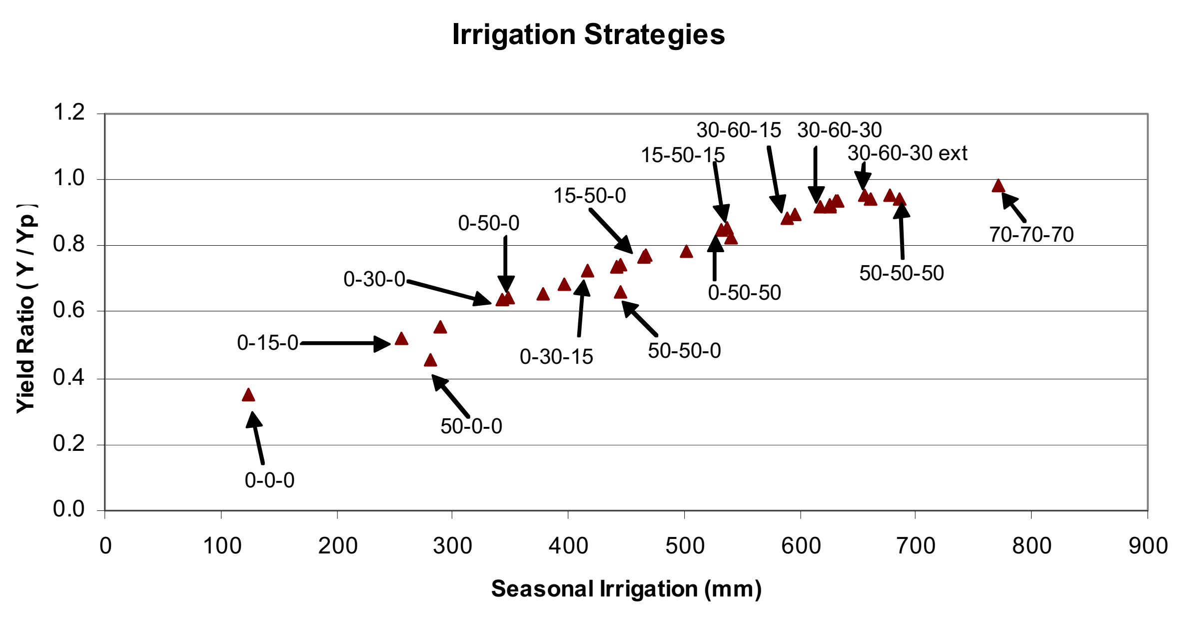

Figure 7. Example of yield-irrigation relationship with selected strategies labeled. Nisland, SD, all years, 83 mm/m WHC, 63.1 L/s pumping rate.

The basic shape and distribution of points (in relation to each other) in Figure 7 is representative of plots for all simulations. The 0-0-0 strategy, which irrigated only when the wilting point was reached, provided a lower bound on the data set. The 70-70-70 strategy, providing an upper limit on the data set, produced a minimal increase in yield (compared to similar strategies) for the large amount of applied water it required. The 30-60-30 strategy was the original strategy in the SDSU Management Software.

The historical strategy of 50-50-50 resulted in high yields, but it also consistently used more water than other strategies with similar yields. The 50-0-0 and 50-50-0 strategies, representing situations where available irrigation water was used up before the end of the season, consistently performed poorly. This indicates the benefit of good irrigation management, resulting in higher yields for a given supply of water.

Water use efficiency (WUE) is a concept that compares crop production to water used, and has been defined in numerous ways. For pragmatic reasons, WUE here will be considered relative grain yield per unit of irrigation. The best irrigation strategies result in high WUE; that is, they result in a large yield for a given amount of irrigation. On a yield-irrigation graph, “High WUE” strategies are the points above and left of the trend. The High WUE strategies in figure 12 performed well across locations, soil types and pumping rates.

The 0-50-50 and 0-30-15 strategies resulted in High WUE. This indicates that delaying irrigation early in the season (unless wilting point is reached), a deficit strategy that is relatively easy to implement, results in good water use efficiency. Yield and irrigation data for these and other strategies are shown in Table 2.

Table 2. Yield ratio and seasonal irrigation (mm) for High WUE strategies. Data is averaged over all soil types, pumping rates, and years.

Strategy	Akron, CO	Brookings, SD	Nisland, SD	Oakes, ND	Ord, NE	Rock Port, MO	St. John, KS
30-60-30 ext	0.903	0.987	0.920	0.988	0.976	0.986	0.937
	691	348	637	333	428	362	567
30-60-30	0.875	0.976	0.891	0.977	0.960	0.974	0.913
	656	328	610	311	406	336	533
30-60-15	0.838	0.959	0.848	0.963	0.939	0.953	0.886
	611	308	567	293	381	312	497
15-50-15	0.797	0.929	0.806	0.936	0.908	0.927	0.847
	544	268	516	257	335	264	432
0-50-50	0.791	0.906	0.793	0.897	0.888	0.920	0.839
	530	264	519	243	334	269	429
15-50-0	0.740	0.906	0.728	0.914	0.878	0.897	0.805
	480	246	447	238	305	231	383
0-30-15	0.668	0.827	0.668	0.826	0.801	0.841	0.736
	380	183	392	172	232	172	297
0-50-0	0.622	0.810	0.594	0.812	0.781	0.820	0.705
	326	167	325	159	213	149	260
0-30-0	0.605	0.794	0.584	0.794	0.764	0.801	0.687
	312	156	318	146	197	134	244
0-15-0	0.498	0.682	0.463	0.670	0.659	0.720	0.596
	215	91	228	86	123	79	163

Data from Table 2 (or yield-irrigation graphs) can be used for long term planning. As a simple example, consider a corn producer in Nisland, SD, with enough irrigation water to apply 320 mm (13 in) of irrigation water on 55 hectares (135 acres) with his center pivot irrigator. Would it be beneficial for him to apply 640 mm on half of his field, and leave the other half fallow? According to the table, yield ratios of 0.92 and 0.58 could be expected on average. Since 0.58 * Y_p * 55 hectares is greater than 0.92 * Y_p * 27.5 hectares, deficit irrigation is preferred to full irrigation in this case. In fact, similar results to this question would be found for all locations in this study, where average seasonal precipitation exceeds the amount of water typically lost to evaporation (when planting more acres, the benefit from rainfall outweighs the increased evaporative losses). Planting one half the field to a dryland crop (instead of fallow), however, could change the results.

For practical management purposes, the many strategies in Table 6 are not necessary. Of the High WUE strategies, four were selected that resulted in good spacing and covered a range of deficit and full irrigation conditions. Recommended deficit irrigation strategies are 15-50-0, 0-30-0, and 0-15-0 for minimal, moderate, and severe water restrictions. The recommended maximum yield strategy is 30-60-30 extended for Akron, CO, Nisland, SD, Ord, NE, and St. John, KS. For Brookings, SD, Oakes, ND, and Rock Port, MO, where the 30-60-30 extended provided little yield benefit for the extra water required, the recommended maximum yield strategy is 30-60-30. These strategies will be incorporated into the SDSU Management Software. Producers can select the best strategy based on the amount of water available to them, and have the option of changing strategies mid-season due to atypical rainfall or other factors.

Simulation data from the recommended maximum yield strategies were compared to results from a traditional strategy (50-50-50). Water savings and changes in relative yield are reported in Table 3.

Table 3. Benefit of recommended maximum yield strategies. All WHCs, pumping rates, and years.

		Akron, CO	Brookings, SD	Nisland, SD	Oakes, ND	Ord, NE	Rock Port, MO	St. John, KS
I (mm)	Traditional	720	372	671	359	456	392	593
	Recommended	691	328	637	311	428	336	567
	Change	-29	-44	-34	-47	-27	-56	-26
Y / Y_p	Traditional	0.892	0.983	0.910	0.984	0.968	0.981	0.924
	Recommended	0.903	0.976	0.920	0.977	0.976	0.974	0.937
	Change	0.011	-0.007	0.011	-0.007	0.008	-0.007	0.013

Annual Variation

Each irrigation strategy resulted in a different yield ratio and irrigation use for each year. Figure 8 shows error bars (standard deviation) on a yield-irrigation plot for both an arid and a sub-humid climate. There was more annual variation in irrigation use for strategies with higher water use. There was more annual variation in yield for strategies with lower water use. This information is valuable for risk management. For example, a deficit irrigation strategy may be economically beneficial on average, but the producer would have to be willing to accept greater variability in yield from year to year.

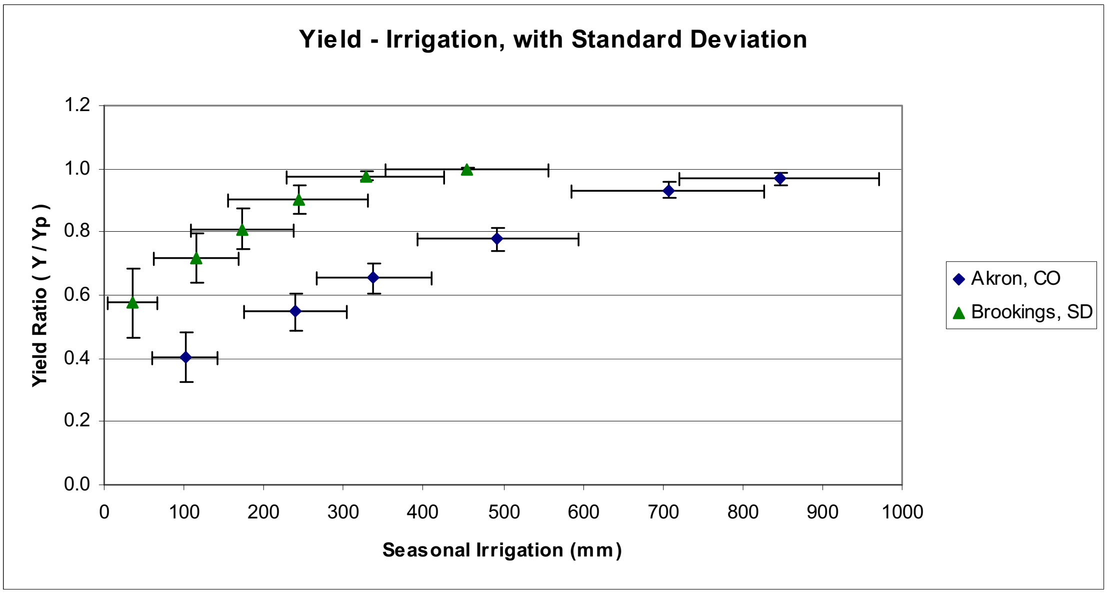

Figure 8. Example of standard deviation (for annual variation) shown on a yield-irrigation plot. 83 mm/m WHC, 63.1 L/s pumping rate, all years, 0-0-0, 70-70-70, and recommended strategies.

Soil Type and Pumping Rate

The effect of soil type was also evaluated. Soils with a high WHC had less water loss (i.e. runoff and deep percolation) since they were able to store more of the rain from large rain events. However, Rock Port, MO, was the only site to have increased water use efficiency for heavier soils. Rock Port had the highest mean annual precipitation (573 mm), and, perhaps more importantly, it had the most large rain events (greater than 25 mm) per season (Table 4).

Table 4. Large rain events and their impact on benefits of high WHC.

Location	Large rain events per season	WHC with best WUE
Akron, CO	2.1	83 mm/m
Brookings, SD	3.8	minimal difference
Nisland, SD	0.8	83 mm/m
Oakes, ND	2.7	83 mm/m
Ord, NE	4.2	minimal difference
Rock Port, MO	6.1	167 mm/m
St. John, KS	4.4	minimal difference

A high WHC allowed a soil to take advantage of large rain events, so it is reasonable that Rock Port, MO, would benefit the most from this. According to these simulations, Brookings, SD, Ord, NE, and St. John, KS, showed a minimal difference in WUE among WHC treatments. For Akron, CO, Nisland, SD, and Oakes, ND, however, the 83 mm/m soils performed the best, with 167 mm/m showing the smallest yield for a given irrigation amount. This was due to the increased evaporation loss in heavy soils, which is illustrated in Figure 9 (evaporation loss is indicated by the horizontal space between the ET and T lines).

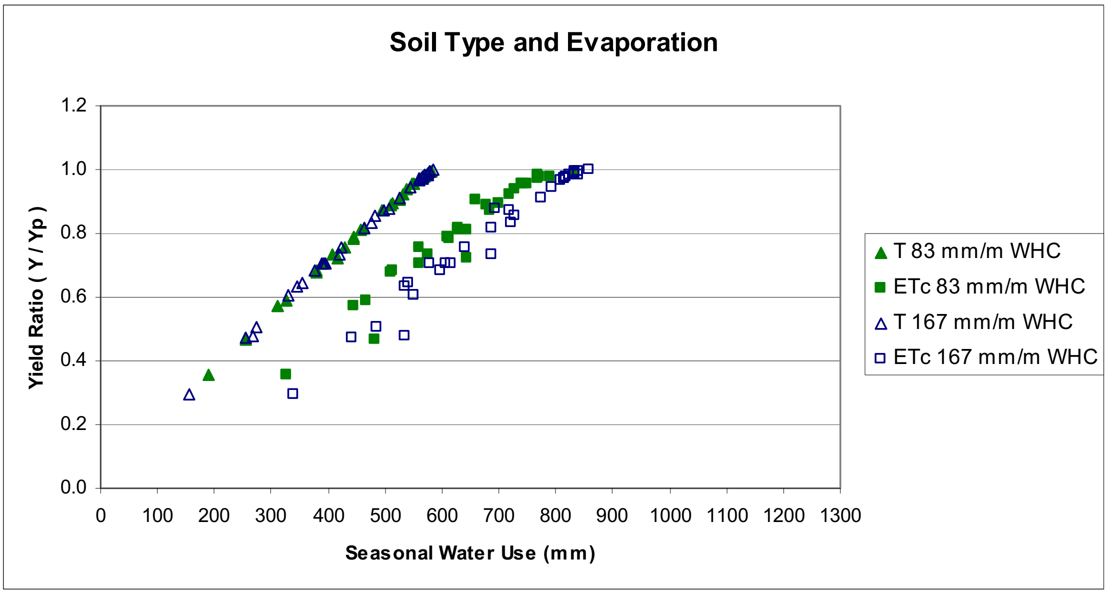

Figure 9. Example of soil type impact on yield-transpiration and yield-actual crop evapotranspiration relationships. Nisland, SD, 1997 (seasonal precipitation near the mean: 210 mm, zero rain events greater than 25 mm), 63.1 L/s pumping rate.

In medium to small rain events (and irrigations), drainage and runoff were small. For a high WHC soil, more of the moisture was held in the surface layer and lost to evaporation; less of the water made it deeper into the root zone to benefit the plant. For locations with few large rainfall events, this drawback overrides the benefits of a heavy soil. Two notes of caution are in order here. Soils with very low WHC, 42 mm/m (0.5 in/ft) for example, were not simulated. It is doubtful that the trend would continue and show such a soil to be desirable. Also, these results are highly dependant on the method for calculating evaporation from the topsoil (Heeren, 2008). Soil parameters describing the amounts of water that topsoil can hold and readily evaporate should be verified with laboratory tests in order to strengthen this observation.

The above analysis regarding WHC and WUE is especially appropriate from a deficit irrigation perspective. It should be noted, however, that if water is not limiting and the maximum yield is desired, a high WHC is preferable. The highest yields from maximum irrigation strategies were consistently obtained by the 167 mm/m WHC soils.

Pumping rates had a negligible effect on which strategies performed best. The same strategies are recommended for all pumping rates. However, for a particular strategy, pumping rate did impact yield. Figure 10, showing the four recommended irrigation strategies, provides an example of the effect that pumping rate has on the yield-irrigation relationship.

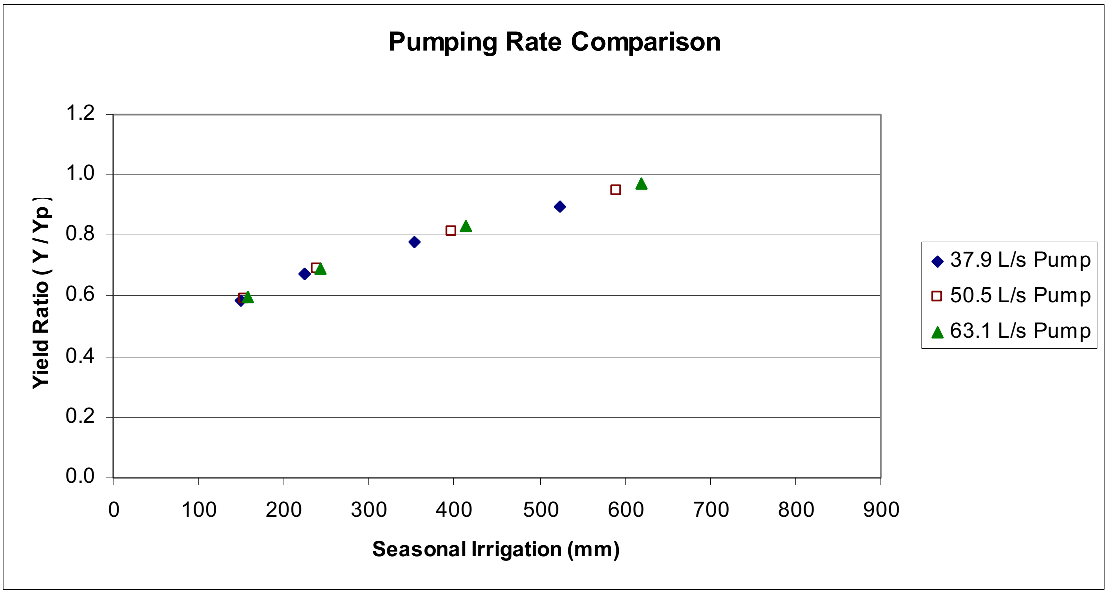

Figure 10. Example of the effects of various pumping rates. St. John, KS, 125 mm/m WHC, all years, recommended irrigation strategies.

Pumping rate appeared to have a small effect on water use efficiency; the points above form a fairly smooth irrigation-yield curve. The primary difference is where they lie on the curve. All sites showed at least a slight reduction in yield when the pumping rate was limited to 37.9 L/s. Akron, CO, Nisland, SD, and St. John, KS, showed substantial yield losses with a pumping rate of 37.9 L/s, and small losses with 50.5 L/s compared to 63.1 L/s. It is not surprising that the sites with the greatest middle and late-season difference between monthly ET and precipitation (Figure 5) showed the largest yield reductions from limited water delivery rates. From a design standpoint, a 50.5 L/s pump may be sufficient to achieve maximum yield in Brookings, SD, Oakes, ND, Ord, NE, and Rock Port, MO. Another implication involves situations where the pumping rate is being reduced due to declining aquifer levels. These data provide indications of the effects on water use and yield in those scenarios.

Conclusions

The recommended maximum yield strategy for corn is 30-60-30 for Brookings, SD, Oakes, ND, and Rock Port, MO, and 30-60-30 extended for Akron, CO, Nisland, SD, Ord, NE, and St. John, KS. Recommended deficit irrigation strategies (for all sites) are 15-50-0 for minimal water restrictions, 0-30-0 for moderate water restrictions, and 0-15-0 for severe water restrictions. Recommended irrigation strategies did not depend on soil type or pumping rate.

Variability in yield from year to year is greatest for strategies that use the least water. Pumping rate had a small effect on the general yield-irrigation relationship, but a rate of 37.9 L/s substantially limited maximum yields in Akron, CO, Nisland, SD, and St. John, KS. The benefit of soils with high WHC may be limited to locations with a high frequency of large rainfall events.

Acknowledgements

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