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Deficit Irrigation Management of Maize in the High Plains Aquifer Region: A Review

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Deficit Irrigation Management of Maize in the High Plains Aquifer Region: A Review

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Research Impact Statement: It is imperative appropriate irrigation management strategies are developed to extend the usable life of the High Plains Aquifer. Past research findings and future research needs are discussed.

ABSTRACT: Irrigated agriculture is a major economic contributor of the High Plains Region and it primarily relies on the High Plains Aquifer as a source of water. Over time, areas of the High Plains Aquifer have experienced drawdowns limiting its ability to supply sufficient water to sustain fully irrigated crop production. This among other reasons, including variable climatic factors and differences in state water policy, has resulted in some areas adopting and practicing deficit irrigation management. Considerable research has been conducted across the High Plains Aquifer region to identify locally appropriate deficit irrigation strategies. This review summarizes and discusses research conducted in Nebraska, Colorado, Kansas, and Texas, as well as highlights areas for future research. ***Editor's note****: This paper is part of the featured series on Optimizing Ogallala Aquifer Water Use to Sustain Food Systems. See the February 2019 issue for the introduction and background to the series.*

(KEYWORDS: deficit irrigation; evapotranspiration; grain yield; High Plains Aquifer; limited irrigation.)

INTRODUCTION

In water-limited areas, including the United States (U.S.) High Plains, irrigation is essential for the economic viability of individual producers as well as rural communities (Terrell et al. 2002; Leatherman et al. 2004; Guerrero et al. 2010). Irrigation provides supplemental water for crop production when precipitation and available soil water are insufficient to meet crop water demands. Irrigated agriculture in the U.S. High Plains primarily relies on the High Plains Aquifer (USGS 2018), which supplies 30% of the nation's irrigated groundwater (Steward et al. 2013). As of 2005, the change in water level of the aquifer ranged from a positive 25.6 m to a negative 84.4 m with an area-weighted average decline of 3.9 m since predevelopment (McGuire 2007). However, in the southern regions, aquifer decline has been much more dramatic as profitable agriculture has heavily depended on irrigation (Colaizzi et al. 2009). Consequently, the

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ability of the aquifer, or parts of it, to support irrigated agriculture at existing production levels in the future is threatened. With irrigated agriculture in the High Plains region having a major economic impact on rural communities from local to national levels, it is imperative that appropriate irrigation management strategies be developed to extend the usable life of the aquifer.

Crop water requirements depend on several factors, including crop type, variety, and growth stage; soil water and nutrient availability; soil physical and chemical properties; micro-meteorological and regional climatic conditions; among others. Unfortunately, applying irrigation to meet full water requirements is becoming less of an option due to drought, declining groundwater levels, reduced streamflow, restricted water allocations, insufficient pumping capacity, load management, scheduling conflicts, water rights, among others (Lingle and Franti 1998; McGuire and Fischer 1999; McGuire 2004; Payero et al. 2008; Klocke et al. 2011). At the same time, there is a large economic and social pressure to reduce irrigation water use. Therefore, management strategies that apply less irrigation than required to meet crop evapotranspiration (ET_c) demand are targeted to balance grain yield, and net profitability, given the amount of water available. These strategies are referred to as deficit, limited, and/or regulated irrigation management practices.

One strategy for managing deficit irrigation consists of trying to mitigate the impact of water stress on crop growth and grain yield by withholding irrigation at growth stages that are less sensitive to water deficit as compared to others. This strategy is called "growth stage deficit irrigation" and is often practiced when there are pumping restrictions (e.g., water allocations), yet the system has sufficient capacity to meet peak ET_c demands. Under situations when peak ET_c demands cannot be met, such as insufficient pumping capacity, a reduced percentage of full irrigation requirement may be a more appropriate strategy (i.e., limited irrigation). This strategy consists of irrigating to satisfy a percentage of a crop's potential ET_c, and therefore, it moderates crop water stress by targeted allocation of the available water throughout the growing season (Irmak 2015a, b). Other alternative irrigation management strategies that address water limitations include: (1) planting crops whose water requirements better match seasonal available water supply, (2) split the land area between the desired crop and a less-water demanding crop, and (3) reducing the total irrigated area by substituting a portion of the field with fallow or a dryland crop (Martin et al. 1989; Klocke et al. 2006, 2011; Araya et al. 2017).

A single deficit irrigation management strategy is unlikely to be the best option across the High Plains region owing to temporal and spatial variability in growing season precipitation and ET_c drivers (i.e., soil, crop type, and variety, and climatic conditions) coupled with differences in producer practices, state/local water policy, and other crop and land management strategies. As a result, extensive research has been conducted across the High Plains for developing locally appropriate deficit irrigation management strategies. Aggregating past research findings within and across the region can provide insight into which deficit irrigation strategies are most appropriate for each location as well as identify current knowledge gaps. This review focuses on research that has been conducted across the High Plains Aquifer region, including Nebraska, Kansas, Colorado, and Texas. The review will discuss reported findings of the investigated deficit or limited irrigation strategies as well as highlight areas for future research.

SELECTED CASE STUDIES ON DEFICIT IRRIGATION MANAGEMENT IN THE HIGH PLAINS REGION

Study Area

The locations of research conducted in four states are presented in Figure 1. Although there are various crops grown in the High Plains, this review focuses on maize (*Zea mays* L.) due to availability of experimental data that span the region. The research sites extend (south to north) from Lubbock, Texas, to Scottsbluff, Nebraska, and (east to west) from Clay Center, Nebraska, to Scottsbluff, Nebraska. A description of the research sites is presented in Table 1. The climate ranges from subhumid/semiarid at Clay Center, Nebraska, to semiarid at the remaining sites. The long-term (1985–2016) seasonal (May 1–September 30) precipitation is greatest at Clay Center, Nebraska, with 408 mm and lowest in Scottsbluff, Nebraska, with 206 mm (High Plains Regional Climate Center). The research sites are mostly composed of medium-textured soils that have relatively high soil plant available water holding capacities of 125–167 mm/m. The research sites vary in the driving factors that warrant the adoption of deficit and/or limited irrigation management, including differences in: (1) ground and/or surface water resources (Figure 1); (2) climatic factors, including the magnitude and distribution of precipitation (Table 1); (3) state water policy on the management of ground and surface water, which can include installation of pumping station water meters, moratoriums on drilling new wells, and implementation of fixed multiyear water allocations (Payero et al. 2008); and (4) programs for educating producers on different deficit irrigation management strategies.

Performance Indicators

While optimal crop performance or productivity is difficult to determine using a single metric, a combination of indices or measures can inform suitable options for management strategies. Crop water use efficiency (CWUE, kg/m^3) and irrigation water use efficiency (IWUE, kg/m^3) are two measures commonly used to assess irrigation management strategies and are calculated as follows:

$$\mathrm{CWUE} = \frac{\mathrm{GY}}{\mathrm{ET_c}} \tag{1}$$

$$\mathrm{IWUE} = \frac{\mathrm{GY}_i - \mathrm{GY}_r}{I}, \tag{2}$$

where GY is grain yield (Mg/ha) adjusted to 15.5% moisture content, $\mathrm{ET_c}$ is seasonal crop evapotranspiration

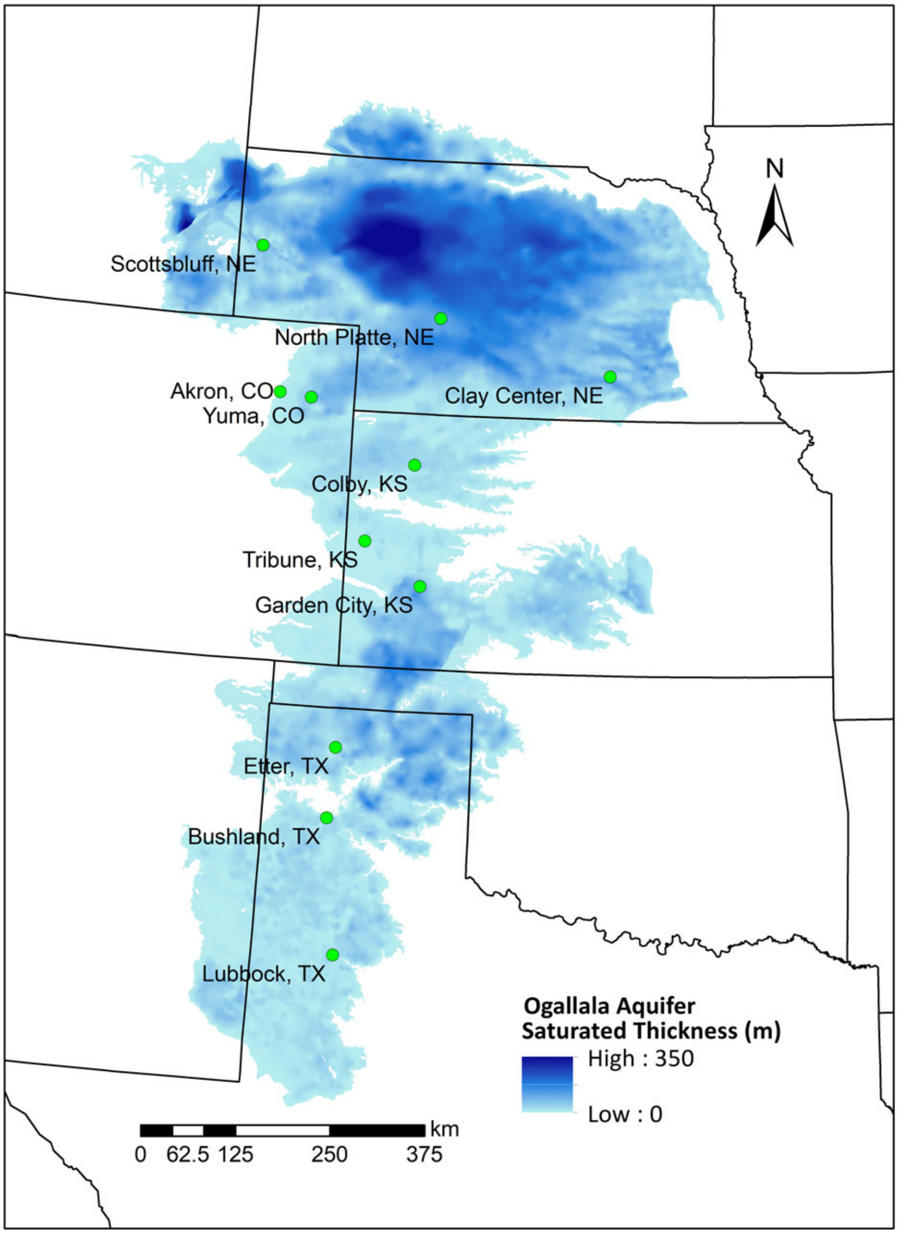

FIGURE 1. Deficit or limited irrigation management research sites in Nebraska (NE), Kansas (KS), Colorado (CO), and Texas (TX). The blue shading is the saturated thickness (m) of the Ogallala Aquifer (adapted from McGuire et al. 2012).

TABLE 1. Description of the research sites located in Nebraska, Kansas, Colorado, and Texas, including climate, soil type, and long-term seasonal (May 1–September 30) precipitation.

Location	Climate	Soil mapping units	Precipitation (mm)
Nebraska			
Clay Center	Subhumid/Semiarid	Hastings silt loam	408
North Platte	Semiarid	Cozad silt loam	317
Scottsbluff	Semiarid/Arid	Tripp very fine sandy loam	206
Kansas			
Colby	Semiarid	Keith silt loam	305
Tribune	Semiarid	Ulysses silt loam	298
Garden City	Semiarid	Ulysses silt loam	287
Colorado			
Akron	Semiarid	Weld/Rago silt loam	341
Yuma	Semiarid	Haxtun sandy loam	284
Texas			
Etter	Semiarid	Sherm silty clay loam	293[1]
Bushland	Semiarid	Pullman clay loam	353
Lubbock/Plainview	Semiarid	Pullman clay loam	305

Note: The long-term (1985–2016) precipitation was collected from the High Plains Regional Climate Center (hprcc.unl.edu) and National Oceanic and Atmospheric Administration (noaa.gov).
[1]1981–2010 Average precipitation collected from PRISM Climate Group, Oregon State University (prism.oregonstate.edu; on January 26, 2017).

(mm), I is seasonal applied irrigation (mm), and subscripts i and r represent irrigated and rainfed settings, respectively. Seasonal ET_c was quantified in various ways among the reported studies, including soil water balance via lysimeters and water content estimation; calibrated mathematical models; among others. Although there are recognized differences in the accuracy of ET_c methods as described by Wegenhenkel and Gerke (2013), this review does not differentiate between them. Furthermore, the studies were conducted under various irrigation systems, including center pivot, lateral move, solid set sprinkler, and subsurface drip (SDI), which range in their potential application efficiency.

Changes in CWUE and IWUE are affected by climatic conditions as well as by production management and genetics. The authors recognize that advances in crop breeding, and consequently, genetic interactions with management practices have occurred over time, which further influence the comparison of results across studies. Therefore, past and more recent irrigation research findings were compiled to provide a more comprehensive understanding of how deficit irrigation strategies responded to changes in genetics, environment, and management. Performance of the deficit irrigation strategies reported in the literature were summarized in terms of grain yield adjusted to 15.5% moisture content, seasonal ET_c, CWUE, IWUE, and economic return by comparing them with non-water-limiting production management practices (i.e., full irrigation to meet 100% of ET_c).

FINDINGS FROM CASE STUDIES

Nebraska

The research projects in Nebraska were conducted at the University of Nebraska-Lincoln South Central Agricultural Laboratory (SCAL) near Clay Center, Nebraska (Irmak 2015a, b; Rudnick et al. 2016), the West Central Research and Extension Center (WCREC) in North Platte, Nebraska (Hergert et al. 1993; Payero et al. 2008, 2009; van Donk et al. 2012), and the Panhandle Research and Extension Center (PREC) in Scottsbluff, Nebraska (Spurgeon and Yonts 2013). In Nebraska, irrigation demand increases and growing season length for maize decreases from SCAL (south central) to PREC (northwest) (Sharma and Irmak 2012; Rudnick et al. 2015b). The climate is semiarid/arid at PREC, semiarid at WCREC, and a transition zone with subhumid/semiarid at SCAL (Table 1).

Irmak (2015a, b) evaluated maize 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) were more critical in terms of impact(s) of climatic variables (precipitation, temperature, solar radiation, vapor pressure deficit, and wind speed) on the slope of the production functions as well as the interannual variabilities of production functions and their slopes for full and limited irrigation and rainfed settings. The treatments were full irrigation (FIT or 100%); limited irrigation of 75%, 60%, and 50% of FIT;

TABLE 2. Performance indicators, including grain yield (Mg/ha), seasonal crop evapotranspiration (ET_c, mm), crop water use efficiency (CWUE, kg/m^3), and irrigation water use efficiency (IWUE, kg/m^3) of various irrigation treatments at the study sites in Nebraska.

References and years	Irrigation system	Treatment		Grain yield (Mg/ha)		ET_c (mm)		CWUE (kg/m^3)		IWUE (kg/m^3)
Clay Center, Nebraska										
Irmak (2015a, b)[1] 2005–2010	Center pivot	Full irrigation treatment (FIT)		15.32		655		2.34		3.79
		75% of full		14.78		638		2.31		4.54
		60% of full		14.06		614		2.29		4.58
		50% of full		13.52		604		2.24		4.29
		Rainfed		9.10		517		1.71		—
North Platte, Nebraska										
Hergert et al. (1993)[2] 1982–1991	Solid set	M-M: full		11.30		—		—		1.11
		M-M: limited		8.79		—		—		3.05
		M-M: rainfed		4.14		—		—		—
		WW-M-SB: full		11.80		—		—		0.94
		WW-M-SB: limited		9.54		—		—		2.70
		WW-M-SB: rainfed		5.46		—		—		—
Payero et al. (2008) 2005–2006	Subsurface drip irrigation (SDI)	2005	2006	2005	2006	2005	2006	2005	2006	
		T1: 53 mm	T9: 22 mm	9.99	5.39	580	466	1.72	1.16	
		T2: 76 mm	T10: 66 mm	10.66	8.42	586	537	1.82	1.57	—
		T3: 102 mm	T11: 97 mm	11.03	9.63	612	570	1.80	1.69	—
		T4: 153 mm	T12: 130 mm	11.06	10.36	633	627	1.75	1.65	—
		T5: 221 mm	T13: 184 mm	12.09	11.28	663	639	1.82	1.76	—
		T6: 254 mm	T14: 173 mm	12.84	11.33	655	656	1.96	1.73	—
		T7: 306 mm	T15: 197 mm	11.64	10.97	655	651	1.78	1.68	—
		T8: 356 mm	T16: 226 mm	12.31	11.04	655	653	1.88	1.69	—
Payero et al. (2009)[3] 2005–2006	SDI	2005	2006	2005	2006	2005	2006	2005	2006	
		T1: [50-25-25]	T9: [25-50-25]	11.63	8.46	609	544	1.91	1.56	—
		T2: [57-43-0]	T10: [100-0-0]	12.96	11.32	633	589	2.05	1.92	—
		T3: [33-67-0]	T11: [0-100-0]	11.52	9.73	633	565	1.82	1.72	—
		T4: [33-0-67]	T12: [0-0-100]	10.81	7.59	592	505	1.82	1.50	—
		T5: [33-50-17]	T13: [0-50-50]	11.34	9.12	631	577	1.80	1.58	—
		T6: [67-33-0]	T14: [50-50-0]	12.76	11.35	638	622	2.00	1.82	—
		T7: [40-30-30]	T15: [33-34-33]	11.87	8.58	635	546	1.87	1.57	—
		T8: [33-34-33]	T16: [0-67-33]	12.02	9.00	626	571	1.92	1.58	—
van Donk et al. (2012) 2007–2009	SDI	100% ET_c		11.42		545		2.10		—
		75% of ET_c		11.09		546		2.03		—
		50% of ET_c		10.54		524		2.01		—
		50%–100% three week at VT — 50%		11.09		540		2.05		—
		50%–100% four week at VT — 50%		11.43		560		2.04		—
		75%–100% four week at VT — 75%		11.32		560		2.02		—
		Rainfed		9.70		490		1.98		—
Scottsbluff, Nebraska										
Spurgeon and Yonts (2013)[4] 2005–2008	SDI	125% of full		11.19		—		—		1.78
		FIT		11.14		—		—		2.16
		75% of full		10.13		—		—		2.46
		50% of full		9.17		—		—		3.11
		Rainfed		2.97		—		—		—

[1]FIT and rainfed treatments (2005–2010); 75%, 60%, and 50% of FIT treatments (2006–2010).
[2]M-M: continuous maize rotation; WW-M-SB: winter wheat, maize, soybean rotation.
[3]Payero et al. (2009): Percentage of 150 mm irrigation allocation received during (July, August, September).
[4]Rainfed reported by United States Department of Agriculture-National Agricultural Statistics Service (USDA-NASS).

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 average grain yields, ET_c, and CWUE ranged from 9.10 to 15.32 Mg/ha, 517 to 655 mm, and 1.73 to 2.34 kg/m^3, respectively (Table 2). The author reported considerable interannual variation in grain yield, ET_c, and CWUE. Rainfed production always resulted in the lowest CWUE, and the highest CWUE was usually obtained under FIT. In most years, no significant differences were observed between FIT and 75% FIT in terms of grain yield and CWUE. In addition to CWUE and IWUE, the author also quantified and discussed the implications of evapotranspiration water use efficiency as well as annual and growing season precipitation use efficiency to overall water supply vs. crop production relationships.

A similar study was conducted at SCAL under linear move sprinkler from 2011 to 2014 to evaluate grain yield, CWUE, IWUE, and economic return of maize under different irrigation (FIT, 75% FIT, and rainfed settings) and nitrogen (N) fertilizer rates (0, 84, 140, 196, and 252 kg N/ha) (Rudnick et al. 2016). The authors assessed the relationship between economic return (i.e., relative net income) and CWUE to further evaluate differences among the irrigation treatments (Figure 2). They observed linear relationships between CWUE and net income for all years, and lower CWUE values were associated with lower net income values. The results showed that maximum net income was achieved under FIT, and therefore, under non-water-limiting conditions, full irrigation should be adopted for south central Nebraska (Rudnick et al. 2016). However, if local conditions prevent full irrigation then 75% of full is an appropriate management strategy that has shown to have minimal impact on grain yield and CWUE in south central Nebraska.

At the WCREC site in west central Nebraska, two companion studies were conducted to assess the effects of irrigation amount ranging from deficit to excessive (Payero et al. 2008) and timing of a deficit allocation of 150 mm (Payero et al. 2009) on maize ET_c, yield, CWUE, and dry matter production under SDI. For the irrigation amount study (Payero et al. 2008), the authors imposed eight irrigation treatments, ranging from 53 to 356 mm in 2005 and from 22 to 226 mm in 2006 (Table 2). The seasonal ET_c ranged from 580 to 663 mm in 2005 and from 466 to 656 mm in 2006, and the yields differed by as much as 22% in 2005 and 52% in 2006. The production function showed that maximum grain yield occurred at 254 and 173 mm of applied irrigation in 2005 and 2006, respectively, under nearly normal precipitation and evaporative demand. They reported

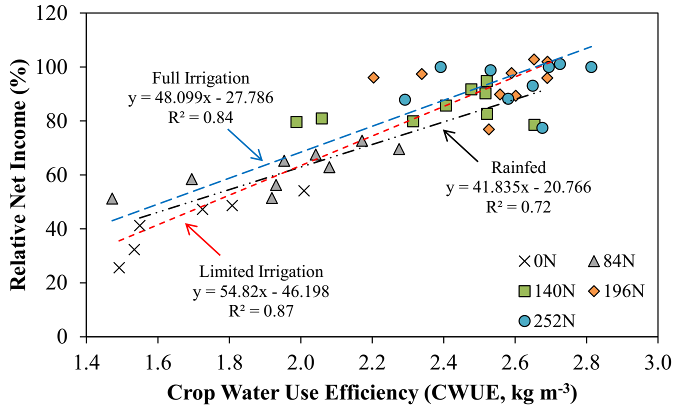

FIGURE 2. Relative net income (RNI) vs. CWUE for 0, 84, 140, 196, and 252 kg/ha nitrogen (N) rates under FIT, limited irrigation (75% of full), and rainfed settings for the pooled 2011, 2012, and 2014 growing seasons at the University of Nebraska-Lincoln (UNL) South Central Agricultural Laboratory (SCAL) near Clay Center, Nebraska. RNI of a treatment was calculated as a percentage of the FIT-252 kg N/ha treatment (i.e., non-limiting water and N). Taken from Rudnick et al. (2016).

that the average yield response factor (i.e., relative reduction in yield to relative reduction in ET_c) over the two years was 1.58. To evaluate the effect of timing of deficit irrigation, the authors investigated 16 treatments (eight each year) comprised of different percentages of a 150 mm allocation during July, August, and September (Table 2). The 150 mm allocation was selected based on Hergert et al. (1993) who reported that irrigation districts in southwest Nebraska were considering whether to establish irrigation allocations of 150–200 mm per year in the early 1980s following the report of Lappala (1978). The 150 mm allocation represented an irrigation reduction of 41% and 13% relative to full irrigation requirements reported in Payero et al. (2008) for 2005 and 2006, respectively. Grain yield achieved its highest positive response to irrigation in July, and then the response considerably decreased in August, and became negative for irrigation applied in September. Yield was strongly correlated with water stress (i.e., yield decreased with increased level of stress) during the milk and dough growth stages (Weeks 12–14 following emergence) but was poorly or negatively correlated with water stress afterward. The authors found that evenly distributing the 150 mm allocation among July, August, and September was a good strategy but was susceptible to interannual variability, whereas applying a large portion of the allocation in July was a good strategy across years.

In addition to irrigation timing, crop rotations can also influence maize IWUE due to changes in starting soil water conditions. Hergert et al. (1993) evaluated limited irrigation (maximum of 165 mm water allocation) against fully irrigated and rainfed conditions under continuous maize (M-M) and winter wheat–maize–soybean (WW-M-SB) rotations at WCREC from 1982 to 1991. The authors delayed the limited irrigation treatment until tassel or silk emergence based on the findings of Maurer et al. (1979) who concluded that the silt loam soils had sufficient stored water to allow for normal crop development with minimal stress during vegetative growth. The authors observed the WW-M-SB rotation had statistically greater maize yields than the M-M rotation for all irrigation treatments (full, limited, and rainfed) and concluded that differences were due to a longer soil water storage period in the WW-M-SB rotation. The limited irrigation treatment suppressed yield in relation to the full treatment on average by 19% and 22% for the WW-M-SB and M-M rotations, respectively. The nine-year average IWUE for the limited irrigation treatments were 3.05 and 2.70 kg/m^3 for the M-M and WW-M-SB rotations, respectively. The authors reported that the greater IWUE under the M-M rotation was due to greater rainfed yields under the WW-M-SB rotation.

van Donk et al. (2012) expanded on the findings of the aforementioned studies by evaluating a series of deficit irrigation strategies under SDI at WCREC in 2007–2009. The strategies comprised of deficit irrigation treatments that allowed various levels of water stress as a percentage of ET_c 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_c replacement and rainfed. They observed only a 5% yield decrease for the treatment with the greatest reduction in irrigation (Treatment: start with 50% ET_c, 100% ET_c replacement during two weeks starting at tasseling, then 50% ET_c) as compared to 100% ET_c replacement, while reducing irrigation withdrawal by more than 100 mm. In this study, tasseling occurred in mid to late July and all three years experienced above-normal precipitation. Collectively, the 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. Furthermore, their results indicated that it is critical to minimize crop water stress during Weeks 12–14 (milk to dough stages).

A limited irrigation study was conducted at PREC under SDI from 2005 to 2008 to evaluate water productivity of a maize and dry bean (*Phaseolus vulgaris* L.) rotation (Spurgeon and Yonts 2013). The authors investigated FIT, 125% FIT, 75% FIT, and 50% FIT (Table 2). Excluding 125% FIT, the average maize yield response to irrigation was 1.05 kg/m^3. Maximum maize yield was observed with 300 mm of irrigation in wet years and approximately 375 mm of irrigation in dry years. On an average precipitation year such as 2008, the 75% FIT yield of 10.67 Mg/ha was significantly less than FIT yield of 12.20 Mg/ha; however, IWUE was not statistically different across the treatments with 2.45 and 2.53 kg/m^3, 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, the 75% FIT may be a suitable limited irrigation strategy; however, reducing below that will result in considerable yield reduction in normal to dry years.

Colorado

The research projects in Colorado were conducted at the Central Great Plains Research Station (CGPRS) located in Akron, Colorado (Saseendran et al. 2008; Schneekloth et al. 2012; Benjamin et al. 2015) and the Irrigation Research Farm (IRF) in Yuma, Colorado (Al-Kaisi and Yin 2003). A description of the research sites is presented in Table 1. The two research sites are located in north-eastern Colorado and are approximately 48 km apart. Both sites experience a semiarid climate with long-term growing season precipitation of 341 and 284 mm for CGPRS and IRF, respectively.

Schneekloth et al. (2012) evaluated the impacts of irrigation capacity and timing on maize production under solid set sprinkler irrigation at CGPRS from 2009 to 2012. The authors imposed three irrigation treatments, including full irrigation (6.35 mm/day), inadequate capacity (3.18 mm/day), and growth stage initiation (8.38 mm/day starting at two weeks before tassel). These treatments were designed to represent potential options that could be used by producers under limited irrigation system capacity and/or water allocations as described by Klocke et al. (2011). The inadequate capacity treatment mimicked producers planting the entire field to maize and initiating irrigation early and continuing throughout the season. The FIT mimicked producers planting a percentage of the field to maize and managing irrigation according to best management practices throughout the season. Lastly, the growth stage initiation strategy mimicked planting a percentage of the field to maize 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 maize would be based on the irrigation well capacity, so that 100% of maize ET_c demand 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 in yield 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. However, 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%–45% of the full irrigation, whereas grain yields of the growth stage initiation strategy were not significantly different from full irrigation. Irrigation amount per hectare for growth stage initiation was less than full irrigation in two of the three 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 two of the three years. The CWUE and IWUE for the full and growth stage initiation strategies were not different between each other in two of the three 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_c rate. On average, the growth stage initiation strategy had greater CWUE and IWUE of 2.34 and 3.62 kg/m^3, respectively, with less than a 2% yield reduction as compared to the full irrigation strategy (Table 3). Economic analysis of the impact of only irrigating a portion of the field and/or introducing a crop rotation as compared with deficit irrigating the entire field is required.

A long-term continuous deficit irrigation study was also performed at CGPRS under sprinkler irrigation from 2001 to 2006 by Benjamin et al. (2015). The authors evaluated the cumulative effect of deficit irrigation on soil water storage and grain yield as compared with FIT. The FIT supplied irrigation each week based on ET_c demand minus effective rainfall, whereas the deficit irrigation treatment supplied no irrigation during the vegetative period, and then added irrigation equivalent to the FIT during the reproductive period. The deficit irrigation treatment revealed less soil water storage in the 1.8 m soil profile at the start and end of the growing season as compared to FIT. 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 was statistically significant ($p < 0.05$). The deficit irrigation treatment continued to deplete stored soil water over time because of insufficient off-season recharge. Consequently, yield and CWUE for the deficit

TABLE 3. Performance indicators, including grain yield (Mg/ha), ET_c (mm), CWUE (kg/m^3), and IWUE (kg/m^3) of various irrigation treatments at the study sites in Colorado.

References & years	Irrigation system	Treatment	Grain yield (Mg/ha)	ET_c (mm)	CWUE (kg/m^3)	IWUE (kg/m^3)
Akron, Colorado						
Schneekloth et al. (2012)[1] 2009–2011	Solid set sprinkler	Full irrigation	13.29	586	2.27	3.31
		Growth stage initiation	13.09	559	2.34	3.62
		Inadequate capacity	9.82	531	1.85	2.91
		Rainfed	3.59	—	—	—
Yuma, Colorado						
Al-Kaisi and Yin (2003)[2] 1998–2000	Center pivot	100% ET_c — 360N	12.17		1.92	—
		100% ET_c — 250N	11.96	635	1.88	—
		100% ET_c — 140N	10.93		1.72	—
		100% ET_c — 30N	10.22		1.61	—
		80% ET_c — 360N	10.66		2.10	—
		80% ET_c — 250N	10.20	508	2.01	—
		80% ET_c — 140N	9.64		1.90	—
		80% ET_c — 30N	8.69		1.71	—
		60% ET_c — 360N	6.38		1.67	—
		60% ET_c — 250N	7.48	381	1.96	—
		60% ET_c — 140N	6.35		1.67	—
		60% ET_c — 30N	4.65		1.22	—

[1]Rainfed reported by USDA-NASS.

[2]Treatment means of grain yield, ET_c, and CWUE are averaged over plant population densities and ET_c rates are based on average of all sub-treatments within an irrigation treatment. N expressed in kg/ha.

irrigation treatment decreased over time. In 2001, there were no significant differences in grain yield between treatments, whereas 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%–51% for 2003, 2004, and 2006 growing seasons. The authors concluded that this strategy for managing deficit irrigation might be an option for short-term or emergency situations, but not a suitable long-term option as it was determined to be detrimental to yield and CWUE.

Saseendran et al. (2008) calibrated and validated the CERES-maize model for CGPRS to model the optimum allocation of limited irrigation between the vegetative and reproductive periods as well as the optimum soil water depletion in the top 0.45 m depth to initiate limited irrigation. The authors used data collected over eight years at CGPRS under solid set sprinkler irrigation from multiple studies ranging from 1984 to 1997. Simulations from 1912 to 2005 with total season irrigation amounts of 100, 200, 300, 400, 500, 600, and 700 mm, split as: 20:80, 40:60, and 50:50 between the vegetative and reproductive periods, were evaluated. The authors concluded that when irrigation amount was constrained to 100 mm, maximum yield and CWUE were obtained with the 40:60 or 50:50 split, whereas the 20:80 split had greater yield when irrigation availability exceeded 100 mm. Furthermore, they concluded that irrigating 50% of the field and withholding irrigation (i.e., rainfed) from the remaining area resulted in greater overall yield when irrigation amount was constrained to 100 mm, whereas 100% of the field should be irrigated when irrigation amounts exceed 100 mm. Lastly, they found that delaying the initiation of irrigation to when plant available water in the 0.45 m profile was 20% (i.e., 80% depletion) had little effect on grain yield as compared to full irrigation.

At the IRF research site in Yuma, Colorado, Al-Kaisi and Yin (2003) evaluated maize yield and CWUE response to irrigation, N fertilization, and planting population density under center pivot irrigation. The treatments investigated were 60%, 80%, and 100% of ET_c replacement for irrigation; 30, 140, 250, and 360 kg/ha for N fertilization; and 57,000, 69,000, and 81,000 plants per ha for planting population density. The authors reported that the 80% of ET_c replacement had the same or greater CWUE than the other irrigation treatments regardless of N fertility rate (Table 3). No significant differences in water extraction were observed between the 80% and 100% ET_c replacement treatments. The 60% ET_c replacement treatment resulted in lower soil water content in the top 0.9 m soil profile at time of harvest as compared to the other treatments. The authors concluded that 80% of ET_c replacement with N fertility between 140 and 250 kg/ha and planting population between 57,000 and 69,000 plants per ha was the best management strategy for optimizing CWUE.

Kansas

The research projects in Kansas were conducted at the Kansas State University (KSU) Southwest Research and Extension Center near Garden City, Kansas (Klocke et al. 2011, 2014; Kisekka and Lamm 2016; Kisekka et al. 2016), the Northwest Research and Extension Center in Colby, Kansas (Lamm et al. 1995, 2014), and the Southwest Research and Extension Center near Tribune, Kansas (Schlegel et al. 2012). The KSU locations included in this study are located in the semiarid climate of western Kansas and have deep well-drained soils with water holding capacities of 125–167 mm/m.

Long-term deficit irrigation research was conducted under linear move sprinkler irrigation from 2005 to 2009 at Garden City, Kansas, to determine the yield response of maize to irrigation and ET_c under southwest Kansas conditions (Klocke et al. 2011). The study consisted of six treatments: 100%, 80%, 70%, 50%, 40%, and 25% of full irrigation. The authors omitted a rainfed treatment, since in most years crop failure is expected. The treatments were administered by applying 25 mm of irrigation every 5–17 days through a linear move sprinkler system. Maize grain yield and ET_c decreased as irrigation decreased. Five-year treatment average grain yields ranged from 6.1 to 11.9 Mg/ha, and the corresponding ET_c from 454 to 630 mm (Table 4). On average, the 80% treatment yielded 94% of the FIT while reducing irrigation by 60–70 mm depending on prior crop type. Maize CWUE was not significantly different between 100%, 80%, and 70% irrigation treatments, but decreased significantly among deficit treatments of 50%, 40%, and 25% of irrigation requirements. The five-year average CWUE was maximum for the 80% treatment with 1.97 kg/m^3 and was minimum for the 25% treatment with 1.35 kg/m^3. The deficit-irrigated treatments extracted more soil water from deeper layers, which influenced the next year's starting soil water content. Several other studies, Benjamin et al. (2015), Al-Kaisi and Yin (2003), and Lamm et al. (1995), have also concluded that deficit irrigation can reduce stored soil water at season end and depending on off- and early-season recharge and system capacity this may affect the subsequent crop. Consequently, however, fallow efficiency (i.e., stored water during off-season) can increase under deficit irrigation as compared with full irrigation practices.

Since annual precipitation from 2005 to 2009 ranged between 90% and 118% of the 30-year average, the authors continued the study from 2010 to 2012 when annual precipitation was only 60% of the 30-year average (Klocke et al. 2014). The maize production functions from 2005 to 2012 displayed interannual variability (Figure 3), which makes them less suitable for making short-term or seasonal water management decisions. Variability in production functions can be attributed to several factors: (1) seasonal changes in rainfall amounts and patterns; (2) changes in evaporative demand; (3) cultural practices (e.g., irrigation scheduling, fertility management, weed management, and pest and insect management); (4) salinity; (5) differences in crop cultivars and their response to water supply; (6) sensitivity of the crop at different growth stages to water deficit and interdependency of growth stage water stress effects; and (7) other miscellaneous factors such as hail or freeze damage (Kisekka et al. 2016). Interactions among these factors make optimum management of deficit irrigation more complicated as compared to full irrigation. During wet years without hail, the yield vs. irrigation function was curvilinear, while for the drought years of 2011 and 2012, the response functions were linear mimicking the yield vs. ET_c relationship (Figure 3). This indicates that during drought years, CWUE was high with minimal percolation and runoff losses, and it is possible that potential ET_c was not reached by the FIT, thus the yield vs. irrigation curve approximated a straight line. In addition, it can be seen from Figure 4 that uncertainty in crop yield due to deficit irrigation decreased as the amount of irrigation increased, probably because of the reduced effect of unfavorable weather conditions. These results suggest that

TABLE 4. Performance indicators, including grain yield (Mg/ha), ET_c (mm), CWUE (kg/m^3), and IWUE (kg/m^3) of various irrigation treatments at the study sites in Kansas.

References & years	Irrigation system	Treatment	Grain yield (Mg/ha)	ET_c (mm)	CWUE (kg/m^3)	IWUE (kg/m^3)
Garden City, Kansas						
Klocke et al. (2011)[1]	Lateral move	FIT (100%)	11.9	630	1.95	—
2005–2009		80% of full	11.2	585	1.97	—
		70% of full	10.5	570	1.89	—
		50% of full	8.7	518	1.72	—
		40% of full	7.5	490	1.57	—
		25% of full	6.1	454	1.35	—
Colby, Kansas						
Lamm et al. (1995)	Subsurface drip irrigation (SDI)	125% of ET_c	12.6	586	2.15	1.20
1989–1991		100% of ET_c	13.3	586	2.27	1.69
		75% of ET_c	12.5	583	2.14	2.03
		50% of ET_c	10.4	542	1.92	2.32
		25% of ET_c	7.8	494	1.58	2.33
		Rainfed	6.1	459	1.33	—
Tribune, Kansas						
Schlegel et al. (2012)[2]	Lateral move	Pre-water				
2006–2009		5 mm/day — 56K	12.5	739	1.70	—
		5 mm/day — 68K	13.4	751	1.79	—
		5 mm/day — 80K	14.0	751	1.88	—
		3.8 mm/day — 56K	11.3	644	1.74	—
		3.8 mm/day — 68K	12.1	644	1.86	—
		3.8 mm/day — 80K	12.3	654	1.87	—
		2.5 mm/day — 56K	10.5	593	1.74	—
		2.5 mm/day — 68K	11.0	604	1.80	—
		2.5 mm/day — 80K	11.2	610	1.81	—
		No pre-water				
		5 mm/day — 56K	12.3	710	1.74	—
		5 mm/day — 68K	13.0	726	1.78	—
		5 mm/day — 80K	13.7	725	1.89	—
		3.8 mm/day — 56K	10.6	618	1.68	—
		3.8 mm/day — 68K	10.7	613	1.71	—
		3.8 mm/day — 80K	10.5	620	1.65	—
		2.5 mm/day — 56K	9.4	541	1.67	—
		2.5 mm/day — 68K	9.7	547	1.72	—
		2.5 mm/day — 80K	9.6	547	1.68	—

[1]Treatment means of grain yield, ET_c, and CWUE are averaged over maize–maize and sunflower–maize rotations.
[2]Treatments are irrigation capacity (mm/day) and planting population density in thousands.

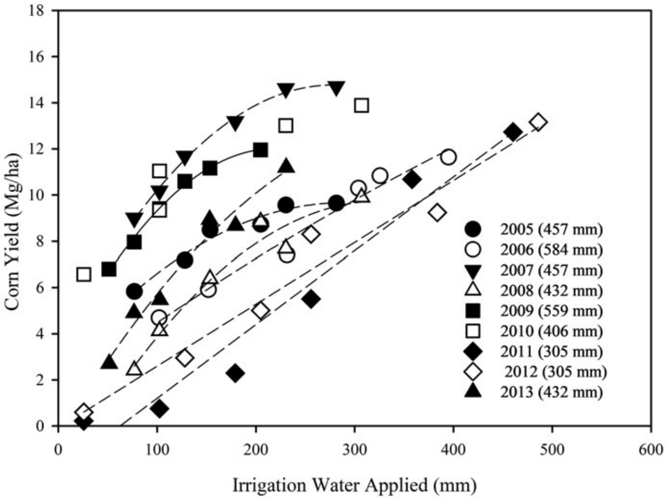

FIGURE 3. Maize grain yield (Mg/ha) response to irrigation from 2005 to 2013. The numbers in parentheses are annual precipitation (mm) recorded at the Kansas State University Southwest Research and Extension Center near Garden City, Kansas. Taken from Klocke et al. (2011, 2014).

greater income risk is associated with deficit irrigation than with full irrigation.

Results of Klocke et al. (2011, 2014) were further used by Kisekka et al. (2016) and Araya et al. (2017) to calibrate and validate a DSSAT-CSM v4.6 CERES-Maize and AquaCrop model, respectively, to assess deficit irrigation management strategies for maximizing net returns of maize under limited water supply. Kisekka et al. (2016) investigated the effects of three factors on crop response and economic return: (1) optimum plant available water threshold to initiate irrigation, (2) effect of percentage soil water depletion at time of planting, and (3) effect of late season irrigation termination. Their analyses concluded with the following recommendations to maximize net return with a limited water supply in southwest Kansas: (1) soil water depletion in the top 1.2 m soil profile should be between 0% and 25% at time of planting through use of pre-watering and agronomic practices to capture and retain off-season rainfall, and (2) irrigation should be terminated between 90 and 95 days after planting using soil water monitoring and management-allowable depletion techniques. The study conducted by Araya et al. (2017) calibrated and validated the AquaCrop model to assess the optimal deficit irrigation management strategies under various irrigation water allocations, long-term growing season precipitation, and planting date scenarios. They reported that maize required an average of 450, 300, and 150 mm of irrigation for dry, normal, and wet growing seasons, respectively, irrespective of planting dates and assuming initial soil water at planting of 70% of field capacity. In addition, the authors evaluated the impact of spreading vs. concentrating water on crop yield and water productivity on two soil types (i.e., sandy clay loam and silt loam) in western Kansas. Spreading refers to a scenario when irrigating more land than available water supply (i.e., deficit irrigation), whereas concentrating water refers to an irrigation management practice where total land irrigated is reduced to match the available water supply (Howell et al. 2012). They concluded that planting 50% of a 46.8 ha field on both sandy loam and silt loam soil produced the highest maize yield and crop water productivity compared to planting 100% of the field, assuming a limited well capacity of 68 m^3/h.

More recent research at Garden City, Kansas evaluated yield response of new maize genetics, DKC 62-27 DGVT2PRO with “drought-tolerant” trait and DKC 62-98 VT2PRO (conventional), under different levels of deficit irrigation during 2014 and 2015 (Kisekka and Lamm 2016). Deficit irrigation reduced ($p < 0.001$) maize yield for both hybrids. The effect of the “drought-tolerant” trait on yield was not significant ($p > 0.05$) in both years. However, both years were wetter than normal; therefore, further research is needed to quantify the effect of deficit irrigated “drought-tolerant” traits on maize yield under normal and dry conditions in western Kansas.

At the KSU Northwest Research and Extension Center in Colby, Kansas, Lamm et al. (1995) evaluated maize yield response to irrigation from 1989 to 1991 under SDI. The irrigation treatments ranged from rainfed to 125% of calculated ET_c requirements. The three-year average irrigation amounts were 541, 425, 316, 185, and 73 mm for the 125%, 100%, 75%,

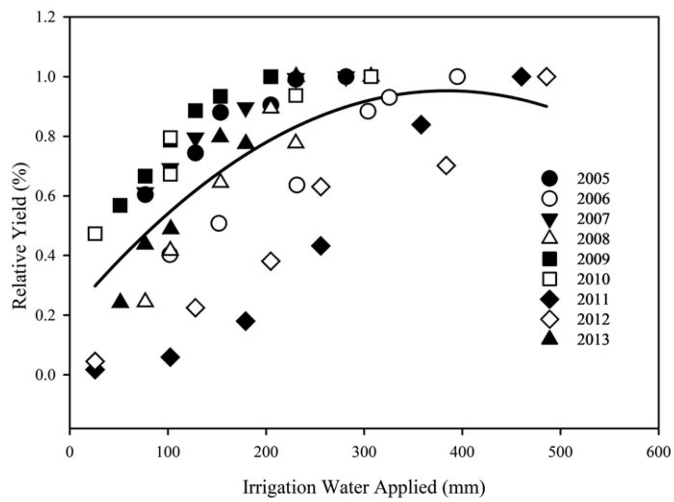

FIGURE 4. Maize relative yield (%) response to irrigation from 2005 to 2013 near Garden City, Kansas. Taken from Klocke et al. (2011, 2014).

50%, and 25% ET_c treatments, respectively. Highest grain yields were obtained when ET_c was not limited by soil water availability. Treatments 75%–125% of ET_c replacement maintained soil water status above 55%–60% of field capacity in the 2.4 m soil profile, whereas the rainfed to 50% ET_c treatments mined the soil water. Their results showed that applying more than full irrigation requirements could reduce CWUE (Table 4). Lamm et al. (2014) evaluated maize yield and CWUE response to irrigation using data from 1989 to 2004. Their results concluded that SDI-irrigated maize peaked at approximately 80% of full irrigation for grain yield and CWUE. These results provide evidence that opportunities exist to practice moderate deficit irrigation in northwest Kansas without substantial reductions in yields and profitability.

Research on deficit-irrigated cropping systems has also been conducted at the KSU Southwest Research and Extension Center near Tribune, Kansas. Besides crop yield response to water, research has explored the effect of late spring preseason irrigation on yield and net returns of maize, among other crops, with low pumping capacities. Based on research conducted in the 1980s and 1990s, it was generalized that in-season irrigation was more beneficial than preseason irrigation, so preseason irrigation was often not warranted (Schlegel et al. 2012). Schlegel et al. (2012) evaluated whether preseason irrigation would be profitable with low pumping capacities at varying maize planting densities. They conducted a factorial experiment under lateral move sprinkler irrigation from 2006 to 2009 with preseason irrigation (0 and 75 mm), irrigation pumping capacities (2.5, 3.8, and 5.0 mm/day), and plant densities (56,000, 68,000, and 80,000 plants per ha) (Table 4). CWUE was not significantly affected by irrigation capacity or preseason irrigation; however, preseason irrigation increased grain yield by approximately 9% and was profitable at all irrigation capacities. These results suggest that, as diminishing well capacities compel the practice of deficit irrigation, recharging the soil profile with preseason irrigation could effectively buffer the crop from detrimental stresses between in-season irrigation and rainfall events.

Texas

The research projects in Texas were conducted at the U.S. Department of Agriculture (USDA)-Agricultural Research Service (ARS), Conservation and Production Research Laboratory in Bushland, Texas (Musick and Dusek 1980; Eck 1986; Howell et al. 1995; Schneider and Howell 1998; Tolk et al. 1999; Baumhardt et al. 2013), the Texas A&M AgriLife Research Station near Etter, Texas (Hao et al. 2015a, b), and at producer sites near Lubbock, Texas (TAWC 2015). The climate is semiarid at all three locations (Table 1).

At the USDA-ARS Conservation and Production Research Laboratory in Bushland, Texas, Musick and Dusek (1980) concluded that limited irrigation of maize in the Southern High Plains involved unacceptably high risks and should not be practiced. This was also supported by Eck (1986) who conducted a four-year study observing five irrigation treatments under graded furrow and level border systems. Irrigation treatments were full irrigation, two- and four-week water deficit periods during vegetative growth, and two- and four-week water deficit periods during grain filling. Average grain yield ranged from 5.06 (four weeks during vegetative growth) to 9.06 Mg/ha (adequate water). They observed a 1.2% yield reduction for each additional day deficit was imposed. Regional declines in well capacities have diminished the ability to meet full ET_c demand leading to more widespread practice of deficit irrigation (Colaizzi et al. 2009). Howell et al. (1995) evaluated maize yield and CWUE under a low energy precision application (LEPA) center pivot system. They investigated six irrigation levels ranging from rainfed to 100% of ET_c (Table 5). Grain yield increased from 6.0 to 12.5 Mg/ha in 1992 and from 4.0 to 15.5 Mg/ha in 1993, with maxima occurring at 80%–100% of full irrigation. Averaged over two years, CWUE was maximal at 1.71 kg/m^3 at the 80% irrigation level, and IWUE was greatest at 2.39 kg/m^3 at the 40% irrigation level. Similar results were reported by Schneider and Howell (1998), where they found the largest CWUE was at or near 100% of ET_c replacement, and the largest IWUE was between 50% and 75% of ET_c replacement (Table 5). Furthermore, no interaction was observed between irrigation amount and sprinkler method; therefore, they concluded that LEPA and spray sprinkler technologies are both suitable irrigation methods for the region.

Also at the USDA-ARS research laboratory in Bushland, Texas, Tolk et al. (1999) investigated the effects of mulch, soil types varying in texture, and irrigation amount on maize yield and components, and CWUE in 1994 and 1995. The study was conducted in lysimeters packed with Pullman, Ulysses, and Amarillo soil series under a rainout shelter. The mulch was comprised of wheat straw and coconut (*Cocus nucifera* L.) fiber. The irrigation amounts in 1994 were 25% and 75% of the long-term seasonal rainfall of 200 mm, whereas the irrigation amounts in 1995 were 60% and 100%. The mulch was applied at 4 and 6.7 Mg/ha at the V3 growth stage in 1994 and 1995, respectively. Mulch did not affect grain yield components, leaf area index, and CWUE in 1994, but did in 1995. In 1995, mulch increased grain

TABLE 5. Performance indicators, including grain yield (Mg/ha), ET_c (mm), CWUE (kg/m^3), and IWUE (kg/m^3) of various irrigation treatments at the study sites in Texas.

References & years	Irrigation system	Treatment		Grain yield (Mg/ha)	ET_c (mm)	CWUE (kg/m^3)	IWUE (kg/m^3)
Bushland, Texas							
Eck (1986)	Graded furrows and	Full irrigation		9.06	912	1.01	—
1976–1979	level borders	Deficit: two weeks late vegetative		7.47	793	0.96	—
		Deficit: two weeks early vegetative		7.47	846	0.88	—
		Deficit: four weeks vegetative		5.06	634	0.83	—
		Deficit: four weeks grain fill		7.29	745	1.00	—
		Deficit: two weeks grain fill		8.32	833	1.02	—
Howell et al. (1995)	Center pivot low energy	100% ET_c		13.98	880	1.59	1.89
1992–1993	precision application (LEPA)	80% ET_c		13.59	793	1.71	2.24
		60% ET_c		11.63	713	1.63	2.11
		40% ET_c		10.29	631	1.64	2.39
		20% ET_c		8.00	536	1.50	2.13
		Rainfed		5.02	458	1.09	—
Schneider and	LEPA sock, LEPA bubble,	100% ET_c		15.97	807	1.98	3.05
Howell (1998)[1]	in-canopy, overhead	75% ET_c		13.58	711	1.91	3.45
1994–1995		50% ET_c		9.72	580	1.68	3.72
		25% ET_c		2.04	471	0.41	1.63
		Rainfed		0.00	315	0	—
Baumhardt et al. (2013)[2]	Lateral move	5.0 mm/day: no till		4.97	518	1.00	—
2006–2009		5.0 mm/day: stubble mulch		4.19	498	0.87	—
		5.0 mm/day: disk till		3.98	501	0.83	—
		2.5 mm/day: no till		2.78	401	0.69	—
		2.5 mm/day: stubble mulch		1.92	383	0.52	—
		2.5 mm/day: disk till		1.49	377	0.41	—
Etter, Texas							
Hao et al. (2015a, b)[3]	Center pivot LESA	Hybrid: P33D49	100% ET_c	13.47	723	1.86	—
2011–2013			75% ET_c	11.55	583	1.98	—
			50% ET_c	6.18	496	1.25	—
		Hybrid: P1151HR	100% ET_c	13.78	696	1.98	—
			75% ET_c	12.55	566	2.22	—
			50% ET_c	7.38	493	1.50	—
		Hybrid: 1324HR	100% ET_c	13.15	716	1.84	—
			75% ET_c	11.67	576	2.03	—
			50% ET_c	6.23	487	1.28	—
		Hybrid: 1498HR	100% ET_c	13.45	714	1.88	—
			75% ET_c	11.77	578	2.04	—
			50% ET_c	6.48	502	1.29	—
		Hybrid: 1564HR	100% ET_c	14.15	677	2.09	—
			75% ET_c	12.48	574	2.18	—
			50% ET_c	7.50	489	1.54	—

[1]Treatments averaged over four irrigation sprinkler types.
[2]Treatments are irrigation capacity (mm/day) and residue management.
[3]Results are averaged across planting population densities of 5.9, 7.4, and 8.4 plants per ha.

yield by 17%, aboveground biomass by 19%, and CWUE by 14% as compared with the bare soil control. The authors attributed the difference in response between 1994 and 1995 to higher evaporative demand, increased mulch mass, and increased irrigation intensity in 1995. They concluded that the effectiveness of mulch could vary among years due to interactions among climate, soil texture, irrigation frequency, and mulch mass. A similar study by Baumhardt et al. (2013) evaluated the effects of irrigation rate, tillage method, and their interactions on maize yield, ET_c, and CWUE in a wheat–maize–fallow rotation from 2006 to 2009 (Table 5). They too hypothesized that retaining surface residue via conservation tillage would increase soil water storage, and therefore, improve the efficiency of deficit irrigation practice. The deficit irrigation treatments included rates based on irrigation system capacities of 2.5 and 5.0 mm/day, and the three tillage practices included disk tillage, stubble mulch, and no-tillage.

The ET_c of the 2.5 mm/day treatment ranged from approximately 54% to 64% of the estimated ET_c of a fully irrigated crop, whereas that of the 5.0 mm/day treatment ranged from 76% to 85% of the estimated full irrigation ET_c. Stubble mulch and no-tillage increased fallow soil water storage by approximately 14 and 50 mm, respectively, as compared with disk tillage, and enhanced grain yield by allocating some of the evaporation to transpiration. However, those advantages were not sufficient to compensate for yield reductions caused by the deficit irrigation treatments.

Hao et al. (2015a, b) evaluated grain yield and CWUE responses of a conventional maize hybrid and four "drought-tolerant" AQUAmax® hybrids (DuPont-Pioneer, Johnston, Iowa) to irrigation at 50%, 75%, and 100% of ET_c, and three planting densities at Etter, Texas from 2011 to 2013 (Table 5). Averaged across years, hybrids, and planting densities, grain yield at 75% ET_c (11.97 Mg/ha) was 88% of the 100% ET_c treatment (13.53 Mg/ha), while CWUE at 75% ET_c (2.08 kg/m^3) was 10% greater than at 100% ET_c (1.90 kg/m^3). The drought-tolerant hybrids used no more water than the conventional hybrid, but did increase grain yield by 9%–12% at the 75% ET_c level and by 19%–20% at the 50% ET_c level, indicating a role for improved hybrids to sustain maize production under limited irrigation practice. The authors concluded that with limited irrigation becoming a normal production practice for maize in Texas (Colaizzi et al. 2009), adoption of drought-tolerant hybrids with deficit irrigation may help sustain future maize production.

The Texas Alliance for Water Conservation (TAWC 2015), affiliated with Texas Tech University, collected crop production data from producers' farms from 2005 to 2015 (Lubbock-Plainview area) to demonstrate methods of managing irrigation to improve CWUE. While not conducting structured scientific experiments, the results represent what producers are attaining under local conditions, using producers' management decisions. Maize grain yield as a function of water supply expressed as a percentage of estimated crop water demand (100% ET_c) is shown in Figure 5. Water supply was estimated as the sum of irrigation applied, effective precipitation (50% of actual annual precipitation), and change in soil water. 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 estimated ET_c, which could be corrected with use of an irrigation scheduling program and/or soil water monitoring. Colaizzi et al. (2009) also concluded that ET-based irrigation scheduling would reduce groundwater withdrawals, and that doubling the area on which ET-based irrigation scheduling was used (in concert with a 10% conversion of gravity to center pivot irrigated acres) could reduce pumping by 14%.

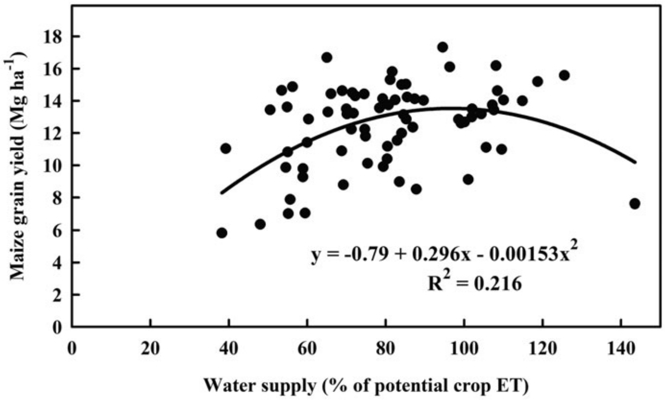

FIGURE 5. Response trend of maize grain yield in the South Plains of Texas from 2005 to 2015 (excluding the severe drought year of 2011) in relation to the sum of water supply from irrigation, effective rain (50% of total rain), and soil moisture changes (n = 62). Adapted from TAWC (2015).

DISCUSSION

A review of investigated deficit irrigation management strategies for maize was conducted across the U.S. High Plains. Research studies from Nebraska, Kansas, Colorado, and Texas were compiled for the review and the performance of the investigated deficit irrigation strategies was described in terms of grain yield, ET_c, CWUE, and IWUE as compared with a fully irrigated crop. The research sites vary in the driving factors that have led to the adoption of deficit irrigation management, including differences in: (1) availability of water resources; (2) state water policy on the management of ground and surface water; and (3) soil and climatic factors, including the magnitude and distribution of precipitation. As expected, differences in drivers have led to varying degrees of success across locations for the same deficit irrigation strategy. For example, crop tolerance to a reduction in full ET replacement irrigation was not the same across sites due to differences in soil type and climatic factors, and therefore the magnitude of deficit irrigation should be based on site-specific conditions.

The review provides insight into attributes of 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 stages) and adopting other best crop and land management practices such as reduced tillage. Soil properties such as texture and depth are important variables when managing under deficit conditions, since soil water reserves can help buffer crop water status between irrigation and rain events (Schlegel et al. 2012; Kisekka et al. 2016). This is especially important for areas that have low system-capacity wells, which are unable to meet peak ET_c demands. An ineffective strategy would be one that disregards the importance of interannual variability of crop growing conditions and their impact on grain yield response to irrigation. As shown by Klocke et al. (2011, 2014), variability in grain yield increased as irrigation decreased, primarily resulting from differences in weather conditions. Payero et al. (2009) also observed that maize receiving an evenly distributed water allocation of 150 mm among July, August, and September in North Platte, Nebraska, was susceptible to interannual variability. Consequently, fixed irrigation scheduling strategies may result in unintended consequences. For example, the deficit irrigation strategy investigated by Benjamin et al. (2015) consisted of withholding 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. However, depending on the magnitude of soil water recharge and early-season precipitation vegetative water stress may affect crop growth and canopy development. This in turn may hinder crop water uptake dynamics during the reproductive period and result in a lower yield response to irrigation than if irrigation was applied during the vegetative period to mitigate prolonged periods of stress.

A common strategy evaluated across most research locations was the use of a percentage reduction in irrigation throughout the growing season. Several locations reported that deficit irrigation of 75%–80% of full irrigation requirement had minimal impact on grain yield and CWUE (Howell et al. 1995; Schneider and Howell 1998; Al-Kaisi and Yin 2003; Klocke et al. 2011; van Donk et al. 2012; Lamm et al. 2014; Irmak 2015a, b; Rudnick et al. 2016). One challenge with managing deficit irrigation using a percentage reduction approach is that the actual reduction is based on soil and weather conditions, and therefore, the magnitude of stress will not be constant across years. As a result, this complicates the ability to predict yield response across years. An alternative to the percentage reduction in irrigation strategy would be scheduling irrigation using known thresholds, such as percentage soil water depletion or crop water stress index. This alternative strategy would allow producers to quantify the maximum potential stress, which can help with prediction of yield response; however, this would result in interannual variability in the percentage of reduction in irrigation. This may complicate planning of multiyear allocations; however, multiyear water allocations allow producers to more efficiently manage water across year-to-year variability compared with single year pumping restrictions. Regions where limited well capacity forces deficit irrigation will be more restricted in their ability to adapt, particularly in drought years. Regardless of the strategy, we suggest using appropriate tools and technology for scheduling deficit irrigation rather than using fixed management practices that do not account for the dynamics of soil and climatic factors. This approach would allow producers to adapt to past, existing, and forecast conditions to better manage their resources. Some irrigation scheduling tools include: soil water monitoring devices (Rudnick et al. 2015a, 2018; Singh et al. 2018), canopy temperature sensors (González-Dugo et al. 2006; Taghvaeian et al. 2012; Meron et al. 2013), ET_c calculators (Bartlett et al. 2015), and remote sensing of ET_c via satellite and/or UAV technology (Gowda et al. 2008; Chávez et al. 2018). However, continued research is required to evaluate and identify appropriate irrigation scheduling tools for various soil, climate, and crop types.

Future research is also required to better understand the response of drought-tolerant hybrids to deficit irrigation strategies across the High Plains as well as their economic implications. Various economic decision frameworks have been developed to assist with managing limited water resources (Martin et al. 1989; English 1990; Amosson et al. 2018). Martin et al. (1989) developed a physically based method to evaluate single-season irrigation management decisions under land- or water-limiting conditions. Their approach related the optimal irrigated area and applied depth of water with prices, costs, and physical parameters. They concluded that the appropriate management strategy under water-limiting conditions is a continuum ranging from irrigating a small area for maximum yield to uniformly applying a limited water supply over the total irrigable area. Howell et al. (2012) termed these strategies as "spreading" and "concentrating" water. Spreading refers to a condition where a producer is willing to accept greater risk by irrigating more area than available water supply. Whereas, concentrating water refers to a condition where a producer is more conservative and reduces the total irrigated area to better match available irrigation capacity. However, the optimal practice is therefore dependent on irrigation system type, soil water content at planting, in-season rainfall, residue levels, subsequent crop, market values, and input costs, among others. Furthermore, risk is associated with economic decision support systems that incorporate yield production functions (i.e., yield vs. irrigation) to estimate optimal water use (English and Vavaid Raja 1996) given the uncertainty in the functions (Kisekka et al. 2016). In addition, the margin of error when managing deficit irrigation can be lower than that of full irrigation due to the diminishing-return shape of the grain yield response to irrigation. Finally, other agronomic and cultural practices may need to be adjusted when practicing deficit irrigation (Santos Pereira et al. 2002), so that all inputs are optimized for maximum economic returns.

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