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DEFICIT IRRIGATION MANAGEMENT OF CORN IN THE HIGH PLAINS: A REVIEW

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INTRODUCTION

In water limiting areas, including the majority of the U.S. High Plains, irrigation is essential for the economic viability of individual producers as well as for the region. Irrigation provides supplemental water for the crop, augmenting depleting stored soil water when precipitation is insufficient to meet crop water demands. Crop water requirements depend on several factors, including crop type, variety, and growth stage; soil water and nutrient availability; soil physical and chemical properties; micrometeorological conditions (i.e., evaporative demand); among others. Unfortunately, applying irrigation to meet full water requirements is not always an option due to the effects of drought, declining groundwater levels, reduced stream flow, water allocations, insufficient irrigation system design capacity, load management, etc. Therefore, deficit irrigation management strategies that apply less water than what is required by the crop to meet potential evapotranspiration (ET) demand are adopted to maximize grain yield, and more importantly profit, given the amount of water available.

The effects of water stress on crop growth and grain yield will depend on the timing and magnitude of water stress as well as crop type, since different crops have different levels of tolerance to water stress (Irmak and Rudnick, 2014). For many field crops the most critical period of water stress is during the transition from vegetative to reproductive growth or from flowering to fruit setting (Doorenbos and Pruitt, 1977). For example, the critical period of water stress on corn is during the early reproduction period. Çakir (2004) reported that a 66 to 93% yield reduction could be expected as a result of prolonged water stress during the tasseling and ear formation growth stages.

One strategy for managing deficit irrigation consists of trying to mitigate the impact of water stress on crop growth and grain yield by withholding water at growth stages that are less sensitive to water deficit as compared to others. This strategy is often practiced when there are pumping restrictions (e.g., water allocations), yet no constraints limiting the system's ability to meet peak ET demands. However, under situations when peak ET demands cannot be met, such as insufficient irrigation system capacity, water availability restrictions, and/or irrigation scheduling delays, adopting a percentage of full irrigation requirement strategy may be more appropriate. This second strategy consists of irrigating enough to satisfy a percentage of a crop's potential ET rate, and therefore, it moderates crop water stress by distributing the total seasonal available water with fixed amounts throughout the growing season independent of crop growth stage (Irmak, 2015a and b). Due to uncertainty and non-uniform distribution of in-season rainfall, the percentage of full irrigation strategy is less susceptible to scheduling errors as compared to the growth stage timing strategy, since the percentage of full irrigation approach does not require withholding water at specific growth stages. Other alternative irrigation strategies available to producers that are subjected to water limitations include: 1) planting crops that match the available water supply (i.e., less water demanding crops), 2) planting the desired crop on a reduced area in combination with a less water demanding crop, and 3) reduce the total irrigated area and substitute with fallow or a dryland crop (Martin et al., 1989; Klocke et al., 2006; Klocke et al., 2011).

It is unlikely that a single deficit irrigation management strategy will work year to year or across regions due to temporal and spatial variability in crop water requirement drivers (i.e., soil, ground water level, and climatic conditions) coupled with differences in state policy and management strategies. As a result, extensive deficit irrigation management research has been conducted across water limited regions so that appropriate and localized management strategies can be developed. This review will focus on some of the research that has been investigated across the U.S. High Plains, including Nebraska, Kansas, Colorado, and Texas. The review will highlight the reported findings of the investigated strategies.

MATERIAL AND METHODS

Study Area

Some of the research projects conducted in Nebraska, Kansas, Colorado, and Texas were compiled for this review and the location of

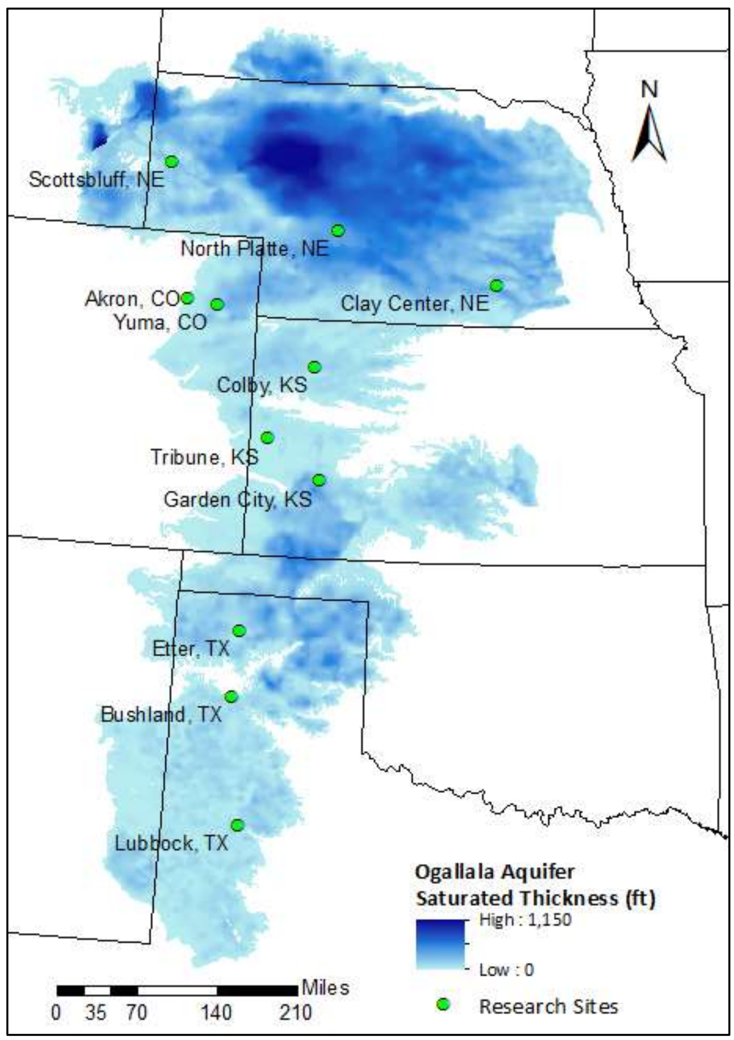

Figure 1. Deficit irrigation management research sites. The background is the saturated thickness (ft) of the Ogallala Aquifer (adapted from McGuire et al., 2012).

each study is presented in Figure 1. Although, there are various types of crops grown in the High Plains, this review focuses on corn production. The research sites span south to north from Lubbock, TX to Scottsbluff, NE and east to west from Clay Center, NE to Scottsbluff, NE. A description of the research sites is presented in Table 1. The climate ranges from sub-humid/semi-arid at Clay Center, NE to semi-arid at the remaining sites. The long-term seasonal (May 1 to Sept. 30) precipitation is greatest at Clay Center, NE with 18.5 inches and lowest in Scottsbluff, NE with 9.6 inches. The research sites are mostly composed of medium textured soils that have relatively high soil water holding capacities. The research sites vary in the driving factors that lead to the adoption of deficit irrigation management, including differences in 1) ground water resources (Figure 1), 2) state water policy on the management of ground and surface water (e.g., mandated single or multi-year water allocations in Nebraska), and 3) climatic factors, including the magnitude and distribution of precipitation (Table 1) and ET demand.

Table 1. Description of the research sites located in Nebraska, Kansas, Colorado, and Texas, including climate, soil type, and long-term seasonal (May 1 – Sept. 30) rainfall. The long-term (1981-2010) rainfall was collected from the PRISM Climate Group, Oregon State University (prism.oregonstate.edu) on January 26, 2017.

Location	Climate	Soil Type	Seasonal Rainfall (inches)
Nebraska			
Clay Center	Sub-Humid/ Semi-Arid	Hastings Silt Loam	18.5
North Platte	Semi-Arid	Cozad Silt Loam	13.8
Scottsbluff	Semi-Arid/ Arid	Tripp Very Fine Sandy Loam	9.6
Kansas			
Colby	Semi-Arid	Keith Silt Loam	13.7
Garden City	Semi-Arid	Ulysses Silt Loam	12.9
Tribune	Semi-Arid	Ulysses Silt Loam	11.9
Colorado			
Akron	Semi-Arid	Weld Silt Loam	11.5
Yuma	Semi-Arid	Haxtun Sandy Loam	12.3
Texas			
Etter	Semi-Arid	Sherm Silty Clay Loam	11.5
Bushland	Semi-Arid	Pullman Clay Loam	13.0
Lubbock/Plainview	Semi-Arid	Pullman Clay Loam	12.4

Performance Indicators

While optimal crop performance or productivity is difficult to determine using a single metric, a combination of indices or measures can be beneficial in suggesting management strategies that result in better crop performance or productivity. Crop water use efficiency (CWUE, bushels per acre-inch of ET) and irrigation water use efficiency (IWUE, incremental bushels per acre-inch of irrigation) are two measures commonly used to assess irrigation management strategies and are calculated as follows:

$$CWUE = \frac{Grain\ Yield}{ET} \tag{1}$$

$$IWUE = \frac{Irrigated\ Yield - Rainfed\ Yield}{Applied\ Irrigation} \tag{2}$$

where grain yield is adjusted to 15.5% moisture content and applied irrigation and ET amounts are the cumulative seasonal total. It is should be noted that changes in CWUE and IWUE are affected by climatic conditions as well as by production management and genetics, where the resultant impact can be derived using the GEM (Genetics × Environment × Management) production concept (Leskovar et al., 2014; ASA, 2016). The authors recognize that changes in seed technology (e.g., seed genetics), and consequently, its interaction with management practices have occurred over-time, which can impact the comparison of CWUE and IWUE across studies. Therefore, the compilation of past and more recent irrigation research findings can provide a more comprehensive understanding of how a deficit irrigation strategy responds to changes in genetics, environment, and management.

Performance of the deficit irrigation management strategies reported in the literature were summarized in terms of grain yield, seasonal evapotranspiration (ET, inches) (i.e., evaporation plus transpiration), crop water use efficiency (CWUE), and irrigation water use efficiency (IWUE) as compared with a non-water limiting crop (i.e., full irrigation). Readers should be mindful of their unique conditions when practicing deficit irrigation, including irrigation system type, soil water at planting, residue levels, subsequent crop, market values, etc. Also, the success of deficit irrigation management will depend, in part, on the ability of the producer to quantify crop water use and/or soil water availability, and therefore, appropriate irrigation scheduling techniques, such as field calibrated soil water sensors or locally developed crop coefficients, should be adopted.

RESULTS AND DISCUSSION

Individual State Assessment

Nebraska:

The research projects in Nebraska were conducted at the University of Nebraska-Lincoln South Central Agricultural Laboratory (SCAL) located near Clay Center, NE (Rudnick et al., 2016; Irmak 2015a and 2015b), the West Central Research and Extension Center (WCREC) in North Platte, NE (Payero et al., 2008; Payero et al., 2009; van Donk et al., 2012), and the Panhandle Research and Extension Center (PREC) in Scottsbluff, NE (Spurgeon and Yonts, 2013). A description of the research sites is presented in Table 1. The climate is semi-arid/arid at PREC, semi-arid at WCREC, and a transition zone with sub-humid/semi-arid at SCAL. Consequently, in Nebraska irrigation demand increases and growing season length for corn decreases from SCAL to PREC (Sharma and Irmak, 2012; Rudnick et al., 2015).

Irmak (2015a and b) evaluated corn limited irrigation management strategies and developed production functions at SCAL from 2005 to 2010 under center pivot irrigation (Table 2). The author also evaluated which month(s) are more critical in terms of impact(s) of climatic variables (precipitation, temperature, solar radiation, vapor pressure deficit, wind speed) on the slope of the production functions as well as the inter-annual variabilities of production functions and their slopes for full and limited irrigation and rainfed settings. The treatments investigated were full irrigation (FIT), limited irrigation of 75%, 60%, and 50% of FIT, and rainfed conditions. The FIT treatment was irrigated to prevent crop water stress, and the limited irrigation treatments received a percentage of the FIT application depth at time of irrigation. Six-year treatment average grain yields were 221, 214, 203, 195, and 132 bu ac^{-1} for the FIT, 75% FIT, 60% FIT, 50% FIT, and rainfed, and the corresponding ET was 25.8, 25.1, 24.2, 23.8, and 20.3 inches, respectively. As a result, the average CWUE values were 9.5, 9.4, 9.3, 9.1, and 7.0 bu per ac-in for the FIT, 75% FIT, 60% FIT, 50% FIT, and rainfed, respectively. The author reported considerable variation in grain yield, ET, and CWUE from year to year and observed that rainfed production always obtained the lowest CWUE and the highest CWUE was usually obtained under FIT. In most years, no significant differences in grain yield and CWUE between the FIT and 75% FIT treatments was observed. A similar study was conducted as SCAL from 2011 to 2014, to evaluate grain yield, CWUE, IWUE, and economic return of corn under irrigation (FIT, 75% FIT, and rainfed settings) and nitrogen (N) fertilizer rates (0, 75, 125, 175, and 225 lb N ac^{-1}) (Rudnick et al., 2016). The authors assessed the relationship between economic return (i.e., net income) and CWUE to further evaluate differences among the FIT, 75% FIT, and rainfed settings. The relationships between CWUE and net income were linear for all years, and in all cases lower CWUE values were associated with lower net income values (Figure 2). The results showed that maximum net income was achieved under FIT, and therefore, under non-water limiting conditions full irrigation with N fertilizer rates not exceeding 175 lb ac^{-1} should be adopted for south central NE (Rudnick et al., 2016). However, the aforementioned studies concluded that under water limiting conditions, applying 75% of full irrigation requirements is a viable and robust strategy to minimize water withdrawal with minimal impact on grain yield and CWUE under south central Nebraska climatic, soil, and crop management conditions.

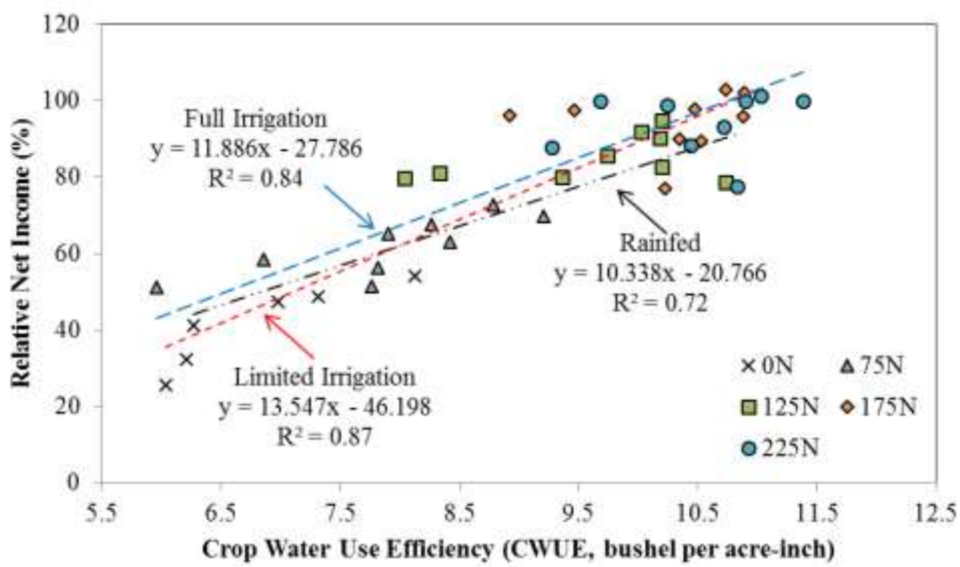

Figure 2. Relationship between relative net income (RNI) and crop water use efficiency (CWUE) for 0, 75, 125, 175, and 225 lb ac^{-1} nitrogen (N) rates under full irrigation (FIT), limited irrigation (75% of Full), and rainfed settings for the pooled 2011, 2012, and 2014 growing seasons at the UNL South Central Agricultural Laboratory (SCAL) near Clay Center, NE. Relative net income of a treatment was calculated as a percentage of the FIT-225 lb N ac^{-1} treatment (i.e., non-limiting water and N). Adapted from Rudnick et al. (2016).

At the WCREC site in west central Nebraska, Payero et al. (2008) evaluated the effects of irrigation amount with subsurface drip (SDI) irrigation on corn ET, yield, CWUE, and dry matter production. The authors imposed eight irrigation treatments, ranging from 2.1 to 14.0 inches in 2005 and from 0.9 to 8.9 inches in 2006 (Table 2). The treatments were designed to represent a wide range of seasonal irrigation allocations in order to develop well-defined crop response functions to irrigation. Several deficit irrigation strategies were evaluated, including scheduling irrigation to minimize stress during the peak ET period in July, and withholding water later in the growing season. The seasonal ET ranged from 22.8 to 26.1 inches in 2005 and from 18.3 to 25.8 inches in 2006, and the yields differed by as much as 22% in 2005 and 52% in 2006. The production function relating grain yield to irrigation showed maximum grain yield occurred at 10 and 7.2 inches of applied irrigation in 2005 and 2006, respectively, under nearly normal precipitation and evaporative demand. The authors also conducted a companion study (Payero et al., 2009) at WCREC in 2005 and 2006 under SDI evaluating the effects of deficit irrigation strategies with a 6 inch water allocation on corn ET, yield, CWUE, and dry mass. Sixteen treatments (eight each year), received different percentages of the 6 inch water allocation during July, August, and September. Grain yield had the highest positive response to irrigation in July, then the response considerably decreased in August, and became negative for irrigation applied in September. Yield was strongly correlated to water stress during the milk and dough growth stages (weeks 12-14 following emergence), but was poorly or negatively correlated with water stress afterwards. The authors found that evenly distributing the 6 inch allocation among July, August, and September was a good strategy but was susceptible to year to year variability; whereas, applying a large portion of the allocation in July was a good strategy across years. Van Donk et al. (2012) expanded on the findings of the aforementioned studies by evaluating a series of deficit irrigation strategies in 2007-2009. The deficit irrigation treatments included treatments that allowed various levels of water stress as a percentage of ET before and after, but not during the critical period of tasseling and silking; whereas, the other treatments included 125%, 100%, 75%, and 50% of ET replacement and rainfed. They observed only a 5% yield decrease for the treatment with the greatest reduction in irrigation (Treatment: start with 50% ET, 100% ET replacement during 2 weeks starting at tasseling, then 50% ET) as compared to 100% ET replacement, while reducing irrigation withdrawal by greater than 4 inches. In this study, tasseling occurred in mid to late July and all three years experienced above normal precipitation. Collectively, the aforementioned studies showed that applying irrigation to meet crop water demands in July, which coincides with tasseling and the early reproductive period, and reducing irrigation late in the season following the dough growth stage is a viable deficit irrigation management strategy in west central Nebraska.

A limited irrigation study was conducted at PREC from 2005 to 2008 evaluating water productivity of a corn and dry bean rotation (Spurgeon and Yonts, 2013). The authors investigated FIT, 125% FIT, 75% FIT, and 50% FIT under SDI (Table 2). Excluding 125% FIT, the average corn yield response to irrigation was 4.2 bushels per acre-inch. Maximum corn yield was observed at 11.8 inches in wet years and approximately 14.8 inches in dry years. On an average precipitation year such as 2008, 75% FIT yield of 154 bu ac^{-1} was significantly less than FIT yield of 176 bu ac^{-1}; however, IWUE was not statistically different across the treatments with 9.9 and 10.2 bushels per acre-in, respectively. In addition, the 50% FIT yield was significantly less than FIT in all years, except the very wet year of 2005. Therefore, depending on water availability restrictions and in-season rainfall distribution 75% FIT may be a suitable limited irrigation strategy; however, reducing below that will result in considerable yield reduction in normal to dry years.

Table 2. Performance indicators, including grain yield (bu per acre), seasonal evapotranspiration (ET, in), crop water use efficiency (CWUE, bu per acre-in of ET), and irrigation water use efficiency (IWUE, incremental bu per acre-in of irrigation) of various irrigation treatments at the study sites in Nebraska.

References & Years	Irrigation System	Treatment		Grain Yield (bu acre^{-1})		ET (inch)		CWUE (bu ac-in^{-1})		IWUE (bu ac-in^{-1})
		Clay Center, NE (SCAL)								
Irmak (2015a,b) 2005-2010	Center Pivot	Full Irrigation		221		25.8		9.45		16.19
		75% of Full		214		25.1		9.37		17.97
		60% of Full		204		24.2		9.25		18.09
		50% of Full		195		23.8		9.05		16.68
		Rainfed		132		20.3		6.99		-
Rudnick et al. (2016) 2011, 2012, & 2014	Lateral Move	Full Irrigation - 125N		189		20.4		9.27		3.18
		Full Irrigation - 175N		210		20.7		10.24		5.33
		Full Irrigation - 225N		219		20.6		10.64		7.34
		75% of Full - 125N		186		19.5		9.59		3.39
		75% of Full - 175N		205		20.4		10.12		5.37
		75% of Full - 225N		211		20.0		10.56		7.94
		Rainfed – 125N		176		17.4		10.08		-
		Rainfed – 175N		187		17.9		10.48		-
		Rainfed – 225N		188		18.4		10.28		-
		North Platte, NE (WCREC)								
Payero et al. (2008) 2005-2006	SDI	2005	2006	2005	2006	2005	2006	2005	2006	
		T1-05: 2.1 in	T9-06: 0.9 in	159	86	22.8	18.3	6.96	4.67	
		T2-05: 3.0 in	T10-06: 2.6 in	169	134	23.1	21.1	7.35	6.33	-
		T3-05: 4.0 in	T11-06: 3.8 in	175	153	24.1	22.4	7.28	6.82	-
		T4-05: 6.0 in	T12-06: 5.1 in	176	165	24.9	24.7	7.06	6.67	-
		T5-05: 8.7 in	T13-06: 7.2 in	192	179	26.1	25.2	7.36	7.13	-
		T6-05: 10.0 in	T14-06: 6.8 in	204	180	25.8	25.8	7.92	6.97	-
		T7-05: 12.0 in	T15-06: 7.8 in	185	174	25.8	25.6	7.18	6.80	-
		T8-05: 14.0 in	T16-06: 8.9 in	196	176	25.8	25.7	7.59	6.83	-
Payero et al. (2009)+ 2005-2006	SDI	2005	2006	2005	2006	2005	2006	2005	2006	
		T1-05 [50-25-50]	T9-06 [25-50-25]	185	135	24.0	21.4	7.71	6.28	-
		T2-05 [57-43-0]	T10-06 [100-0-0]	206	180	24.9	23.2	8.27	7.76	-
		T3-05 [33-67-0]	T11-06 [0-100-0]	183	155	24.9	22.2	7.35	6.95	-
		T4-05 [33-0-67]	T12-06 [0-0-100]	172	121	23.3	19.9	7.37	6.07	-
		T5-05 [33-50-17]	T13-06 [0-50-50]	180	145	24.8	22.7	7.26	6.38	-
		T6-05 [67-33-0]	T14-06 [50-50-0]	203	180	25.1	24.5	8.08	7.37	-
		T7-05 [40-30-30]	T15-06 [33-34-33]	189	136	25.0	21.5	7.55	6.35	-
		T8-05 [33-34-33]	T16-06 [0-67-33]	191	143	24.6	22.5	7.75	6.36	-
van Donk et al. (2012) 2007-2009	SDI	100% ET		180		21.4		8.40		3.20
		75% of ET		177		21.5		8.21		4.45
		50% of ET		167		20.6		8.11		6.88
		50% – 100% 3 Week @ VT – 50%		176		21.3		8.29		4.83
		50% – 100% 4 Week @ VT – 50%		182		22.1		8.25		4.74
		75% – 100% 4 Week @ VT – 75%		179		22.0		8.12		3.51
		Rainfed		156		19.3		8.07		-
		Scottsbluff, NE (PREC)								
Spurgeon and Yonts (2013) 2005-2008	SDI	Full Irrigation		178		-		-		7.19
		125% of Full		177		-		-		8.72
		75% of Full		161		-		-		9.93
		50% of Full		146		-		-		12.56
		Rainfed**		47		-		-		-

+Payero et al. (2009): Percent of 6 inch irrigation allocation received during [July, August, Sept.]; **Rainfed reported by USDA-NASS

Kansas:

The research projects in Kansas were conducted at the Kansas State University (KSU) Northwest Research-Extension Center in Colby, KS (Lamm et al., 2014), the Southwest Research-Extension Center near Garden City, KS (Klocke et al., 2011; Kisekka et al., 2015; Kisekka et al., 2016), and the Southwest Research-Extension Center near Tribune, KS (Schlegel et al., 2012). A description of the research sites is presented in Table 1.

Long term deficit irrigation research at Garden City, KS showed that crop water use functions varied substantially from year to year as shown in Figure 3. The study consisted of six treatments namely 100%, 80%, 70%, 50%, 40%, and 25% of full irrigation (Klocke et al., 2011). From Figure 3, it can be seen that in normal to wet years on average 90% of full irrigation treatments will produce yields equal to those from full irrigation. Also, there is substantial year to year variability in production functions that makes them less suitable for making short term or seasonal water management decisions. The observed variability can be attributed to several factors including: 1) seasonal changes in rainfall amounts and patterns, 2) changes in evaporative demand, 3) cultural practices (e.g., irrigation scheduling, fertility management, weed management, pest and insect management), 4) salinity, 5) differences in crop cultivars and their response to water use, 6) effect of water deficit at different growth stages and inter-dependency of growth stage water stress effects, and 7) other miscellaneous factors such as hail or freeze damage (Kisekka et al., 2015). Interactions among these factors makes optimum management of deficit irrigation more complicated as compared to full irrigation. It can be seen in Figure 3 that during wet years without hail, the yield versus irrigation function are curvilinear while for the two drought years of 2011 and 2012 the response functions were linear mimicking the yield versus ET relationship which is typically linear. This

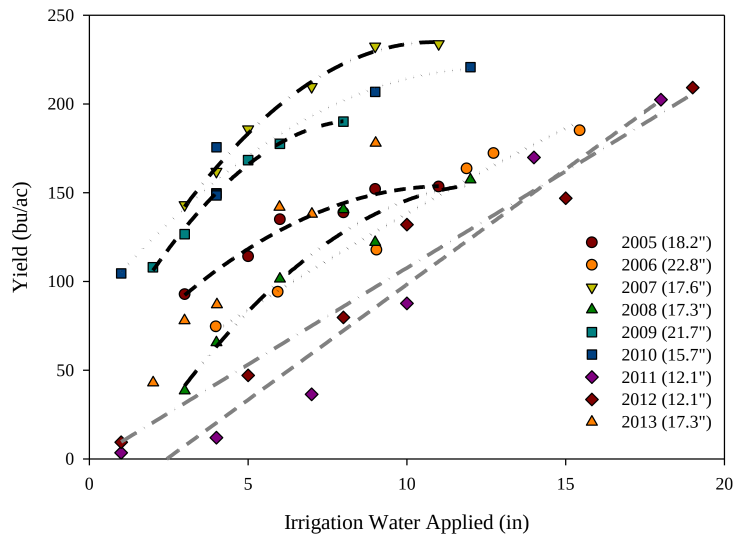

Figure 3. Corn grain yield (bu ac^{-1}) response to irrigation from 2005 to 2013. The numbers in parentheses are annual rainfall recorded at the Kansas State University Southwest Research and Extension Center near Garden City, KS.

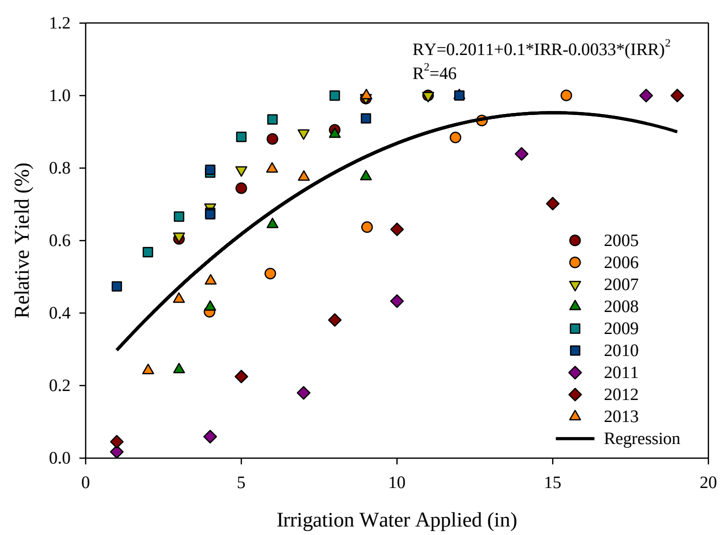

Figure 4. Corn relative yield response to irrigation from 2005 to 2013 near Garden City, KS.

probably indicates that during drought years CWUE was high with minor percolation and runoff losses, thus the yield versus irrigation curve approximated a straight line. Also, it can be seen from Figure 4 that uncertainty in crop yield due to deficit irrigation decreased as the amount of irrigation increased, probably due to the reduced effect of variable weather conditions.

More recent research at Garden City evaluated yield response of new corn genetics (DKC 62-27 DGVT2PRO [drought tolerant trait (DT)] and DKC 62-98 VT2PRO [conventional]) under different levels of deficit irrigation during the 2014 and 2015 growing seasons (Kisekka et al., 2016). As shown in Figure 5, the effect of deficit irrigation on corn yield was significant ($P < 0.001$) for both hybrids. However, the effect of the drought tolerance trait on yield was not significant ($P > 0.05$) in both years (Kisekka et al., 2016). Both 2014 and 2015 growing seasons were wetter than normal; therefore, further research is needed to quantify the effect of new drought tolerant traits on corn yield under deficit irrigation in western Kansas.

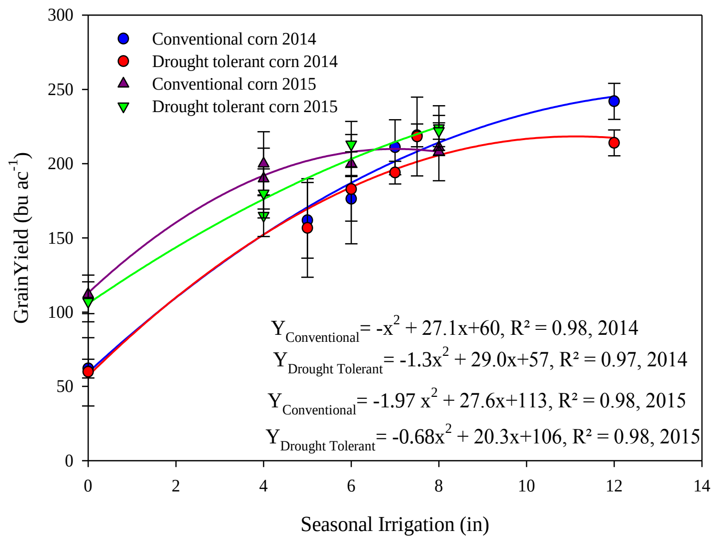

Figure 5. Response of conventional and drought tolerant corn to limited irrigation during the 2014 and 2015 growing seasons at the Kansas State University Southwest Research and Extension Center near Garden City, KS.

At the Kansas State University Northwest Research and Extension Center in Colby, KS, Lamm et al. (2014) evaluated corn yield and CWUE response to irrigation using data from 1989 to 2004. Their results concluded that irrigated corn peaked at approximately 80% of full irrigation for grain yield and CWUE under SDI (Figures 6 and 7). These results provide evidence that opportunities exist to practice moderate deficit irrigation in western Kansas without substantial reductions in yields and profitability.

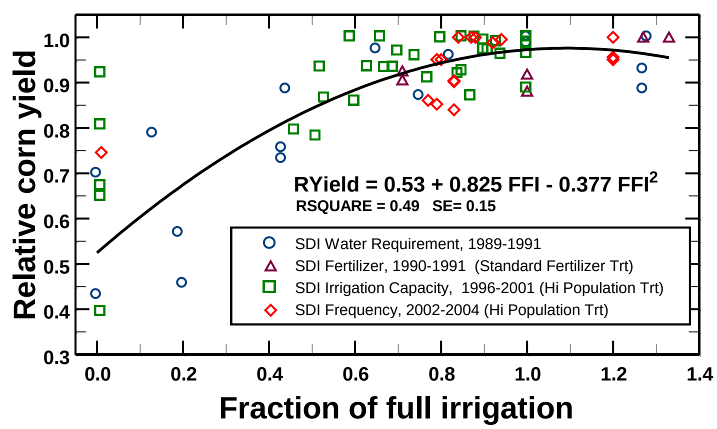

Figure 6. Relative yield of subsurface drip irrigated corn at the Kansas State University Northwest Research and Extension Center in Colby, KS (Lamm et al., 2014).

Many areas in western Kansas have deep well drained silt loam soils with high available water holding capacity of 1.5 to 2.0 inches per foot which helps buffer the crop between irrigation or rainfall events. It is important to note that corn is a high water response crop and severe levels of deficit irrigation can negatively impact yield. Furthermore, their results showed that applying more than 100% of full irrigation can reduce water productivity as shown in Figure 7.

Research on deficit irrigation cropping systems has also been conducted at the Kansas State University Southwest Research and Extension Center near Tribune, KS. Besides crop yield response to water, deficit irrigation research has explored strategic water management such as the effect of late spring preseason irrigation on yield and net returns of corn, among other crops, under low well capacities. Schlegel et al. (2012) reported that preseason irrigation was profitable at low well capacities for corn (Table 3). These results demonstrate that as irrigation well capacities diminish, late spring preseason irrigation used to build up the soil profile could be essential to buffer the crop between in-season irrigation events or rainfall when deficit irrigation is practiced.

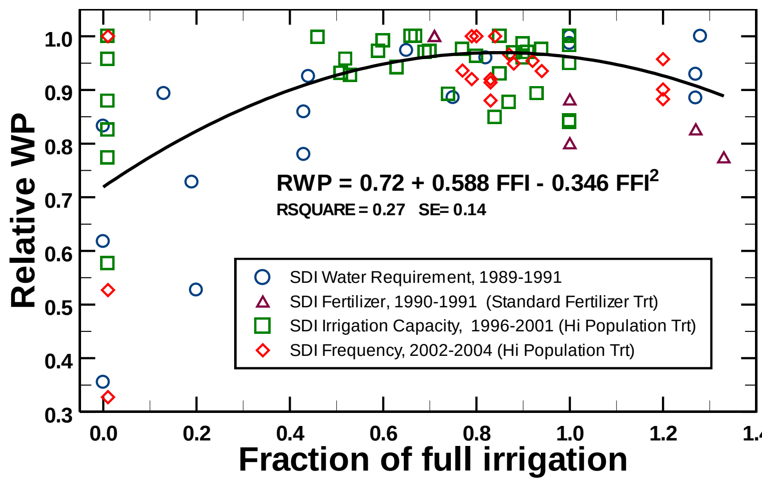

Figure 7. Relative water productivity of subsurface drip irrigated corn at the Kansas State University Northwest Research and Extension Center in Colby, KS (Lamm et al., 2014).

Table 3. Net returns to land, irrigation equipment, and management from preseason irrigation at threes well capacities and seeding rates at Tribune, KS 2006-2009. (Adapted from Schlegel et al., 2012)

Well capacity	Preseason irrigation	Seeding rate (seeds ac^{-1})		
		22,500	27,500	32,500
inches day^{-1}		Net returns \$ ac^{-1}		
0.12	No	231	238	214
	Yes	285	300	297
0.16	No	290	283	261
	Yes	321	352	357
0.20	No	415	449	485
	Yes	417	458	492

Colorado:

The research projects in Colorado were conducted at the Central Great Plains Research Station (CGPRS) located in Akron, CO (Schneekloth et al., 2012; Benjamin et al., 2015) and the Irrigation Research Farm (IRF) in Yuma, CO (Al-Kaisi and Yin, 2003). A description of the research sites is presented in Table 1. The two research sites are located in northeastern Colorado and are approximately 30 miles apart. Both sites experience a semi-arid climate with long-term growing season precipitation of 11.5 and 12.3 inches for CGPRS and IRF, respectively.

Schneekloth et al (2012) evaluated the impacts of irrigation capacity and timing on corn production at CGPRS from 2009 to 2012. The authors imposed three irrigation treatments, including full irrigation (0.25 inches day^{-1}), inadequate capacity (0.125 inches day^{-1}), and growth stage initiation (0.33 inches day^{-1} starting at 2 weeks before tassel). These treatments were designed to represent potential options that could be utilized by producers under limited irrigation system capacity and/or water allocated conditions as described by Klocke et al. (2011). The inadequate capacity treatment mimicked producers planting the entire field to corn and initiating irrigation early in the season and continuing throughout. The full irrigation treatment mimicked producers planting a percentage of the field to corn and managing irrigation according to best management practices (BMPs) throughout the season. Lastly, the growth stage initiation strategy mimicked planting a percentage of the field to corn and waiting to initiate irrigation until two weeks prior to tasseling. For the full and growth stage initiation strategies, the actual percentage of the field planted and irrigated to the desired crop would be based on the irrigation well capacity so that ET demand of the crop is satisfied throughout the desired period. Under these two management strategies, a producer could plant the remaining portion of the field with a rainfed crop and/or a crop that does not require irrigation late in the season, such as winter wheat. The authors reported no statistical differences across irrigation treatments in the wet year of 2009; however, less irrigation was required for the growth stage initiation strategy as compared to the others due to better utilization of precipitation and stored soil water. In 2009, IWUE of the growth stage initiation strategy was approximately 40% and 20% greater than the full irrigation and inadequate capacity, respectively. Whereas, during the drier years of 2010 and 2011, the inadequate capacity strategy had significantly lower yields as compared to the others. Yields were reduced by 33 to 45% of the full irrigation; whereas, grain yields of the growth stage initiation strategy were not significantly different than full irrigation. Irrigation amount per acre for growth stage initiation was less than full irrigation in 2 of the 3 years and less than the inadequate capacity strategy in 2009 (wet year). The CWUE and IWUE values for the inadequate capacity strategy were lower than the full and growth stage initiation strategies in 2 of the 3 years. The CWUE and IWUE for the full and growth stage initiation strategies were not different between each other 2 of the 3 years; however, during a year with above average precipitation such as 2009, growth stage initiation had significantly higher IWUE because of better utilization of irrigation and slightly higher CWUE because of a lower ET rate. On average, the growth stage initiation strategy had higher CWUE and IWUE of 9.4 and 14.5 bu ac-in^{-1}, respectively, with less than a 2% yield reduction as compared to the full irrigation strategy. The successful adoption of the investigated deficit irrigation strategies will depend on an economic analysis to quantify the impact of only irrigating a portion of the field and/or introducing a crop rotation as compared with deficit irrigating the entire field.

A long-term continuous deficit irrigation study was also performed at CGPRS from 2001 to 2006 by Benjamin et al. (2015). The authors were interested in evaluating the cumulative effect of deficit irrigation on soil water storage and grain yield as compared with a full irrigation treatment. The full irrigation treatment supplied irrigation each week based on ET demand minus effective rainfall; whereas, the deficit irrigation treatment supplied no irrigation water during the vegetative period and then added irrigation equivalent to the full irrigation treatment during the reproductive period. The deficit irrigation treatment experienced less soil water storage in the 6 ft soil profile both at the start as well as the end of the growing season as compared to the full irrigation treatment. With the exception of the end of season soil water in 2002 and the soil water status in 2006, the difference between the two treatments were statistically significant ($P < 0.05$). It was observed that the deficit irrigation treatment continued to deplete stored soil water over-time due to insufficient off-season recharge. Consequently, yield and CWUE for the deficit irrigation treatment decreased over-time. In 2001, there were no significant differences in grain yield between treatments, where in other years, except for 2005, deficit irrigation reduced grain yield by 20-65% as compared with full irrigation. The deficit irrigation treatment reduced CWUE by 26 to 51% for 2003, 2004, and 2006 growing seasons. The authors concluded that this strategy for managing deficit irrigation may be an option for short-term or emergency situations, but not a suitable long-term option as it was determined to be detrimental to both yield and CWUE.

At the IRF research site in Yuma, CO, Al-Kaisi and Yin (2003) evaluated corn yield and CWUE response to irrigation, N fertilization, and planting population density. The investigated treatments were 60%, 80%, and 100% of ET replacement for irrigation; 27, 125, 223, and 321 lb ac^{-1} for N fertilization; and 23,000, 27,900, and 32,800 plants ac^{-1} for planting population density. The authors reported that the 80% of full irrigation had the same or greater CWUE than the other irrigation treatments regardless of N fertility rate (Table 4). No significant differences in water extraction were observed between the 80% and full irrigation treatments. The 60% of full irrigation treatment resulted in lower soil water content in the top 3 ft soil profile at time of harvest as compared to the other treatments. The authors concluded that 80% of full irrigation with N fertility between 125 and 223 lb ac^{-1} and planting population between 23,000 and 27,900 plants ac^{-1} is the best management strategy for optimizing CWUE.

Table 4. Performance indicators, including grain yield (bu per acre), seasonal evapotranspiration (ET, in), crop water use efficiency (CWUE, bu per acre-in of ET), and irrigation water use efficiency (IWUE, incremental bu per acre-in of irrigation) of various irrigation treatments at the study sites in Colorado.

References & Years	Irrigation System	Treatment	Grain Yield (bu $acre^{-1}$)	ET (inch)	CWUE (bu $ac\text{-}in^{-1}$)	IWUE (bu $ac\text{-}in^{-1}$)
		Akron, CO				
Schneekloth		Full Irrigation	211	23.1	9.2	13.2
et al. (2012)	Solid Set	Growth Stage Initiation	208	22.0	9.4	14.5
	Sprinkler	Inadequate Capacity	156	20.7	7.4	11.6
2009-2011		Rainfed**	57	-	-	-
		Yuma, CO				
		100% ET - 27N	163	25	6.5	-
		100% ET - 125N	174		7.0	-
		100% ET - 223N	191		7.6	-
		100% ET - 321N	194		7.8	-
Al-Kaisi and		80% ET - 27N	138	20	6.9	-
Yin (2003)+	Center	80% ET - 125N	154		7.7	-
	Pivot	80% ET - 223N	163		8.1	-
1998-2000		80% ET - 321N	170		8.5	-
		60% ET - 27N	74	15	4.9	-
		60% ET - 125N	101		6.7	-
		60% ET - 223N	119		8.0	-
		60% ET - 321N	102		6.8	-

**Schneekloth et al. (2012): Rainfed reported by USDA-NASS; +Treatment means of grain yield, ET, and CWUE are averaged over plant population densities. ET rates are based on average of all sub-treatments within an irrigation treatment.

Similar to Benjamin et al. (2015), Al-Kaisi and Yin (2003) concluded that residual effects of deficit irrigation strategies on the subsequent crop can exist as a result of potential reduction in stored soil water. However, the deficit irrigation strategy investigated by Benjamin et al. (2015) intentionally withheld irrigation during the vegetative growth period regardless of the magnitude and variability of off-season precipitation with the intent that a greater irrigation response would occur during the reproductive period. Such a strategy may result in unintended consequences. For example, years that experience inadequate soil water recharge may result in severe vegetative water stress leading to lasting effects on crop growth and canopy development, which in turn may hinder crop water uptake dynamics during the reproductive period; therefore, resulting in a lower response to irrigation as compared to if the water was applied during the vegetative period to mitigate the prolong period of water stress. As demonstrated by the researchers, this approach was not well suited for the region and a more responsive deficit irrigation approach such as a percentage of ET replacement early in the season followed by growth stage timing later in the season may be required. This would allow for a producer to be more reactive early in the season to prevent detrimental long lasting effects of water-stress that may severely impact the pollination and grain filling periods.

Texas:

The research projects in Texas were conducted at the USDA-Agricultural Research Service, Conservation and Production Research Laboratory in Bushland, TX (Musick and Dusek, 1980; Howell et al., 1995; Schneider and Howell, 1998; Baumhardt et al., 2013), the Texas A&M AgriLife Research Station near Etter, TX (Hao et al., 2015a and b), and at producer sites located around Lubbock, TX (TAWC, 2017). A description of the research sites is presented in Table 1. The Texas High Plains region (northern and southern regions) nominally applies 4.5 million ac-ft of irrigation water annually (Texas State Water Plan, 2007 and 2012). The ability to meet the irrigated agricultural demand is most challenging due to the high ET demand and limited well capacities of the region. Meteorological vapor pressure deficit demands have been recorded at 7 kPa in the southern Texas High Plains during the height of the growing season. Due to the semi-arid environment of the Texas regions (Table 1), the number of irrigations required and applied within a summer growing season typically average from 16 to 22 events annually. The ability to regionally meet full crop water demand has diminished over-time and as a result limited or reduced ET production has become more common (Colaizzi et al., 2009).

Since 1980 in the Texas High Plains, corn yields have generally increased on average by 40% (175 bu ac^{-1} to 250 bu ac^{-1}) with the use of nearly 60% less irrigation water. This fact alone represents a tremendous degree of increased productivity by researchers and producers with less water input. This achievement has been accomplished by the development of progressive, advanced genetic technologies but more so by improved and enhanced systems management technologies. While ”drought-tolerant” technology has been touted by the commercial seed industry, grain yield advances are likely more attributable to heat tolerance rather than drought tolerance. This perspective is based on the fact that while corn rooting parameters have been enhanced in some cases, major or significant overall changes in the ET versus yield function have not been realized. Nonetheless, specific changes in selected new corn hybrids have been detected and published in the literature and thus reflect the differing management scenarios required with targeted (reduced) levels of ET (in terms of total water) for optimal performance with these advanced genetic hybrids. It should also be noted that due to the severity of ET demand in the Texas High Plains, deficit irrigation levels below a 50% ET requirement typically lead to complete crop failure in drought years as shown by Musick and Dusek (1980) and Schneider and Howell (1998) (Table 5). More recent data has shown that irrigation targeted at 75% ET production levels can still sustain an effective and profitable yield as compared to the 100% ET level (Marek et al., 2013a; Hao et al., 2015a and b).

At the USDA-ARS Conservation and Production Research Laboratory in Bushland, Texas, Howell et al. (1995) evaluated corn yield and CWUE under a low energy precision application (LEPA) center-pivot system. They investigated six irrigation levels ranging from rainfed to 100% of crop ET (Table 5). Grain yield increased from 96 to 199 bu ac^{-1} in 1992 and from 64 to 238 bu ac^{-1} in 1993, with maxima occurring at 80 to 100% of full irrigation. Averaged over 2 years, CWUE was maximal at 5.86 bu $ac\text{-}in^{-1}$ at the 80% irrigation level and IWUE was greatest at 9.53 bu $ac\text{-}in^{-1}$ at the 40% irrigation level. Similar results were reported by Schneider and Howell (1998), where they found the largest CWUE at or near 100% of ET replacement and the largest IWUE between 50 and 75% of ET replacement (Table 5). Furthermore, no interaction was observed between irrigation amount and sprinkler method; therefore, they concluded that both LEPA and spray sprinkler technologies are suitable irrigation methods for the region. Also at the USDA-ARS research laboratory in Bushland, TX, Baumhardt et al. (2013) evaluated the effects of irrigation rate, tillage method, and their interactions on corn yield, ET, and CWUE in a wheat-corn-fallow rotation from 2006 to 2009 (Table 5). They hypothesized that retaining surface residue via conservation tillage would increase soil-water storage, and therefore, improve efficiency of deficit irrigation. The deficit irrigation treatments included rates based on system capacities of 0.1 and 0.2 inches per day, and the three tillage practices included disk tillage, stubble-mulch, and no-tillage. The ET rate of the 0.1 inch day^{-1} capacity treatment ranged from approximately 54 to 64% of the estimated ET rate of a fully irrigated crop; whereas, the ET rate of the 0.2 inch day^{-1} capacity treatment ranged from 76 to 85% of the estimated ET rate of a fully irrigated crop. Stubble-mulch and no-tillage increased fallow soil-water storage by approximately 0.6 and 2.0 inches, respectively, as compared with disk tillage, and enhanced grain yield by partitioning some of the evaporation to crop transpiration. However, those advantages were not enough to compensate for yield reductions caused by the deficit irrigation treatments.

Hao et al. (2015a and b) evaluated the grain yield and CWUE responses of a conventional corn hybrid and four “drought tolerant” Aquamax hybrids (DuPont-Pioneer, Johnston, IA) to irrigation at 50, 75, and 100% of crop ET, and three planting densities at Etter, TX (60 miles north of Amarillo). Averaged across years, hybrids, and planting densities the grain yield at 75% ET (190 bu ac^{-1}) was 88% of the 100% ET treatment (215 bu ac^{-1}), while CWUE at 75% ET (8.44 bu $ac\text{-}in^{-1}$) was 10% greater than at 100% ET (7.67 bu $ac\text{-}in^{-1}$). The drought-tolerant hybrids used no more water than the conventional hybrid, but did increase grain yield by 9 to 12% at 75% ET and by 19 to 20% at 50% ET, indicating a role for improved hybrids to sustain corn production under limited irrigation.

The Texas Alliance for Water Conservation (TAWC, 2017), affiliated with Texas Tech University, has collected crop production data from commercial farms from 2005-2015 (Lubbock-Plainview area) to demonstrate methods of managing irrigation to improve CWUE. While not structured experiments, the results represent what producers are actually attaining under local conditions, using their own management decisions. Figure 8 illustrates corn grain yield as a function of water supply expressed as a percentage of crop water demand (potential ET). Water supply includes the sum of irrigation applied, effective rainfall (50% of actual annual rain), and change in soil water. Predicted maximum yield (215 bu $acre^{-1}$) occurred at 97% of ET. Predicted yield at 75% of ET was 204 bu $acre^{-1}$. The regression exhibits high variability because the 62 site-years represented various types of irrigation systems, hybrids, weather patterns, and fertilization practices. The wide range in water supply indicates that some producers are irrigating above 100% of crop demand, which would be corrected with use of an irrigation scheduling program and/or soil water monitoring. Current Texas regional water planning efforts indicate that crop irrigation will continue for the next 50 years, but at different production levels from the past (Marek et al., 2013b; Amosson et al., 2015).

Table 5. Performance indicators, including grain yield (bu per acre), seasonal evapotranspiration (ET, in), crop water use efficiency (CWUE, bu per acre-in of ET), and irrigation water use efficiency (IWUE, incremental bu per acre-in of irrigation) of various irrigation treatments at the study sites in Texas.

References & Years	Irrigation System	Treatment		Grain Yield (bu acre^{-1})	ET (inch)	CWUE (bu ac-in^{-1})	IWUE (bu ac-in^{-1})
Bushland, TX							
Howell et al. (1995) 1992-1993	LEPA Center Pivot	100% ET		222	34.6	6.42	8.72
		80% ET		216	31.2	6.92	10.54
		60% ET		185	28.1	6.59	10.41
		40% ET		164	24.8	6.59	12.67
		20% ET		127	21.1	6.03	14.68
		0% ET		80	18.0	4.42	-
Schneider and Howell (1998) 1994-1995	LEPA In-Canopy Overhead	Rainfed		0	12.4	0.00	-
		25% ET: LEPA Sock		37	18.6	1.86	7.43
		25% ET: LEPA Bubble		25	18.6	1.25	5.07
		25% ET: In-Canopy Spray		21	18.6	1.09	4.28
		25% ET: Overhead Spray		27	18.3	1.47	5.47
		50% ET: LEPA Sock		137	22.5	6.08	13.39
		50% ET: LEPA Bubble		128	22.8	5.61	12.44
		50% ET: In-Canopy Spray		134	22.7	5.92	12.94
		50% ET: Overhead Spray		124	23.3	5.31	12.01
		75% ET: LEPA Sock		191	27.7	6.91	12.26
		75% ET: LEPA Bubble		179	27.9	6.40	11.45
		75% ET: In-Canopy Spray		177	28.1	6.32	11.49
		75% ET: Overhead Spray		183	28.3	6.48	11.87
		100% ET: LEPA Sock		203	32.9	6.18	9.81
		100% ET: LEPA Bubble		213	31.3	6.82	10.32
		100% ET: In-Canopy Spray		215	31.2	6.89	10.44
		100% ET: Overhead Spray		227	31.7	7.15	11.04
Baumhardt et al. (2013) 2006-2009	Lateral Move	0.1 inch day^{-1}: Disk Till		23.7	14.4	1.65	-
		0.1 inch day^{-1}: Stubble Mulch		30.4	14.6	2.08	-
		0.1 inch day^{-1}: No Till		44.1	15.8	2.80	-
		0.2 inch day^{-1}: Disk Till		63.3	18.8	3.36	-
		0.2 inch day^{-1}: Stubble Mulch		66.7	18.9	3.52	-
		0.2 inch day^{-1}: No Till		79.1	19.6	4.03	-
Etter, TX							
Hao et al. (2015a,b)+ 2011-2013	LESA Center Pivot	Hybrid: P33D49	100% ET	215	28.8	7.52	-
			75% ET	184	23.0	8.03	-
			50% ET	98	19.6	5.05	-
		Hybrid: P1151HR	100% ET	220	27.8	8.00	-
			75% ET	200	22.4	8.97	-
			50% ET	118	19.5	6.05	-
		Hybrid: 1324HR	100% ET	209	28.4	7.44	-
			75% ET	186	22.9	8.20	-
			50% ET	99	19.4	5.21	-
		Hybrid: 1498HR	100% ET	214	28.3	7.62	-
			75% ET	188	22.9	8.24	-
			50% ET	103	19.7	5.20	-
		Hybrid: 1564HR	100% ET	225	26.7	8.45	-
			75% ET	199	22.6	8.79	-
			50% ET	120	19.6	6.25	-

[+]Results are averaged across planting population densities of 24, 30, and 34 thousands plants per acre.

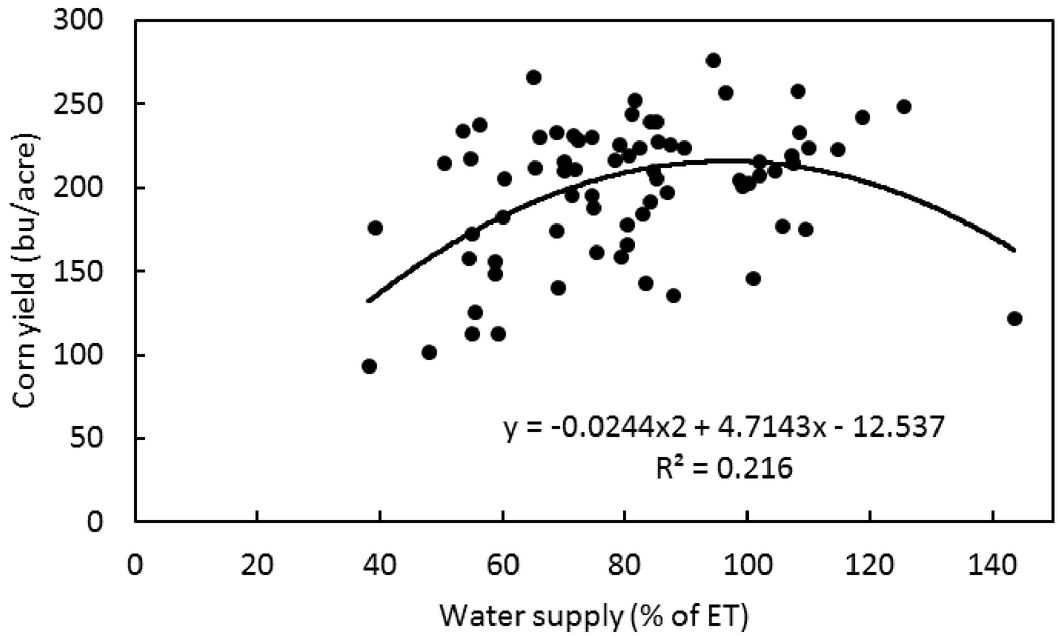

Figure 8. Response trend of corn grain yield in the South Plains of Texas from 2005-2015 (excluding the severe drought year of 2011) in relation to the sum of water supply from irrigation, effective rain (50% of total rain), and soil moisture changes (n=62).

CONCLUSIONS

A review of investigated deficit irrigation management strategies for corn was conducted across the U.S. High Plains. Some research studies from Nebraska, Kansas, Colorado, and Texas were compiled for the review and the performance of the investigated deficit irrigation strategies were described in terms of grain yield, evapotranspiration (ET), crop water use efficiency (CWUE), and irrigation water use efficiency (IWUE) as compared with a fully-irrigated crop. The research sites vary in the driving factors that lead to the adoption of deficit irrigation management, including differences in 1) ground water resources, 2) state water policy on the management of ground and surface water (e.g., mandated single or multi-year water allocations in Nebraska), and 3) climatic factors, including the magnitude and distribution of precipitation and ET. As expected these differences in drivers have led to varying degrees of success for the same deficit irrigation strategy across locations. For example, crop tolerance to a reduction in full irrigation requirement is not the same across regions due to differences in soil type and climatic factors, and therefore, the percentage reduction in full irrigation requirement should be based on site-specific conditions. The review also provided insight on attributes for both effective and ineffective strategies, regardless of research location. Notable attributes of an effective deficit irrigation strategy, included preventing crop water stress at critical growth stages (i.e., tasseling to blister growth sages) as well as adopting other best crop and land management practices such as reduced tillage. Whereas, a notable attribute of an ineffective strategy would be disregarding the importance of inter-annual variability of crop growing conditions and their impact on the grain yield response to irrigation. A static based management practice that does not respond to existing conditions can lead to unintended consequences, and therefore, a dynamic approach is preferred. Readers should be mindful of their unique conditions when practicing deficit irrigation, including irrigation system type, soil water at planting, residue levels, subsequent crop, and market values, among others.

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