Agricultural Water Management 159 (2015) 107–114

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Cumulative deficit irrigation effects on corn biomass and grain yield under two tillage systems

J.G. Benjamin*, D.C. Nielsen, M.F. Vigil, M.M. Mikha, F. Calderon

Central Great Plains Research Station, 40335 Co. Road GG, Akron, CO 80720, USA

ARTICLE INFO

Article history:
Received 29 September 2014
Received in revised form 14 May 2015
Accepted 23 May 2015
Available online 16 June 2015

Keywords:
Corn
Irrigation
Water stress
Tillage
Water use efficiency
Soil water

ABSTRACT

Deficit irrigation (DI) is sometimes used to cope with dwindling irrigation water supplies or limited water allocations. A study at Akron, Colorado, USA from 2001 to 2006 investigated the effects of consecutive years of DI on soil water use, soil water content, biomass production, grain yield and water use efficiency (WUE) in a continuous corn system. In 2001, DI and full irrigation (FI) had the same grain yield. In 2002, DI reduced grain yield by 20% relative to FI. By 2006, continued DI reduced grain yield by 65% compared with FI. Significant increases in soil water storage during the non-crop period occurred only in 2005 and 2006. This resulted in a slow but continual decrease in soil water storage as the years progressed. By 2006, soil water storage in the 60- to 90-cm depth remained lower for DI than for FI during the entire growing season. WUE declined for DI compared with FI over the years. WUE was the same for DI and FI in 2001, but WUE for DI declined to only 65% of FI by 2006. DI may be an option for short term or emergency situations when insufficient irrigation water is available for FI in one year. However, long-term use of DI, without replenishment of stored soil water during the non-cropped period, was detrimental to both corn production and water use efficiency under these experimental conditions.

Published by Elsevier B.V.

1. Introduction

Greater demands for water due to urbanization and lower water table levels in aquifers in the central and western regions of the United States have led to lesser amounts of water available to agriculture. Investigations into irrigation scheduling and water needs through crop life cycles have shown that several crops, notably wheat (*Triticum aestivum* L.) and grain sorghum (*Sorghum bicolor* L.), can be irrigated with less than full crop water requirements and suffer only mild reductions in crop yields with a corresponding increase in water productivity (Hanks et al., 1969; Geerts and Raes, 2009). Corn (*Zea mays* L.) suffered greater proportional yield loss due to deficit irrigation (DI). Corn, however, continues to be the predominant irrigated crop in the central Great Plains (Norwood, 2000).

Timing of water availability is critical for corn production. Denmead and Shaw (1960) noted that water stress during the vegetative stage of corn production reduced grain yield by 25%, water stress during silking reduced grain yield by 50%, while water stress during grain fill reduced grain yield by 21%. Saseendran et al. (2008) modeled corn production with limited irrigation in northeast Colorado and concluded that yields and water use efficiency were maximized when available irrigation amount was split with 20% applied during the vegetative growth stage and 80% during the reproductive growth stage. With rain-fed agriculture in the semi-arid west, the amount of rainfall during the critical tasseling to early dough stage of corn (VT to R4, growth stage as per Ritchie and Hanway, 1982) is highly correlated to overall grain production (Nielsen et al., 2009). They showed that planting time soil water content is poorly correlated to overall grain production, but a high level of planting time soil water allows for sufficient vegetative production to use rainfall later in the growing season. It would seem that relatively small amounts of irrigation during the critical tassel – silking period have the potential to greatly increase grain production in dry climates. Research on limited irrigation has focused on providing irrigation water to the critical period of corn production.

Some limited irrigation work has been done in relatively humid areas (Newel and Wilhelm, 1987; NeSmith and Ritchie, 1992), where recharge of soil water would be expected during the over-winter period. In semi-arid climates, one strategy for limited irrigation is to expect sufficient water recharge during the fallow period to provide water for the vegetative stage of corn production and little or no irrigation is added during vegetative growth. Irrigation then begins at corn tasselling and continues through grain fill (Hergert et al., 1993; Payero et al., 2006; Klocke et al., 2007). Another strategy for limited irrigation is to start water

* Corresponding author. Tel.: +1 970 345 0518; fax: +1 970 345 2088.
E-mail address: Joseph.Benjamin@ars.usda.gov (J.G. Benjamin).

http://dx.doi.org/10.1016/j.agwat.2015.05.025
0378-3774/Published by Elsevier B.V.

Table 1
Details of cropping history for rotations, 2001–2006.

Year	Variety	Population (seeds ha^{-1})	N–P–K–Zn (kg ha^{-1})	Planting date
2001	Dekalb DK 493	80,000	160–22–0–0	May 14
2002	Dekalb DK 493	80,000	160–22–0–0	May 3
2003	NK N42-B7	86,000	215–22–0–0	May 5
2004	Laser L62-C2	86,000	215–22–0–0.6	May 4
2005	N65-C5	86,000	215–22–0–0.6	May 13
2006	NK N70-C7RR	86,000	215–22–0–0.6	May 5

applications at some pre-determined level of soil water depletion, such as 50% plant available water (Klocke et al., 2011), and then irrigate at some reduced level below full crop requirements.

Multi-year studies of limited irrigation sometimes place the plots in new areas of the field that were not subject to previous limited irrigation (Cakir, 2004; Payero et al., 2006) or corn is grown in rotation with an extended fallow period preceding the corn crop (Norwood, 2000; Baumhardt et al., 2013; Klocke et al., 2011).

Little work has been done to evaluate the cumulative effect of DI on soil water replenishment with continuous corn production. The objective of this study was to evaluate the effects of multiple years of DI on soil water replenishment, soil water availability during corn production, and the cumulative effect of DI on corn grain yield and WUE.

2. Materials and methods

The study was conducted at the USDA-ARS Central Great Plains Research Station near Akron, Colorado, USA. The station lies at 40.15° N lat and 103.15° W long. The elevation of the station is 1384 m above mean sea level. The research station location is within a semi-arid climate with approximately 400 mm annual precipitation and approximately 1600 mm pan evaporation. The soil is a Weld silt loam (fine, smectitic, mesic Aridic Paleustolls). This soil has a silt loam Ap horizon from about 0 to 120 mm with fine granular structure. A silty clay loam Bt1 horizon with fine to medium subangular blocky structure extends from about 120 to 240 mm with a smooth boundary to a silty clay loam Bt2 horizon, also with fine to medium subangular blocky structure to about 410 mm. A silty clay loam Btk horizon with fine to medium subangular blocky structure extends to about 640 mm.

The irrigation-tillage experiment started in 2001 and ended in 2006. Prior to the initiation of the experiment, the field had been in fully irrigated (FI), continuous corn production since 1997. The experiment was organized as a split-plot design with three replications. The main plot was an irrigation treatment of either FI or DI. Irrigation treatments in 2001–2003 and 2005–2006 included a FI treatment and a DI treatment. The FI treatment supplied irrigation water each week based on the evapotranspiration (ET) demand during the entire growing season. Credit was given for any rainfall each week. The DI treatment supplied no irrigation water during the vegetative portion of the growth cycle (from emergence to appearance of tassel) and then added irrigation water equivalent to the FI plots during the reproductive stage. In 2003, the DI plots showed severe water stress during the vegetative growth stage, which was attributed to depletion of soil water storage. In an attempt to compensate for previous water depletion, all the plots were FI in 2004. All irrigation was applied with a sprinkler irrigation system. Irrigation rates were based on calculated ET demands (Allen, 2000; Allen et al., 1998; Nielsen and Hinkle, 1996; Jensen et al., 1990).

Tillage subplots (18 m by 9 m) were randomized within the main irrigation plots. Two levels of tillage were: (1) a no-till system (NT) consisting of planting directly into the previous crop residues and (2) a chisel plow system (CP) consisting of a fall chisel plow operation 0.35 m deep with a parabolic shank deep ripper. The shanks on the ripper for CP had 0.6-m centers. CP was followed in the spring by one or two passes with a mulch treader 5 cm deep to break up clods and smooth the soil surface in preparation for planting. Plot size and machinery working widths were such that the wheel tracks for field operations followed a controlled wheel traffic pattern. All plots were in continuous corn planted approximately 5 cm deep in 0.76-cm rows. Corn varieties, planting populations, fertilizer treatments and planting dates are given in Table 1.

Soil water content measurements were taken during the 2002–2006 growing seasons with a neutron probe. Due to personnel constraints, no soil water content measurements were made with the neutron probe in 2001. One neutron access tube was installed in the center row of each plot shortly after planting. A delay occurred in 2003 such that the access tubes were not installed until the V6 growth stage. Water measurements were collected at 0.3 m, 0.6 m, 0.9 m, 1.2 m, 1.5 m, and 1.8 m depths immediately before irrigation and as soon after irrigation as field entry was possible, generally the next day. The neutron probe was calibrated against gravimetric soil samples taken at the time of access tube installation in an adjacent experiment with the same soil type. The gravimetric soil water contents estimated from the neutron probe measurements were converted to volumetric soil water contents by multiplying by the bulk density, also measured on the samples taken at the time of neutron probe access tube installation. Total water storage (S, cm) in the 1.8-m soil profile was calculated by

$$S = \sum_{d} 30\,\theta_d \quad (1)$$

where θ_d is the volumetric water content in each 30-cm depth increment d. Change in water content (ΔS_i) between sampling dates was calculated by

$$\Delta S_i = S_j - S_k \quad (2)$$

where S_j and S_k are the bounds of the interval of interest. Total water use for a growth interval (TWU_i, cm) for each growth stage was calculated by

$$TWU_i = \Delta S_i + I_i + R_i \quad (3)$$

where I_i is the irrigation that occurred for the interval and R_i is the rainfall that occurred for the interval i.

Growth stage measurements were made each week after emergence. Ten representative plants were identified in each plot and the leaf number for each plant was marked with an indelible marker as the leaf emerged from the whorl. Corn growth stage was evaluated as described in Ritchie and Hanway (1982). The growth stage was determined by averaging the growth stages of the individual plants. Plant biomass samples were collected at the plot average R1 growth stage in 2002 and at the V6, V12, and R1 growth stages in 2003–2006. Dates of biomass harvest are shown in Table 2. Four adjacent plants, representative of the plot area and approximately 1 m from the plants used for growth stage determination, were collected at each sampling time. Plant population (pop) was measured for each plot (plant ha^{-1}) and the biomass for four plants (b_{4s}, g) was converted to biomass per unit area for the growth stage interval (b_s, kg ha^{-1}) by

$$b_s = 0.00025\, b_{4s}\, pop \quad (4)$$

Table 2
Dates of biomass harvest. ND indicates that no data were collected for that growth stage.

Year	V6	V12	R1
2002	ND	ND	August 1
2003	June 26	July 15	July 22
2004	June 28	July 26	August 4
2005	June 26	July 21	July 29
2006	June 20	July 12	July 31

Grain yield (y) was collected from two 6.1 m rows in the center of the plot with a plot combine. Water use efficiency (WUE, kg ha^{-1} cm^{-1}) was calculated by

$$WUE = y\,TWU_e^{-1} \quad (5)$$

where TWU_e is the total water use at the end of the growing season.

Statistical analysis was done using SAS GLM procedure (SAS 9.3 TS Level 1M2, ©2002–2010 SAS Institute Inc., Cary, NC, USA). Analyses for initial water storage, ending water storage, and change in water storage were conducted by year. Significance of the irrigation main effect was tested by the rep*irrigation interaction. Statistical analyses of water use between growth stages, biomass production, grain yield and WUE were conducted by combining years. Significance of the year main effect was tested by the rep*year interaction and significance of the irrigation main effects was tested by the rep*irrigation interaction. Significance of the year*irrigation effect was tested by the rep*year*irrigation interaction. Treatment differences were considered significant at $\alpha = 0.05$.

3. Results

Two events greatly affected the results of water dynamics and plant growth and yield during the study. In 2002, a large hail storm on August 24 (day 238) caused major damage to the crop during grain filling. In 2005, early season biomass production was reduced due to high jackrabbit (*Lepus* sp.) depredation.

3.1. Water use and soil water recharge

Average growing season rainfall for the study was 24.1 cm (Table 3) compared with the 98-year average May to September rainfall of 29.0 cm. The first year of the study (2001) had experiment-wise average rainfall, while 2002 and 2003, had below average rainfall. The next two years (2004 and 2005) had rainfall near the 98-year average and the sixth year (2006) had below average rainfall. Rainfall amounts during the growing season affected the amount of irrigation water applied. Average total irrigation water applied for FI was 34.6 cm (±3.1 cm). Average total irrigation water applied for the DI was 23.2 cm (±3.5 cm).

Table 3
Total rainfall and irrigation for full irrigation (FI) and deficit irrigation (DI) during each growing season.

Year	Irrigation	Rainfall (cm)	Irrigation (cm)	Total (cm)
2001	FI	24.5	34.3	58.8
	DI	24.5	20.3	44.8
2002	FI	18.2	37.7	55.9
	DI	18.2	28.6	46.8
2003	FI	23.0	32.4	55.4
	DI	23.0	26.6	49.6
2004	FI	27.8	31.8	59.6
	DI	27.8	31.8	59.6
2005	FI	28.5	32.4	60.9
	DI	28.5	20.4	48.9
2006	FI	22.5	39.3	61.8
	DI	22.5	20.3	42.8

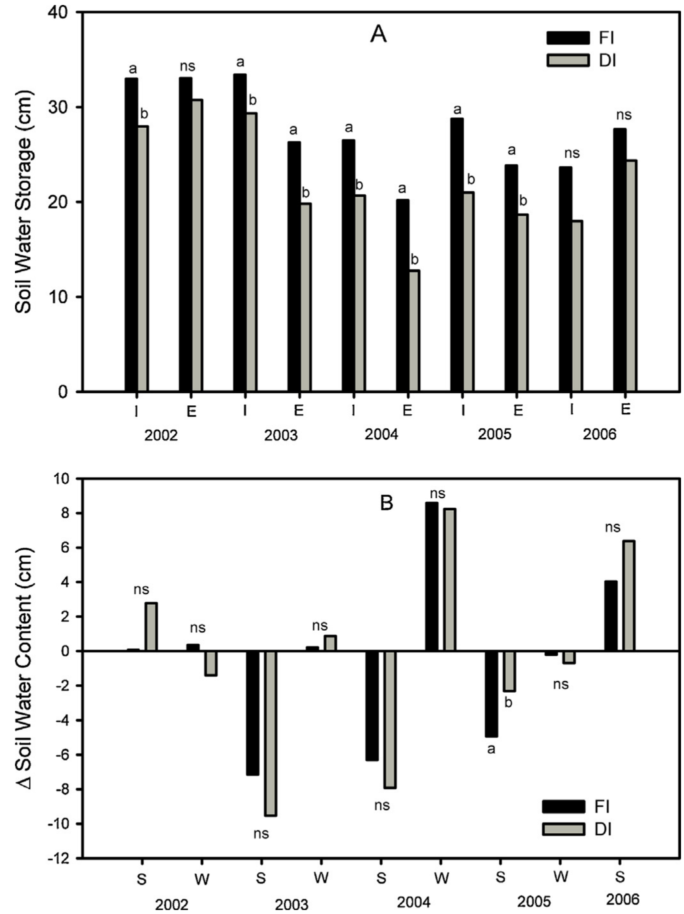

Fig. 1. Total water storage (A) and change in water storage (B) in the surface 180 cm. In subfigure A, I indicates the initial water storage at the beginning of the growing season for the year and E indicates the ending water storage at harvest for the year. In subfigure B, S indicates the water change during the growing season for the year and W indicates the change of water storage after harvest until the following spring. Different letters indicate a significant difference between means at $P = 0.05$.

Soil water dynamics during the course of the experiment was highly dependent on the amount of precipitation that occurred during the non-cropped period. The 98-year average precipitation for the October through April winter period is 12.8 cm. During the winter of 2001–2002 only 5.5 cm of precipitation was received. There was less water storage in the surface 180 cm with DI than for FI at the start of the 2002 growing season (Fig. 1A). Even though there was not a significant difference in the change in water storage for the summer of 2002 (Fig. 1B), the change in water storage led to no significant difference in water storage at the end of the 2002 growing season. Above average precipitation occurred during the winter of 2002–2003 (17.7 cm) but there was very little change in total soil water content. This resulted in significantly lower initial water storage for the DI treatment than the FI treatment in the spring of 2003. Total water depletion was similar for both treatments during the summer of 2003, resulting in lower water storage at the end of 2003. This trend continued through the experiment. In each year after 2002, the DI treatment had lower total water storage at the beginning and end of the growing season than the FI treatment, until 2006, when no difference between treatments was observed. Very little soil recharge occurred during the winters of 2002, 2003, and 2005, which received 5.5 cm, 17.7 cm, and 10.8 cm of precipitation, respectively. There was between 4 and 8 cm of soil water recharge during the winters of 2004 and 2006, which received 8.3 cm and 14.2 cm of precipitation, respectively. Stored soil water decreased from about 33 cm and 28 cm in the FI and DI, respectively, at the

Table 4
Statistical analysis of treatment effects on soil water use and total water use from 2002 to 2006.

Source	Soil water use				Total water use			
	V6	V12	R1	Harvest	V6	V12	R1	Harvest
Year (Y)	**	**	**	**	**	**	**	**
Irrigation (I)	ns	ns	ns	ns	ns	ns	*	**
Tillage (T)	ns	ns	ns	ns	ns	ns	ns	ns
Y*I	*	ns	ns	ns	ns	*	*	**
Y*T	ns	ns	*	**	ns	ns	*	*
I*T	ns	ns	ns	ns	ns	ns	ns	ns
Y*I*T	ns	ns	ns	ns	ns	ns	ns	ns

* Statistical significance at $P = 0.05$.
** Significance at $P = 0.01$.
ns indicates no significant treatment effect at $P = 0.05$.

start of the 2002 growing season, to about 24 cm and 18 cm in the respective irrigation treatment at the start of 2006. Tillage had no significant effect on either water storage or change in water storage for any year or replenishment interval of the experiment, nor was there a significant tillage*irrigation interaction.

Year had a significant effect on ΔS for all growth stages (Table 4) while irrigation and tillage did not. There was a significant interaction between year and irrigation only at the V6 growth stage while the interaction between year and tillage was significant only at the R1 and Harvest growth stages. Year had a significant effect on *TWU* for all growth stages. Irrigation had a significant effect on *TWU* at the R1 and Harvest growth stages but not at the V6 or V12 growth stages. There was no significant tillage effect on *TWU*. There was a significant interaction between year and irrigation on *TWU* at the V12, R1, and Harvest growth stages, but not at the V6 growth stage. There was a significant interaction between year and tillage on *TWU* for the R1 and Harvest growth stages, but not at the V6 or V12 growth stages. There were no significant interactions for irrigation by tillage or year by irrigation by tillage for any growth stage for either ΔS or *TWU*.

At the beginning of the 2002 growing season, there were similar water contents following either full or DI in 2001 in the 0- to 30-cm depths and 30- to 60-cm depths (Fig. 2). Water contents were significantly lower following DI in the 60- to 90-cm depth from May 15 (day 135) to July 19 (day 200). Soil water depletion after July 19 resulted in similar water contents between the two irrigation schemes at the 60- to 90-cm depth. A severe hail storm on August 24 (day 238) was accompanied by rain that replenished soil moisture at all intervals in the 0- to 90- cm depths. Loss of leaf material from hail limited evapotranspiration demand and lowered further water depletion for the rest of the growing season. There were no treatment differences in water contents below 90 cm here, or in subsequent years. Water contents remained constant at about 0.3 $cm^3\ cm^{-3}$ throughout the growing season for all years. These data are not shown for the sake of brevity.

Since little net water recharge occurred over the winter of 2002, the initial water contents and water distribution in the spring of 2003 were similar to the ending water contents of 2002 (Fig. 2). Water use and irrigation resulted in periodically lower water contents for DI compared with FI in the surface 30 cm. These

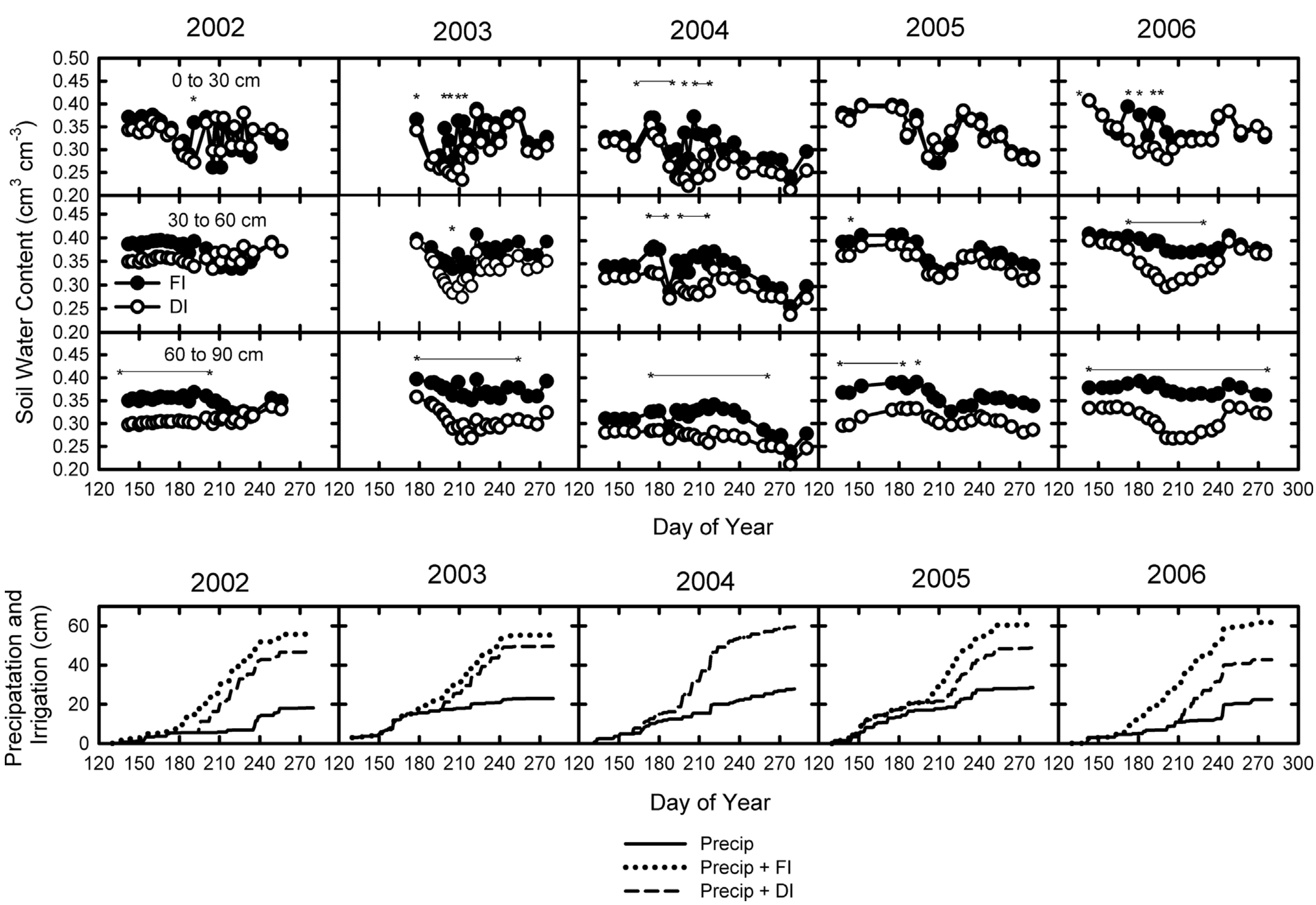

Fig. 2. Water contents in the 0- to 30-cm, 30- to 60-cm, and 60- to 90-cm soil depths and total water applied for 2002–2006. An * indicates significant difference ($P = 0.05$) in water content at a particular date and soil depth. An * connected with another * by a bar indicates significant differences for all dates within the bar.

Table 5
Year, irrigation and tillage effects on change in soil water storage (ΔS) between the installation of neutron access tubes and designated growth stage for 2002 through 2006. Irrigation treatments include full irrigation (FI) and deficit irrigation (DI). Tillage effects include no-till (NT) and chisel plow (CP). Positive values indicate a gain in soil water storage and negative values indicate a loss in soil water storage. Year means at a particular growth stage (row) followed by a different letter indicate a significant year effect at $P = 0.05$. Irrigation or tillage means within year and growth stage (column) followed by a different letter indicate a significant irrigation or tillage effect at $P = 0.05$. A dash (–) indicates that the measurement was not determined for that growth stage.

Source	Growth Stage	Treatment	2002 (cm)	2003 (cm)	2004 (cm)	2005 (cm)	2006 (cm)
Year (Y)	V6		–	–	2.0a	1.8a	−1.0b
	V12		–	–	−0.7a	−1.0a	−3.8b
	R1		1.8a	−7.4e	−3.6c	−2.2b	−5.9d
	Harvest		1.4a	−8.3e	−7.1d	−4.0c	−2.8b
Y*Irrigation	V6	FI	–	–	3.1a	0.8	0.8a
		DI	–	–	1.0b	2.8	−2.9b
	V12	FI	–	–	3.9a	−1.0	0.4a
		DI	–	–	−5.3b	−1.1	−8.0b
	R1	FI	0.6b	−5.3a	−1.5	−3.5b	−3.3a
		DI	3.1a	−9.4b	−5.8	−0.9a	−8.5b
	Harvest	FI	0.1	−7.1	−6.3	−5.1	−3.1
		DI	2.8	−9.5	−7.9	−3.0	−2.4
Y*Tillage	V6	CP	–	–	1.9	1.9	−0.5
		NT	–	–	2.1	1.4	−1.2
	V12	CP	–	–	−1.0	−2.0	−2.9
		NT	–	–	−0.4	−0.7	−3.6
	R1	CP	2.3	−8.2b	−2.8a	−2.9b	−4.8
		NT	1.6	−6.8a	−4.2b	−0.8a	−6.6
	Harvest	CP	1.3	−9.4b	−4.7a	−4.3b	−2.1
		NT	1.5	−7.6a	−8.9b	−3.1a	−4.0

differences occurred early in the growing season, before irrigation started with DI. After irrigation began for the DI, the water contents in the surface 30 were similar for the two irrigation schemes. Even though there was water depletion in the 30- to 60-cm depth, there was only one sampling date where water contents were significantly lower in the DI compared with the FI. There were significantly lower water contents in the DI plots compared with the FI plots at the 60- to 90-cm depth for most of the growing season.

At the start of 2004, water contents were similar between the FI and DI treatments (Fig. 2). Even though all treatments were irrigated the same in 2004, the DI treatment had lower water contents at the 0- to 30-cm and 30- to 60-cm layers for part of the vegetative growth stages. Water contents were significantly lower in the DI treatment, compared with the FI treatment, in the 60- to 90-cm layer for most of the growing season.

Early spring rains and lower evapotranspiration demand due to vegetative loss from jackrabbit depredation caused the water contents in the 0- to 30-cm and 30- to 60-cm layers to be similar for nearly the entire growing season in 2005 (Fig. 2). Water contents were significantly lower in the DI treatment, compared with the FI treatment, in the 60- to 90-cm layer during the early part of the growing season, but no differences were detected between treatments later in the growing season.

There were few irrigation treatment differences in water contents in the 0- to 30-cm and 30- to 60-cm layers at the beginning of 2006 (Fig. 2). As the growing season progressed, the DI treatment had lower water contents than the FI treatment in these layers until irrigation started in the DI plots. The DI treatment had lower water contents in the 60- to 90-cm layer during the entire growing season.

Table 6
Year, irrigation and tillage effects on total water use (*TWU*) between the installation of neutron access tubes and designated growth stage for 2002 through 2006. Irrigation treatments include full irrigation (FI) and deficit irrigation (DI). Tillage effects include no-till (NT) and chisel plow (CP). Year means at a particular growth stage (row) followed by a different letter indicate a significant year effect at $P = 0.05$. Irrigation or tillage means within year and growth stage (column) followed by a different letter indicate a significant irrigation or tillage effect at $P = 0.05$. A dash (–) indicates that the measurement was not determined for that growth stage.

Source	Growth stage	Treatment	2002 (cm)	2003 (cm)	2004 (cm)	2005 (cm)	2006 (cm)
Year (Y)	V6		–	–	10.5b	14.0a	6.3c
	V12		–	–	30.2a	21.2b	15.6c
	R1		24.0c	16.2d	40.8a	27.0b	26.0c
	Harvest		49.0c	49.4c	71.4a	59.8b	60.0b
Y*Irrigation	V6	FI	–	–	9.5b	15.0	6.7
		DI	–	–	11.5a	13.0	5.9
	V12	FI	–	–	25.5b	22.1	18.1a
		DI	–	–	34.8a	20.4	13.1b
	R1	FI	30.1a	17.0a	38.7	33.1a	32.9a
		DI	18.4b	15.4b	42.9	21.0b	19.0b
	Harvest	FI	54.0a	52.7a	70.5	66.9a	70.3a
		Deficit	43.9b	46.0b	72.2	52.7b	49.8b
Y*Tillage	V6	CP	–	–	10.6	13.8	5.8
		NT	–	–	10.4	14.3	6.7
	V12	CP	–	–	30.5	22.2a	14.7
		NT	–	–	30.0	19.6b	16.4
	R1	CP	24.4	17.0a	40.0	27.8	24.8b
		NT	24.2	15.6b	41.4	25.7	28.0a
	Harvest	CP	49.5	50.4	68.9b	60.0	60.0
		NT	48.6	48.6	73.1a	58.8	61.9

Table 7
Statistical analysis of year, irrigation and tillage effects on corn biomass, corn grain yield and water use efficiency (WUE) from 2002 to 2006.

Source	Biomass				WUE			
	V6	V12	R1	Grain	V6	V12	R1	Grain
Year (Y)	**	**	**	**	**	*	**	**
Irrigation (I)	ns	**	**	*	ns	**	ns	ns
Tillage (T)	ns	ns	ns	*	ns	ns	ns	ns
Y*I	ns	ns	**	**	ns	ns	*	**
Y*T	**	*	ns	*	ns	ns	ns	*
I*T	ns	ns	ns	ns	ns	ns	*	ns
Y*I*T	ns	ns	*	ns	ns	ns	ns	ns

* Statistical significance at $P = 0.05$.
** Significance at $P = 0.01$.
ns indicates no significant treatment effect at $P = 0.05$.

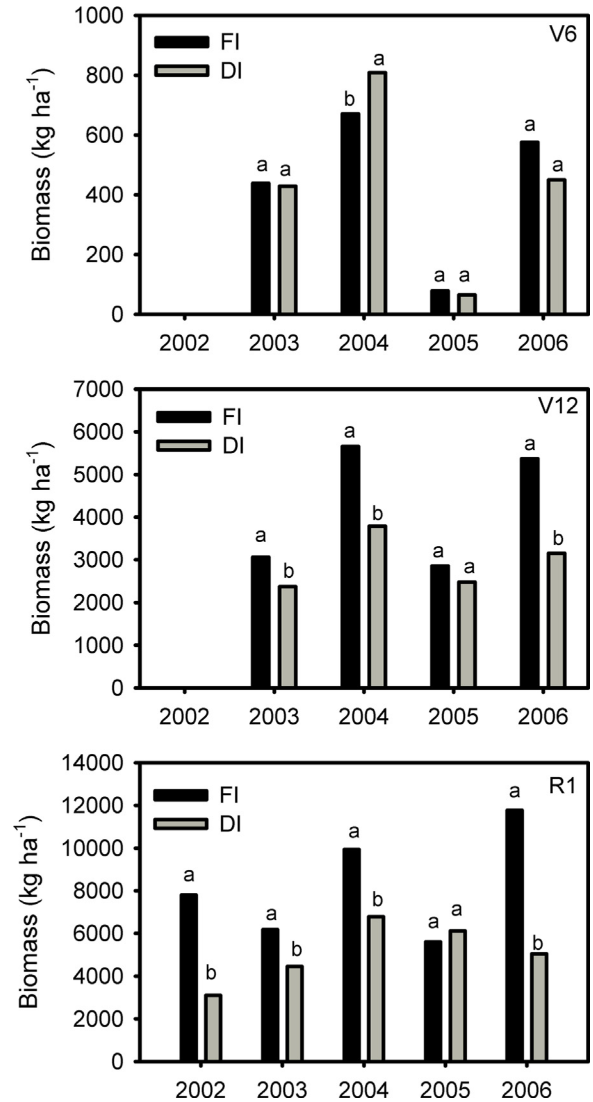

Fig. 3. Irrigation effects on biomass production at V6, V12, and R1 growth stages for full irrigation (FI) and deficit irrigation (DI). No biomass measurements were made at V6 and V12 in 2002. Depredation by jackrabbits greatly reduced early biomass production in 2005. Bars with different letters within year indicate significant irrigation effects at $P = 0.05$.

Soil water content at the R1 and harvest stages increased in 2002 due to less irrigation water used by the crop after the hail, but decreased during the subsequent years (Table 5). After 2002, in nine of 14 comparisons (64% of the time), soil water content decreased more with the DI than FI at all growth stages, The exception to this trend occurred in 2005, when rabbit depredation decreased overall early biomass production. Tillage effects on ΔS were inconsistent. In certain years (2003, 2005), NT had less soil water content than CP. In other years, CP had less soil water content than NT (2004) or there was no tillage effect (2002, 2006).

As expected, *TWU* at harvest varied by year (Table 6). TWU was greatest in 2004 since all plots were fully irrigated. TWU was greater in 2005 and 2006 compared with 2002 and 2003 because irrigation rates increased in those years to compensate for higher plant population and fertilizer rates.

3.2. Biomass production and grain yield

Year had a significant effect on biomass production at each growth stage (Table 7). Irrigation effects were significant for the V12 and R1 growth stages, but not for the V6 growth stage. There was a significant interaction between irrigation and year for the R1 growth stage, but not for the V6 and V12 growth stages. Tillage as a main effect had no significant effect on biomass production for any growth stage. There was a significant year by tillage interaction at the V6 and V12 growth stages, but not for the R1 growth stage.

Biomass production at the V6 growth stage was little affected by irrigation scheme (Fig. 3). Only in 2004 was there an irrigation effect on biomass, where DI had 20% greater biomass than FI. At the V12 and R1 growth stages, FI had between 20% and 150% greater biomass than DI for all years except 2005, where jackrabbit depredation decreased apparent biomass production.

There was no overall advantage for tillage system on biomass production during the study (Fig. 4). In 2003, CP had between 19% and 70% greater biomass than NT, depending on growth stage. In 2004, CP had between 9% and 23% less biomass than NT, depending on growth stage. In 2005, CP had 23% greater biomass than NT, but only at the R1 growth stage. In other years, there were no differences in biomass due to tillage at any growth stage.

Year, irrigation and tillage all had significant effects on grain yield (Table 7). There was also a significant year by irrigation and year by tillage interaction. Irrigation by tillage interaction and the three-way interaction were not significant.

In 2001, there was no irrigation effect on grain yield (Fig. 5). In all other years, except 2005, DI reduced grain yield by 20–65% compared with FI. This was even true for 2004, when all plots were fully irrigated, indicating a residual effect of previous DI on stored soil water. In 2005, rabbit depredation decreased early biomass production, which led to 26% greater grain yield for the DI vs. FI.

Tillage had no effect on grain yield in 2001 (Fig. 6). In 2002, CP reduced grain yield by 15% compared with NT plots. In 2003 grain yield was 10% greater in the CP plots than the NT plots. In 2004, 2005 and 2006, grain yield was consistently 12–18% greater in the NT plots than the CP plots.

Year had a significant effect on corn grain WUE (Table 7), but irrigation or tillage main effects were not significant. However, there were significant year by irrigation and year by tillage interactions. Irrigation by tillage interaction and the three-way interaction were not significant.

Irrigation scheme had no effect on corn grain WUE in 2002 (Fig. 7). DI caused a 26–51% reduction in WUE for 2003, 2004, and 2006. WUE increased by 70% for DI compared with FI in 2005. CP reduced WUE by 8–16% in four of the five years compared with NT (Fig. 8). There was an 8% WUE increase for CP compared with NT in 2003.

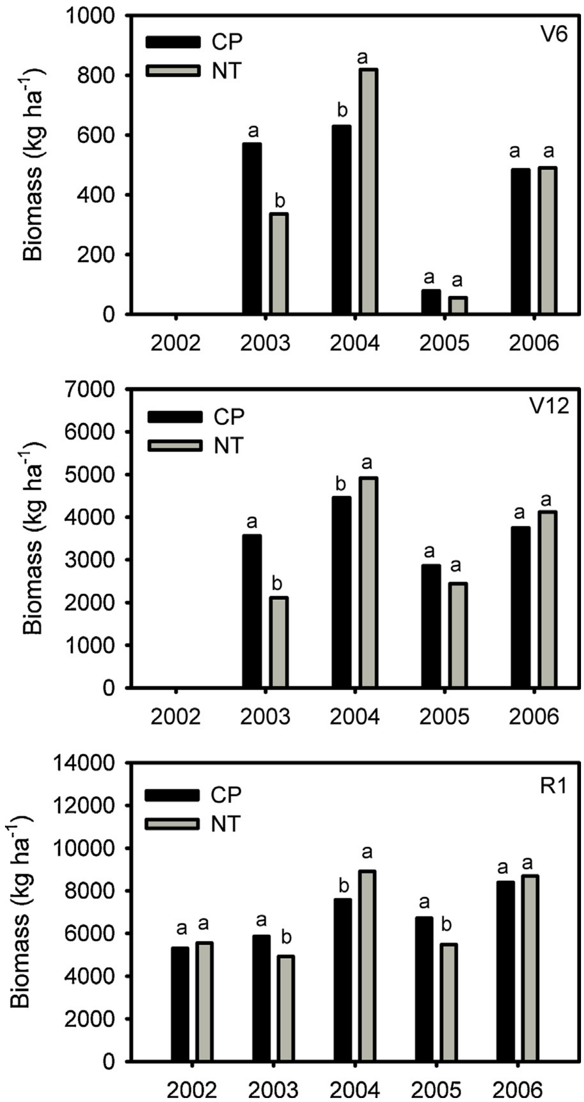

Fig. 4. Tillage effects on biomass production at V6, V12, and R1 growth stages for chisel plow (CP) and no-till (NT) systems. No biomass measurements were made at V6 and V12 in 2002. Depredation by jackrabbits greatly reduced early biomass production in 2005. Bars with different letters within year indicate significant tillage effects at $P = 0.05$.

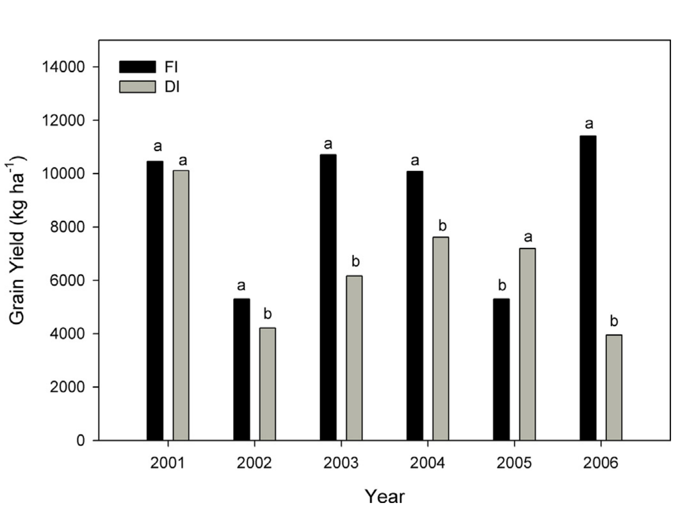

Fig. 5. Irrigation effects on grain yield for 2001–2006 for full irrigation (FI) and deficit irrigation (DI). Bars with different letters within year indicate significant irrigation effects at $P = 0.05$.

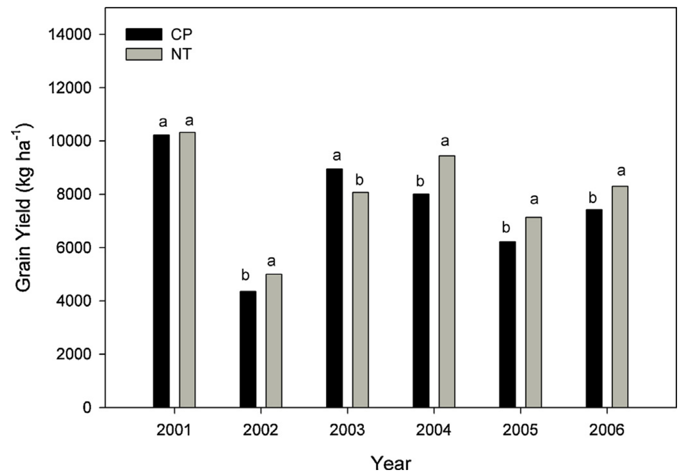

Fig. 6. Tillage effects on grain yield for 2001–2006 for chisel plow (CP) and no-till (NT) systems. Bars with different letters within year indicate significant tillage effects at $P = 0.05$.

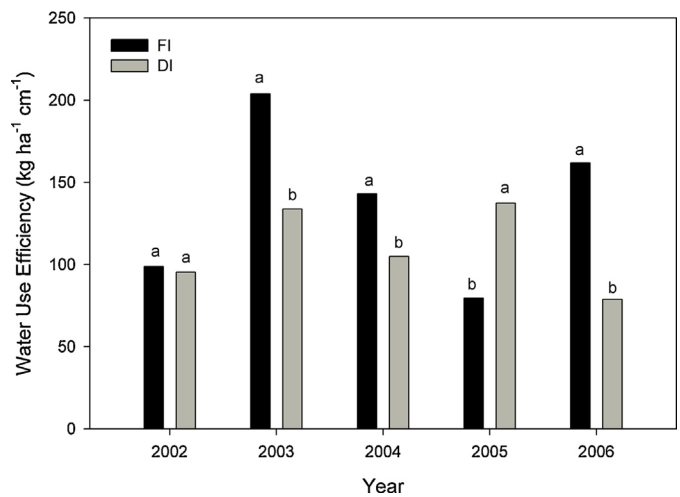

Fig. 7. Irrigation effects on water use efficiency for 2002–2006 for full irrigation (FI) and deficit irrigation (DI). Bars with different letters within year indicate significant irrigation effects at $P = 0.05$.

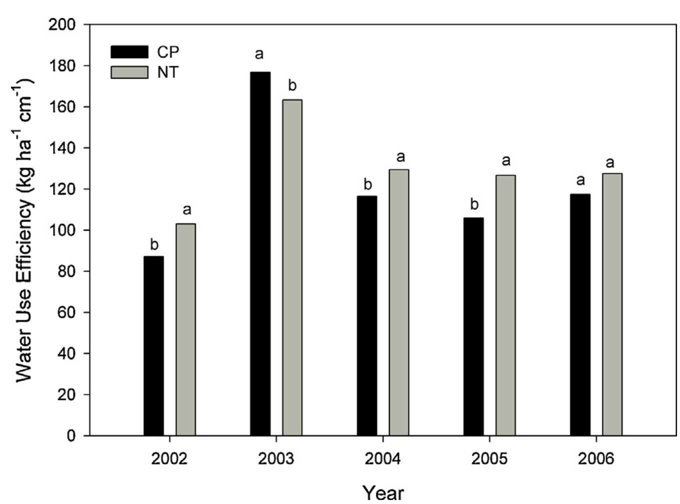

Fig. 8. Tillage effects on water use efficiency for 2002–2006 for chisel plow (CP) and no-till (NT) systems. Bars with different letters within year indicate significant tillage effects at $P = 0.05$.

4. Discussion

One premise concerning DI in the central Great Plains is that sufficient water will be stored in the soil during the non-crop period such that the stored soil water will be used for corn vegetative growth. Irrigation water will then be applied during the critical reproductive stage of corn growth (Hergert et al., 1993; Norwood, 2000; Payero et al., 2006, 2009; Baumhardt et al., 2013). This assumes that sufficient overwinter precipitation will be stored as soil water to accommodate vegetative growth needs. For the first year of this study, this assumption appears valid. There was no grain yield difference between FI and DI in 2001. In four out of five of the subsequent years, grain yield was less with DI compared with FI. In the second year of DI, grain yield was 20% lower with DI than for FI. By the 6th year, DI reduced crop yield by 65% compared with FI. The effect of DI was noted even when FI resumed. In 2004, after three years of previous DI, crop yield was reduced by 25% in the plots that had previous DI compared with plots that had been fully irrigated, even though all plots received FI.

The effects of DI on grain yield can be attributed to the decrease in stored soil water as time progressed. In three out of five years there was very little replenishment of stored soil water during the non-crop period. There was a progressively greater depletion in stored soil water over time such that, by the sixth year of the study, water contents in the 60–90 cm depth were lower throughout the growing season with DI compared with FI. It would appear that regional precipitation and evaporation patterns should be considered when contemplating the use of DI to ensure that sufficient late fall, winter, and early spring moisture is available to replenish stored soil water. The assumption that soil water recharge will be sufficient to replenish soil water storage for continued DI may not be warranted in many regions of the Great Plains.

For DI to be successful there should not be a serious decline in WUE compared with FI. Trooien et al. (1999) found an increase in WUE for corn grain using DI compared with FI in central Kansas. In their study, the DI and FI plots were re-randomized each year, so effects of DI were not applied to the same land area each year. Klocke et al. (2007) also showed increased WUE using DI compared with FI in central Nebraska. In this study, WUE was the same between FI and DI in 2002, which was consistent with several other researchers on first- or second-year DI studies (Norwood, 2000; Baumhardt et al., 2013). These results showed that the discrepancy in corn grain WUE between FI and DI widened as time progressed WUE was lower in DI plots than FI plots in three of the next four years. By 2006, WUE for DI was half of that of FI. This agrees with Klocke et al. (2011) who showed a consistent decline of WUE for DI as crop water use declined. The only year that WUE was greater for DI than FI was when plant material was lost due to jackrabbits early in the growing season (2005). It is unclear why early season biomass loss would have led to increased WUE for DI in 2005. It appears that WUE can be maintained with DI if sufficient soil water recharge can occur during the winter season or if corn is grown in rotation with crops with lower water demand so that some soil water recharge can occur in the rotation.

NT crop management resulted in greater grain yield than CP in four out of six years and greater WUE in three out of five years. In one year of the study, there was no tillage effect on either grain yield or WUE. In one year of the study, CP had greater grain yield and WUE than NT. These findings are consistent with other published results. Norwood (2000) reported greater corn grain yield and greater WUE for NT vs. sweep tillage in two out of four years in a wheat-corn-fallow rotation. In the other two years, there were no tillage differences in grain yield or WUE. Baumhardt et al. (2013) reported greater corn grain yield for NT vs. sweep tillage or disk tillage in two out of four years in a wheat-corn-fallow rotation and greater WUE for NT vs. sweep tillage or disk tillage in one out of four years. In other years there were no tillage differences. It appears that using NT crop management holds a slight, positive advantage when using DI.

5. Conclusions

These data suggest that DI may be used in the short term for emergency situations when insufficient irrigation water is available for FI in one year. However, long-term use of DI, without replenishment of stored soil water during the non-cropped period, is detrimental to both corn production and WUE. In the situation when the allocation of irrigation water is limiting, a crop rotation might be considered, such that the field would be divided and the irrigation water allocation applied to fully irrigate the portion of the field planted to corn. The remaining portion of the field might then be planted to a non-irrigated crop with a lower water use. In the situation where irrigation water is limited due to low capacity water source, pre-season and post season irrigation may be warranted to store soil water for use by the corn crop during peak demand in the summer.

References

Allen, R.G., 2000. REF-ET Reference Evapotranspiration Calculator V 2.01.14. University of Idaho Research and Extension Center, Kimberly, ID.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration – guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper No. 56.

Baumhardt, R.L., Schwartz, R., Howell, T., Evett, S.R., Colaizzi, P., 2013. Residue management effects on water use and yield of deficit irrigated corn. Agron. J. 105, 1035–1044.

Cakir, R., 2004. Effect of water stress at different development stages on vegetative and reproductive growth of corn. Field Crops Res. 89, 1–16.

Denmead, O.T., Shaw, R.F., 1960. The effects of soil moisture stress at different stages of growth on the development and yield of corn. Agron. J. 52, 272–274.

Geerts, S., Raes, D., 2009. Deficit irrigation as an on-farm strategy to maximize crop water productivity in dry areas. Agric. Water Manage. 96, 1275–1284.

Hanks, R.J., Gardner, H.R., Florian, R.L., 1969. Plant growth-evapotranspiration relations for several crops in the central Great Plains. Agron. J. 61, 30–34.

Hergert, G.W., Klocke, N.L., Petersen, J.L., Nordquist, P.T., Clark, R.T., Wicks, G.A., 1993. Cropping systems for stretching limited irrigation supplies. J. Prod. Agric. 6, 520–529.

Jensen, M.E., Burman, R.D., Allen, R.G., 1990. Evapotranspiration and irrigation water requirements. ASCE Manuals and Reports on Engineering Practice No. 70. Am. Soc. Civil Eng. New York.

Klocke, N.L., Currie, R.S., Tomsicek, D.J., Koehn, J., 2011. Corn yield response to deficit irrigation. Trans. ASABE 54, 931–940.

Klocke, N.L., Payero, J.O., Schneekloth, J.P., 2007. Long-term response of corn to limited irrigation and crop rotations. Trans. ASABE 50, 2117–2124.

NeSmith, D.S., Ritchie, J.T., 1992. Maize (*Zea mays* L.) response to a severe soil water-deficit during grain-filling. Field Crops Res. 29, 23–35.

Newel, R.L., Wilhelm, W.W., 1987. Conservation tillage and irrigation effects on corn root development. Agron. J. 79, 160–165.

Nielsen, D.C., Hinkle, S.E., 1996. Field evaluation of basal crop coefficients for corn based on growing degree days, growth stage, or time. Trans. ASAE 39, 97–103.

Nielsen, D.C., Vigil, M.F., Benjamin, J.G., 2009. The variable response of dryland corn yield to soil water content at planting. Agric. Water Manage. 96, 330–336.

Norwood, C.A., 2000. Water use and yield of limited-irrigated and dryland corn. Soil Sci. Soc. Am. J. 64, 365–370.

Payero, J.O., Melvin, S.R., Irmak, S., Tarkalson, D., 2006. Yield response of corn to deficit irrigation in a semiarid climate. Agric. Water Manage. 84, 101–112.

Payero, J.O., Tarkalson, D.D., Irmak, S., Davison, D., Petersen, J.L., 2009. Effect of timing of a deficit-irrigation allocation on corn evapotranspiration, yield, water use efficiency and dry mass. Agric. Water Manage. 96, 1387–1397.

Ritchie, S.W., Hanway, J.J., 1982. How a Corn Plant Develops. Special report no. 48 Iowa State University of Science and Technology. Cooperative Extension Service.

Saseendran, S.A., Ahuja, L.R., Nielsen, D.C., Trout, T.J., Ma, L., 2008. Use of crop simulation models to evaluate limited irrigation management options for corn in a semiarid environment. Water Resour. Res. 44.

Trooien, T.P., Buschman, L.L., Sloderbeck, P., Dhuyvetter, K.C., Spurgeon, W.E., 1999. Water use efficiency of different maturity corn hybrids and grain sorghum in the central Great Plains. J. Prod. Agric. 12, 377–382.