Published online July 13, 2017

Effect of Deficit Irrigation Timing on Sugarbeet

David D. Tarkalson* and Bradley A. King

ABSTRACT

Increased water demands and drought have resulted in a need to determine the impact of deficit water management in irrigated sugarbeet (*Beta vulgaris* L.) production. This study was conducted over 3 yr at USDA-ARS in Kimberly, ID, on a Portneuf silt loam soil. Eight irrigation treatments consisted of crop evapotranspiration (ETc) rates combined with application timing. Treatments were: W1 Even: approximately (≈) 100% ETc evenly throughout the growing season; W2 Even: ≈65% crop evapotranspiration; W2 Early: ≈100% ETc early in season, ≈55% ETc the remainder of the season; W2 Late: rain-fed from emergence to end of July, ≈100% ETc the remainder of the season; W3 Even: ≈40% ETc; W3 Early: ≈100% ETc early in season, ≈25% the remainder of the season; W3 Late: rain-fed through mid-August, ≈100% ETc the remainder of the season, and rain-fed: no post emergence irrigation. Results showed that within deficit irrigation treatments, higher yields were obtained when water was applied evenly throughout the season (Even) or ≈100% of ETc was applied early with deficit irrigation later in the season (Early). Thus, the W2 Even and W2 Early treatments had 31.6, 32.9, and 28.2% greater estimated recoverable sucrose (ERS) yields compared to the W2 Late treatment in 2011, 2012, and 2016, respectively. Across all years, ERS yields increased at rates ranging from 17.3 to 22.0 kg ha^{-1} mm^{-1} actual crop water evapotranspiration (ETa). Generally, sugarbeet with greater water stress early in the season followed by ≈100% ETc later had lower yields and sucrose content (late treatments).

Core Ideas

- Water allocation timing under drip irrigation effected sugarbeet yield.
- Excessive water stress early in the season reduced yields.
- Areas with water shortages have options to grow sugarbeet.

Increased water demand from agriculture and non-agricultural sectors, and variable regional and seasonal precipitation has resulted in concerns over water supplies for irrigation in the northwestern United States. Increased irrigation costs are also a concern. Alternative irrigation management practices need to be developed and evaluated for crops like sugarbeet to accommodate drought years and increasing irrigation costs. Also, with increasing water demands science is being relied on to determine how to use water more efficiently. With irrigated agriculture being a major water consumer, it is vital that the industry adopts new methods and management practices that will increase water use efficiency while sustaining profitable farm enterprises.

In recent years numerous research studies have focused on crop production under deficit water input conditions. This research has been conducted all over the world and has focused on a variety of crops. For example, studies have focused on field corn (*Zea mays* L.) (Kang et al., 2000; O'Neill et al., 2004; Payero et al., 2006, 2008), cotton (*Gossypium hirsutum* L.) (Pettigrew, 2004; Tang et al., 2005; Du et al., 2006; Wen et al., 2013), and wheat (*Triticum aestivum* L.) (Zhang et al., 2006). Several studies have evaluated the effect of deficit irrigation in sugarbeets in other parts of the United States (Erie and French 1968; Carter et al.,1980; Hang and Miller, 1986; Hills et al., 1990; Yonts et al., 2003; Yonts, 2011). However, limited research exists for timing of deficit irrigation on sugarbeet during the growing season in the Northwest. A few studies have been conducted in several states, including Idaho where sugarbeet is irrigated. These studies, however, had conflicting results and have mostly been conducted decades ago with crop cultivars that are no longer in widespread use. For example, in Idaho, Carter et al. (1980) concluded that irrigation could be eliminated late in the season (1 August, swelling growth stage) on a silt loam soil without reducing sucrose yield as long as there was at least a 1.6-m soil depth at field capacity and the soil contained at least 200 mm of available water on 1 August early in the root swelling stage. They further suggested that implementing seasonal deficit irrigation management strategies in August, September, and October could reduce seasonal irrigation requirements by up to 30%, thus decreasing production costs. They found that although deficit irrigation would reduce leaf growth and canopy cover, it would not affect root sucrose accumulation. However, in Arizona on a silt loam soil, Erie and French (1968) found that imposing water stress on sugarbeet 3 to 4 wk prior to harvest in the fall reduced root and sucrose yields compared to a non-stressed crop. In the Panhandle region of Nebraska, Yonts et al. (2003) found that sugar yield was decreased by 7% when irrigation

Published in Agron. J. 109:1–9 (2017)
doi:10.2134/agronj2017.01.0061

USDA-ARS Northwest Irrigation and Soils Research Lab., Kimberly, ID 83341. Received 1 Jan. 2017. Accepted 29 May 2017.
*Corresponding author (david.tarkalson@ars.usda.gov).

Abbreviations: ERS, estimated recoverable sucrose; ETa, actual crop water evapotranspiration; ETc, crop evapotranspiration.

was terminated in mid-August on a fine sandy loam soil. However, another study in Nebraska where irrigation was restricted in August resulted in sugar yields that were similar to full irrigation (Yonts, 2011). In eastern Washington, Hang and Miller (1986) was able to reduce irrigation water application rates to 40 and 50% of estimated ETc in mid-June to early July without impacting sugar yield on a loam soil, but sugar yields were reduced on a sandy soil when irrigation water application rates dropped below 85% of estimated ETc during the same time frame. Hills et al. (1990) found that deficit irrigation could be used late in the season before harvest as a means to reduce costs of added irrigations and to reduce harvest costs, but suggested that excessive water stress would reduce sucrose yield enough to reduce economic returns. It is possible that the differences between studies were in part due to differences in cumulative heat units, rainfall, and soil types. Soil types and heat units play a large role because they are associated with soil water storage and ETc rates.

Recent research evaluating modern sugarbeet varieties under deficit irrigation allocation strategies is limited. The objective of this study was to evaluate deficit irrigation water allocations on production factors of a common modern sugarbeet cultivar in Pacific Northwest sugarbeet production.

MATERIALS AND METHODS

Site Description

This study was conducted in 2011, 2012, and 2016 at the USDA-ARS Northwest Irrigation and Soils Research Laboratory in Kimberly, ID. The climate at Kimberly is arid, with average annual precipitation and alfalfa (*Medicago sativa* L.)-reference evapotranspiration of approximately 237 and 1443 mm, respectively. On average, about 36% of the annual precipitation occurs during the growing season, which extends from late April to mid-October (Bureau of Reclamation AgriMet System). The monthly precipitation during the study growing seasons is located in Table 1. The soil at the experimental site is a Portneuf silt loam (coarse-silty, mixed, superactive, mesic Durinodic Xeric Haplocalcid). There was no root restrictive layer down to 1.2 m (estimated sugarbeet rooting depth) at the research site. Plant available water was determined based on calculated water content at field capacity (0.32 m^3 m^{-3}) and water at permanent wilting point (0.14 m^3 m^{-3}).

Experimental Design

The study was conducted using a randomized complete block design with eight irrigation treatments and four replications. The irrigation treatments were a combination of irrigation amounts based on end of season cumulative model calculated ETc and irrigation timing. Irrigation for the treatments was applied three times a week with a surface drip irrigation system to match rates of ETc (approximately (≈)100% [W1], ≈ 65% [W2], and ≈ 40% [W3]). For the W2 and W3 water input rates, three water allocation timings were utilized (even, early, and late). For Even treatments, irrigation water was applied in amounts sufficient to meet accumulated ETc according to typical recommended practices. This required application on at least a week basis from emergence to mid-season and up to two to three times per week thereafter. Irrigation water was applied to the Early and Late treatments at the same times as to the Even treatments at their respective ETc rate percentages. For the Early and Late treatments, the dates for changing the rate of applied ETc were calculated based on historic ETc rates for sugarbeet grown at the study site. For each year of the study these change dates were similar. Table 2 shows growth stages that correspond to the change dates. Growth stages for sugarbeet used in this paper were defined by Fabeiro et al. (2003) and adjusted based on local data and experience. Sugarbeet exhibits a biennial growth habit so that during the first growing season only vegetative growth and root development take place. Reproductive stages take place during the second growing season after proper vernalization occurs in winter months. In sugar production cropping systems, the sugarbeet root is harvested after the first growing season. Early vegetative growth stages are well defined based on the number of leaves formed and are related to growing degree

Table 1. Ten-year mean precipitation and precipitation, mean air temperature, mean daily solar radiation, and reference evapotranspiration (ET) for the study growing seasons.

Year	Month	10-Year mean precipitation	Precipitation	Mean air temperature	Mean daily solar radiation	Mean daily reference ET
		mm		°C	MJ m^{-2}	mm
2011	May	31.0	48.5	10.5	21.5	5.08
	June	16.6	10.4	15.8	27.9	7.37
	July	7.7	1.8	21.5	29.2	8.38
	Aug.	7.7	4.6	21.9	24.8	7.37
	Sep.	5.1	1.0	17.8	20.4	5.84
	Oct.	24.6	27.2	10.2	12.1	2.79
2012	May	31.0	14.7	13.2	26.6	6.60
	June	16.6	2.8	17.9	29.8	8.64
	July	7.7	10.9	23.2	25.5	8.38
	Aug.	7.7	7.9	22.1	22.7	7.62
	Sep.	5.1	0.0	17.2	19.0	5.84
	Oct.	24.6	17.0	9.6	13.1	3.30
2016	May	31.0	39.1	13.2	21.7	5.59
	June	16.6	4.6	19.7	25.2	8.13
	July	7.7	6.4	21.5	26.0	8.64
	Aug.	7.7	0.8	20.5	22.3	7.37
	Sep.	5.1	59.4	15.0	15.3	4.32
	Oct.	24.6	74.7	10.6	9.8	2.79

Table 2. Study dates for growing stages of sugarbeet.

Stage	Duration range†	2011	2012	2016
Settling‡	1 Apr.–31 May	2–19 May	2–20 May	6–19 May
Development§	1 June–25 July	20 May –15 July	21 May–15 July	21 May–15 July
Swelling¶	26 July–31 Aug.	16 July–31 Aug.	16 July–31 Aug.	16 July–31 Aug.
Ripening#	1 Sept. to harvest	1 Sept.–14 Oct.	1 Sept.–3 Oct.	1 Sept.–6 Oct.

† Actual range of dates varies due to climate and location.

‡ Settling = planting to emergence.

§ Development = Vegetative development to full ground cover. Vegetation development is based on a vegetation leaf number index used by the sugar beet industry in the United States (Carlyle and Dexter, 1997). Full ground cover date was based on field observations.

¶ Swelling = Full ground cover to start of higher rate of sucrose accumulation. The date of start of higher rate of sucrose accumulation (1 Sept.) is an arbitrary date based on field/grower knowledge, not research data.

Harvest data can vary from end of September through October, based on contract harvest date and weather.

days (Carlyle and Dexter, 1997). Root development growth stages are not as well defined or referred to in U.S. sugarbeet production, thus the terms defined by Fabeiro et al. (2003) were used. Table 3 gives descriptions of the irrigation treatments. Experimental plots were 2.24 m wide by 12.19 m long, which accommodated four rows of sugarbeet.

Irrigation System and Irrigation Scheduling

The Kimberly–Penman ET model (Wright, 1982) estimates ETc by modeling alfalfa-reference ET from measured data from a local (Kimberly, ID) Agrimet weather station (U.S. Bureau of Reclamation, Boise, ID) and multiplying the reference ET by a crop coefficient (Kc) that varies through the season depending on the growth stage of the sugarbeet crop (Wright, 1982). The Kc values range from 0.22 at emergence, 1.0 at full cover, and 0.7 at harvest (U.S. Bureau of Reclamation, 2017) www.usbr.gov/pn/agrimet/cropcurves/BEETcc.html. Calculated ETc rates were based on non-water stressed conditions. Irrigation was applied to all treatments two to three times a week depending on ETc demand through the growing season and irrigation was adjusted to account for precipitation. To prevent runoff potential, irrigation frequencies were timed so individual irrigations did not exceed 8.6 mm.

Experimental plots were irrigated using a surface drip irrigation system that was installed immediately after sugarbeet emergence. The drip laterals were spaced every 0.56 m (every crop row in the plot) and were placed approximately 10 cm from the sugarbeet rows. Drip laterals were T-Tape (T-Systems); U.S. Model 508-06-670 with 8 mil thinwall dripperlines with emitters spaced every 15 cm and an inside diameter of 1.6 cm. The nominal flow of each emitter was 0.75 L h^{-1} at a nominal pressure of 55 kPa. Irrigation supply water was filtered using a FILTOMAT M100-750 hydraulic turbine self-cleaning filter (Amiad Filtration Systems). Irrigation water was supplied through a manifold instrumented with flowmeters, manual valves, and 70 kPa pressure regulators installed in the supply line to each plot. Irrigation depths and timing to each plot were controlled manually. Prior to installation of the drip irrigation system and implementation of the irrigation treatments, the entire experimental area was irrigated with 69, 104, and 16 mm of water from 6 to 19 May 2011, 11 to 24 May 2012, and 11 to 18 May 2016, respectively, using overhead sprinklers to ensure uniform sugarbeet emergence in all plots. These pre-emergence irrigations were not included in the seasonal ETa calculations.

Soil water balances (Evett et al., 2012) were used during and after the season to determine crop water use (ETa, Table 4). Actual crop ET was calculated as:

$$\mathrm{ETa} = \Delta S + P + I - R - \mathrm{DP} \quad [1]$$

where, ΔS is the change in soil water storage in the soil profile (1.07 m) between sugarbeet emergence and harvest, P is cumulative precipitation, I is cumulative irrigation, R is the net runoff and run on, DP is water percolating below the 1.07 root depth. All units are in millimeters. Precipitation was measured using a weather station located adjacent to the study area. Runoff did not occur during the study as a result of soil berms around each plot that contained all applied water. The DP was assumed to be zero based on soil water content being less than field capacity from emergence through harvest over the measured soil depth.

Table 3. Treatment name and description. To meet treatment estimated evapotranspiration crop evapotranspiration (ETc) requirements. The Kimberly–Penman ET model was used to calculate crop ETc (Wright, 1982) using data from an Agrimet weather station (U.S. Bureau of Reclamation, Boise, ID). Treatment actual crop water use values calculated from Eq. [1] are presented in Table 4.

Treatment	Target water input/ETc†	Treatment description
W1 Even	100	≈100% ETc applied throughout the growing season.
W2 Even	65	≈65% ETc applied throughout the growing season.
W2 Early	65	≈100% ETc from emergence to end of June (V6–V8), ≈55% ETc from end of June to harvest.
W2 Late	65	Rain-fed from emergence to end of July (swelling, 5–15 d past full cover), ≈100% ETc end of July to harvest.
W3 Even	35	≈40% ETc applied throughout the growing season.
W3 Early	35	≈100% ETc from emergence to end of June (V6–V8), ≈25% ETc from end of June to harvest.
W3 Late	35	Rain-fed from emergence to mid August (swelling, 35–40 d past full cover), ≈100% ETc mid-August to harvest.
Rain-fed	–	No post emergence irrigation.

† Irrigation was scheduled to match ETc at given percentages.

Cultural Practices

To determine crop nutrient needs, three soil cores (4.4 cm diam.) in 0.3 m increments to a depth of 0.6 m were taken each spring prior to planting across the study area. Soil samples were composited by depth increment. Soil samples were analyzed for nitrate N (NO_3–N) and ammonium N (NH_4–N) after extraction in 2 M KCl (Mulvaney, 1996) using a flow injection analyzer (Lachat Instruments, Loveland, CO). The 0 to 0.3 m soil samples were tested for sodium bicarbonate extractable P and exchangeable K concentrations (Olson et al., 1954). The study site was fertilized uniformly based on the University of Idaho recommendations. After fertilizer was applied, the study site was tilled using moldboard plow followed by roller harrowing and bedding.

Sugarbeet seed was planted on 2 May in 2011 and 2012 (cultivar Betaseed 27RR10), and on 6 May in 2016 (cultivar Betaseed 21RR25). The seeds for all years were treated with the insecticide Pancho Beta (60 g a.i. clothianidin [1-(2-Chloro-1,3-thiazol-5-ylmethyl)-3-methyl-2-nitroguanidine] and 8 g a.i. β-cyfluthrin {[(R)-cyano-[4-fluoro-3-(phenoxy)phenyl]methyl] (1R,3R)-3-(2,2-dichloroethenyl)-2,2-dimethylcyclopropane-1-carboxylate}per 100,000 seeds), and the fungicides Allegiance and Thiram. The crop was planted at 0.56 m row spacing at a seeding spacing of 76.2 mm. After planting, approximately 50 mm of water was uniformly applied to all plots using sprinklers to ensure even plant emergence. Following emergence, the entire study area was thinned by hand to a plant population of approximately 88,070 plants ha^{-1}.

To monitor treatment effects on soil water, volumetric soil water content at soil depths of 0 to 0.15, 0.15 to 0.30, 0.30 to 0.45, 0.45 to 0.61, 0.61 to 0.76, 0.76 to 0.91, and 0.91 to 1.07 m was measured using the neutron probe method (Evett and Steiner, 1995) on a week basis following plant emergence from three replications of each treatment. In 2012 and 2016, time domain reflectometry (TDR) probes were used as an additional measure of soil water content in the 0- to 0.15-m depth. Volumetric soil water measurements were multiplied by soil depth to obtain soil water depth. For each measurement date, soil water depths for each depth of measurement were summed over a depth of 1.07 m to determine total profile water content. A management allowable depletion (MAD) level of 55% was set as the depletion level of available water, above which (greater water depletion levels) would likely result in plant water stress (Jensen et al., 1990).

On 14 Oct. 2011, 3 Oct. 2012, and 6 Oct. 2016, roots in the center two rows of each plot were counted and harvested. Total root yield was determined from each plot using a load cell-scale mounted on the plot harvester. From each plot, two samples consisting of eight roots each were collected and sent to the Amalgamated Sugar Co. tare lab for analysis of root sucrose concentration and impurities. Root sucrose concentration was determined using an Autopol 880 polarimeter (Rudolph Research Analytical, Hackettstown, NJ), a half-normal weight sample dilution, and aluminum sulfate clarification method (ICUMSA Method GS6-3 1994) (Bartens, 2005). Conductivity was measured using a Foxboro conductivity meter Model 871EC (Foxboro, Foxboro, MA) and brei nitrate was measured using a multimeter Model 250 (Denver Instruments, Denver, CO) with Orion probes 900200 and 9300 BNWP (Krackler

Table 4. Study growing seasons soil water change (emergence-harvest), precipitation, irrigation, runoff, measured crop evapotranspiration (ETa), ETa/ETc (model calculated crop ET), and water input (irrigation + precipitation)/ETc for study irrigation treatments.

Year	Treatment	ΔS†	*P*	*I*	*R*	ETa	ETa/ETc‡	Water input/ETc
		mm					%	
2011	W1 Even	41	57	781	0	879	117	111
	W2 Even	97	57	450	0	604	80	67
	W2 Early	108	57	450	0	615	82	67
	W2 Late	77	57	450	0	584	78	67
	W3 Even	122	57	244	0	423	56	40
	W3 Early	145	57	244	0	446	59	40
	W3 Late	76	57	244	0	377	50	40
	Rain-fed	177	57	0	0	234	31	8
2012	W1 Even	–24	36	755	0	767	104	107
	W2 Even	96	36	444	0	576	78	65
	W2 Early	98	36	444	0	579	79	65
	W2 Late	38	36	444	0	518	70	65
	W3 Even	127	36	245	0	408	55	38
	W3 Early	134	36	245	0	415	56	38
	W3 Late	79	36	245	0	360	49	38
	Rain-fed	153	36	0	0	190	26	5
2016	W1 Even	83	89	686	0	857	111	100
	W2 Even	142	89	393	0	624	81	63
	W2 Early	152	89	393	0	634	82	63
	W2 Late	82	89	393	0	564	73	63
	W3 Even	140	89	214	0	444	58	39
	W3 Early	170	89	214	0	473	61	39
	W3 Late	105	89	214	0	408	53	39
	Rain-fed	178	89	0	0	268	35	12

† ΔS = soil water decrease (emergence-harvest), *P* = precipitation, *I* = irrigation, *R* = runoff.

‡ ETa/ETc × 100. ETc = ET calculated from the Kimberly–Penman ET model (Wright, 1982) to supply 100% of crop water requirement.

Scientific, Inc., Albany, NY). Recoverable sucrose yield per ton of roots was estimated by:

$$[(\text{extraction})\ (0.01)\ (\text{gross sucrose ha}^{-1})]/(\text{Mg ha}^{-1}), \text{ where extraction} = 250 + \{[(1255.2)\ (\text{conductivity}) - (15{,}000)\ (\text{percent sucrose} - 6185)]/[(\text{percent sucrose})\ (98.66 - [(7.845)(\text{conductivity})])]\} \text{ and gross sucrose} = \{[(\text{Mg ha}^{-1})\ (\text{percent sucrose})]\ (0.01)\}\ (1000\ \text{kg Mg}^{-1}). \qquad [2]$$

Recoverable sucrose yield will be referred to as estimated recoverable sucrose (ERS) in this paper.

Statistical Analyses

Analysis of variance and mean separation by the LSD method was conducted using Statistix 8 (Analytical Software, 2003). Significance was determined at the 0.05 significance level. Linear and quadratic regression models were used to describe relationships between dependent and independent variables.

RESULTS AND DISCUSSION

Differences in root yields and ERS yields across treatments were similar in 2011 and 2016. In 2011 and 2016, all production factors had significant treatment differences (Table 5). In 2012, only root and ERS yields had significant treatment differences. During all 3 yr, the 100% Even treatment had the greatest root and ERS yields. During all 3 yr the W2 Even and W2 Early treatments had similar root and ERS yields, and had greater yields than the W2 Late allocation treatment. The W2 Even and W2 Early treatments had 19.6, 25.0, and 24.1% greater root yields compared to the W2 Late treatment in 2011, 2012, and 2016, respectively. The W2 Even and W2 Early treatments had 31.6, 32.9, and 28.2% greater ERS yields compared to the W2 Late treatment in 2011, 2012, and 2016, respectively. In 2011 and 2016, the W3 Even and W3 Early treatments had greater ERS yields (43.6 and 35.2%, respectively) than the W3 Late treatment. However in 2012 there were no significant differences in ERS yields among W3 treatments. Root yield differences did not follow the same pattern for the W3 allocation treatments (W3 Even > W3 Early > W3 Late in 2011 and 2016, and W3 Even > W3 Early, W3 Even = W3 late, W3 Early = W3 Late in 2012). Yield differences followed the trend in ETc rates (Table 4). In 2011 and 2016, sucrose concentrations were lower for the W2 Late and W3 Late treatments compared to all other treatments (Table 5). However, in 2012 there were no significant differences in sucrose concentrations between treatments, although there were trends for differences similar to the significant differences that existed in 2011 and 2016 (Table 5). The effects of the treatments on brei nitrate

Table 5. Root yield, estimated recoverable sucrose (ERS) yield, brei nitrate concentration, and root sucrose concentration for study irrigation treatments. Analysis of variance effects of irrigation treatment for stated measurements.

Year	Treatment†	Root yield	ERS	Brei nitrate	Sucrose
		Mg ha^{-1}	kg ha^{-1}	mg kg^{-1}	%
2011	W1 Even	109.2a	13140a	517.0c	14.8a
	W2 Even	94.9b	11494b	519.1c	14.9a
	W2 Early	92.9b	10852b	550.8bc	14.5a
	W2 Late	75.5c	7644c	784.4ab	12.9b
	W3 Even	65.9d	7416c	542.1bc	14.0a
	W3 Early	55.0e	6635c	498.0c	14.7a
	W3 Late	44.9 f	3963d	879.5a	11.5c
	Rain-fed	22.5 g	2679e	464.3c	14.4a
	ANOVA				
	Treatment	<0.001	<0.001	0.016	<0.001
2012	W1 Even	81.0a	11351a	329.6	16.4
	W2 Even	71.1ab	9385b	232.6	15.4
	W2 Early	67.5b	9023b	230.6	15.6
	W2 Late	52.0c	6176c	442.3	14.0
	W3 Even	41.6cd	5391cd	245.1	15.1
	W3 Early	27.8e	3809d	177.9	15.9
	W3 Late	38.0de	3933d	517.3	12.7
	Rain-fed	0.6f	74e	276.8	14.5
	ANOVA				
	Treatment	<0.001	<0.001	0.518	0.890
2016	W1 Even	96.6a	14819a	132.9b	18.1a
	W2 Even	79.5b	11764b	162.9b	17.6ab
	W2 Early	75.0b	11679b	136.4b	18.2a
	W2 Late	58.6c	8420c	184.8b	17.1b
	W3 Even	54.9c	7531c	205.9b	16.3c
	W3 Early	46.0d	6204d	239.1b	16.1c
	W3 Late	36.7e	4379e	507.1a	14.4d
	Rain-fed	22.2f	2719f	409.8a	14.7d
	ANOVA				
	Treatment	<0.001	<0.001	<0.001	<0.001

concentration were not consistent over time. Overall, this data indicates that when managing deficit irrigation, the greatest reductions in yield occur when sugarbeet is stressed early in the season. Availability of water and reducing water stress early in the season was important to maximize yield under deficit water conditions. There may be an effect of water stress timing and sugarbeet N uptake/internal processing and sucrose production. However, with the difference in results between years, more research is needed to elucidate the effects of water amount and application timing on sugar and impurity accumulation.

It is hard to compare data from our study with those from other studies due to the variations in the deficit irrigation allocation treatments between studies. For example, Carter et al. (1980) irrigated beets at the same location as our study at 100% ETc until 15 July and 1August, then applied no more irrigation the remainder of the season. In a 1-yr study in Albacete Spain, Fabeiro et al. (2003) compared full irrigation with water deficits imposed during the development, swelling, and ripening stages. No root yield differences among water timing treatments were reported. The lack of yield response was likely due to there being sufficient soil water to meet water needs during the season. However, because the study was only conducted for 1 yr, if soil water status at the beginning of the season was highly variable in the growing area, different results could have been observed in years when soil water content was lower at the beginning of the season. Due to this lack of yield differences, the authors suggested choosing water strategies based on the highest water use efficiency. Davidoff and Hanks (1989) conducted a line source study near Logan, UT, where irrigation treatments (full to rain-fed) were determined by parallel distance from the line. Irrigation was terminated on 1 August or 4 September to assess mid- and late-season irrigation termination effects on sugarbeet yield. No yield differences between the two irrigation termination dates were observed. The lack of differences was attributed to sufficient soil water storage.

These referenced studies demonstrate that the amount of available water in the soil can greatly influence the response of sugarbeet to deficit irrigation inputs. Soil water measurements in our study helped in understanding the effects of treatments on production factors. Within each year, cumulative water application amounts for the W2 and W3 treatments were equal across all allocation timings

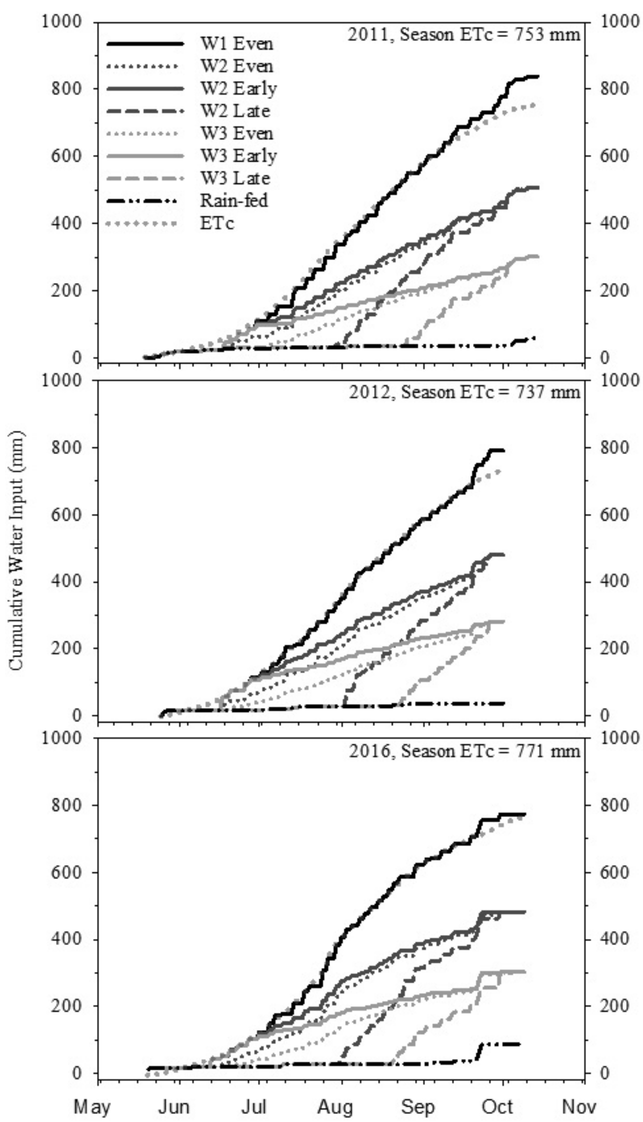

Fig. 1. Cumulative water (irrigation and precipitation) input of irrigation treatments over the study growing seasons.

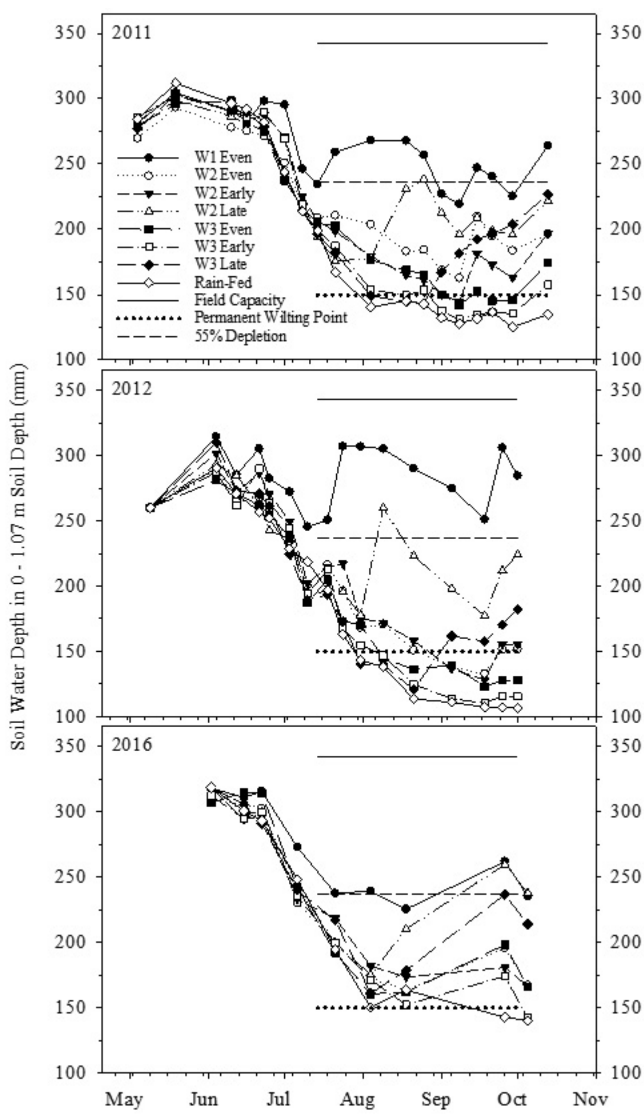

Fig. 2. Soil water depth of study irrigation treatments in the 0- to 1.07-m soil depth over the study growing seasons. Each point is the average of three treatment replications. Lines representing field capacity, permanent wilting point, and 55% depletion of available water are shown from dates of approximate full 1.07-m rooting depth to harvest.

(Table 4, Fig. 1). The only variation for each deficit treatment was the water allocation timing. The W1 Even treatment had the smallest change in soil water over the growing seasons for all treatments (Table 4). Generally, the soil water depth for the W1 Even treatment remained between field capacity (FC) and 55% depletion of available water throughout the period from end of the development stage (full canopy cover and estimated full rooting depth of 1.07 m) to harvest, indicating that the crop was grown under water stress-free conditions (Fig. 2). The deficit irrigation treatments had soil water depths less than the 55% depletion and permanent wilting point during this same period indicating the sugarbeets were likely under water stress. Actual crop ET for the Late treatments was less over most of the growing seasons compared to the Even and Early treatments (Fig. 3). At the end of each season the ETa difference between the Late and Early treatments decreased but did not catch up to the Early treatments (Fig. 3, Table 4). This data indicates that the degree of early season water stress and the inability of the crop's ETa to catch up can negatively affect yields.

Data suggests that severe water stress early in the season results in the inability to recover yield potential. Seasonal ETa within the W2 and W3 allocation treatments varied due to differences in soil water extraction (Table 4). The W2 Even and Early treatments had greater soil water extraction and similar ETa relative to the W1 Even treatment (Table 4, Fig. 3). The

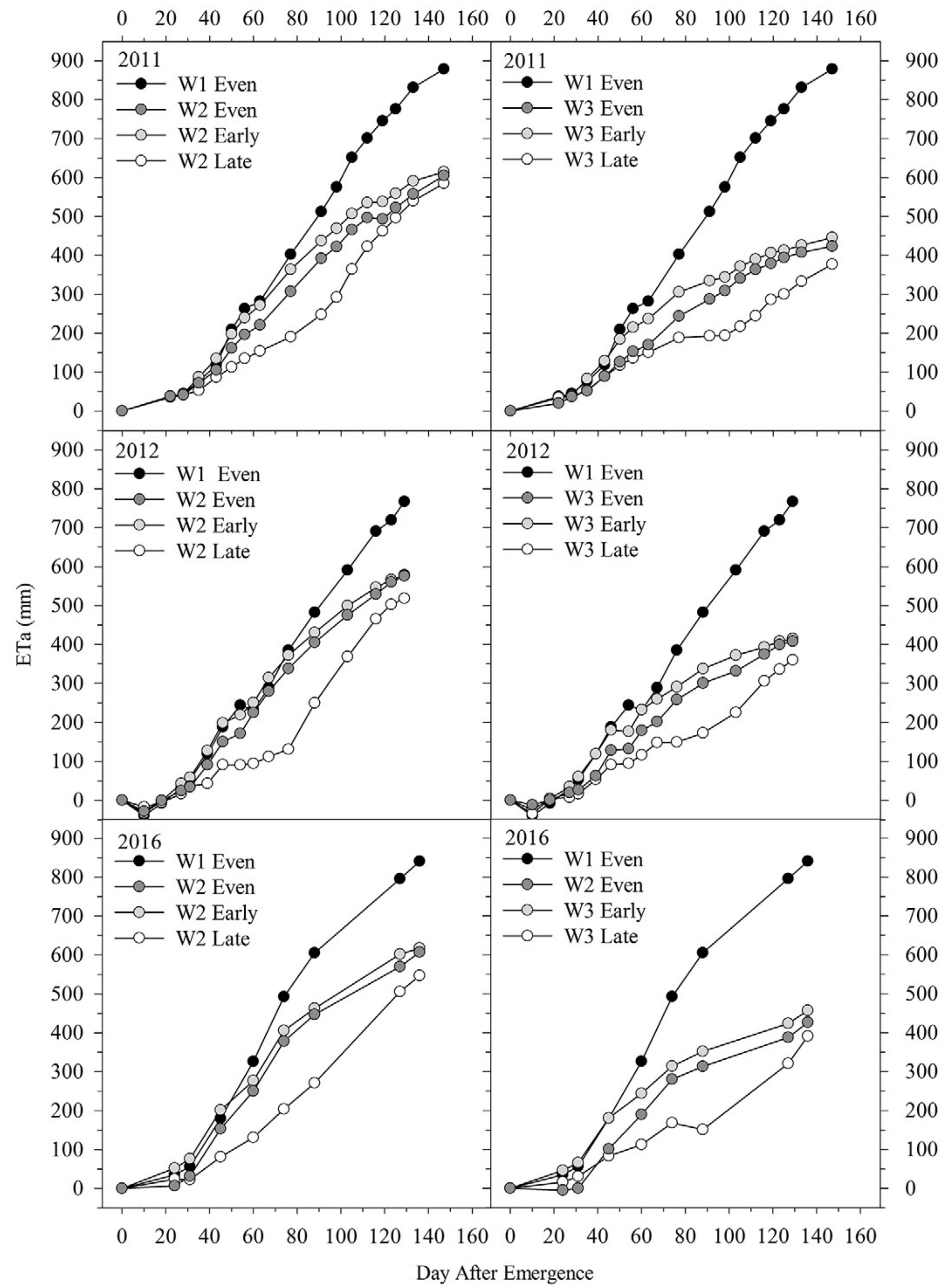

Fig. 3. Actual crop water evapotranspiration (ETa) over time for selected treatments.

ETa/ETc for the W2 Even and Early were 80 and 82% in 2011, 78, and 79% in 2012, and 81 and 82 in 2016, respectively. The W2 Late treatment had ETa/ETc values of 78, 70, and 73% in 2011, 2012, and 2016, respectively (Table 4). The same pattern was found in the W3 allocation treatments (Table 4). Changes in soil water based on the treatment water applications, especially the Late treatments, are noticeable in Fig. 2. However, the increased soil water content in the Late treatments did not result in rates of water uptake great enough to match the ETc of the Even and Early treatments (Fig. 3). This indicates that severe water stress early in the season resulted in less water use under equal cumulative water application depths, and yield potential which cannot be recovered by reducing water stress late in the season for this allocation treatment. It is possible that severe early season water stress results in plant physiological damage that cannot be recovered. One potential reason is a decrease in leaf area with severe water stress which decreased the photosynthetic rate. Leaf area was not measured in the study and would need to be evaluated to determine if this was a contributing factor. However, differences in plant size and soil cover were visually present. Linear relationships between ERS and root yields and ETa were evident all 3 yr (Fig. 4). The ERS yield increased at a rate of 17.3, 20.5, and 22.0 kg ha^{-1} mm^{-1} ETa in 2011, 2012, and 2016, respectively. Root yield increased at a rate of 0.139, 0.144, and 0.131 Mg ha^{-1} mm^{-1} ETa in 2011, 2012, and 2016, respectively. In general, for all years, yields for the W2 Even and Early treatments were greater per millimeter ETa than the average W2 Late treatments, based on the relationship of the treatment means relative to the linear regression models (Fig. 4). This pattern was also observed for the W3 treatments in 2011 and 2016, but not in 2012. This result was possibly the reason for the lack of yield differences between the W3 allocations in 2012 (Table 5). It was also noted that reference ET was greater and precipitation for May and June were lower in 2012 than in 2011 and 2016 (Table 1). These differences could explain partially why differences between some treatment results exist year to year. However, continued research is needed to help determine the exact reason(s) for these differences between treatments.

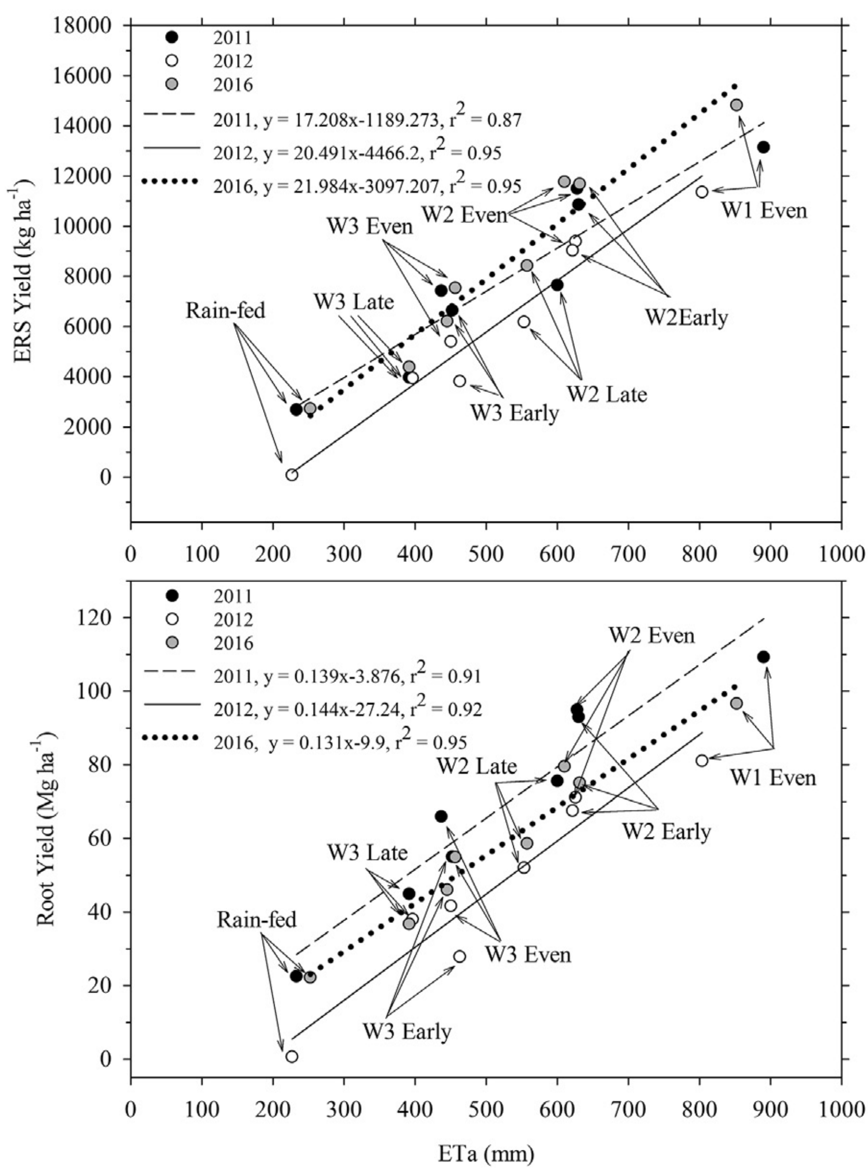

Fig. 4. Estimated recoverable sucrose (ERS) and root yields vs. actual crop water evapotranspiration (ETa).

CONCLUSIONS

Under seasonal deficit irrigation conditions on a deep silt loam soil with no root restrictive layers, supplying some irrigation water (either full or deficit) early in the growing season was important to maximize sugarbeet root and sucrose yield compared to causing too much water stress early and applying the water later in the season. For the W2 treatments (65% ETc), across all years of the study, even and early treatments increased root and sucrose yields by 23 and 31% compared the late treatment, respectively. Across all years, ERS yields increased at rates ranging from 17.3 to 22.0 kg ha^{-1} mm^{-1} ETa, and root yields increase at rates ranging from 0.131 to 0.144 Mg ha^{-1} mm^{-1} ETa. Greater water stress early in the season resulted in increased brei nitrate and decreased sucrose concentrations in roots. Severe water stress early in the season potentially resulted in decreased leaf area and rates of photosynthesis preventing reversal of yield loss even when water was supplied later in the season. Continued research could help determine the exact causes of this yield loss.

REFERENCES

Analytical Software. 2003. Statistix 8. Analytical Software, Tallahassee, FL.

Bartens, A. 2005. International commission for uniform methods of sugar analysis methods book 2005. Dr. Albert Bartens KG, Berlin. Elsevier, Amsterdam, the Netherlands. p. 431.

Carlyle, D.H., and A.G. Dexter. 1997. A growing degree day equation for early growth sugarbeet leaf stages. Sugarbeet Research and Extension Board of Minnesota and North Dakota. Sugarbeet Res. and Ext. Rep. 27:152–157.

Carter, J.M., M.E. Jensen, and D.J. Traveller. 1980. Effect of mid- to late-season water stress on sugarbeet growth and yield. Agron. J. 72:806–815. doi:10.2134/agronj1980.00021962007200050028x

Davidoff, B., and R.J. Hanks. 1989. Sugar beet production as influenced by limited irrigation. Irrig. Sci. 10:1–17.

Du, T., S. Kang, J. Zhang, F. Li, and X. Hu. 2006. Yield and physiological responses of cotton to partial root-zone irrigation in the oasis field of northwest China. Agric. Water Manage. 84:41–52. doi:10.1016/j.agwat.2006.01.010

Erie, L.J., and O.F. French. 1968. Water management of fall-planted sugar beets in Salt River Valley of Arizona. Trans. ASAE 11:792–795. doi:10.13031/2013.39524

Evett, S.R., R.C. Schwartz, J.J. Casanova, and L.K. Heng. 2012. Soil water sensing for water balance ET and WUE. Agric. Water Manage. 104:1–9. doi:10.1016/j.agwat.2011.12.002

Evett, S.R., and J.L. Steiner. 1995. Precision of neutron scattering and capacitance type soil water content gauges from field calibration. Soil Sci. Soc. Am. J. 59:961–968. doi:10.2136/sssaj1995.03615995005900040001x

Fabeiro, C., F. Martin de Santa Olalla, R. Lopez, and A. Dominguez. 2003. Production and quality of the sugar beet (*Beta vulgaris* L.) cultivated under controlled deficit irrigation conditions in a semi-arid climate. Agric. Water Manage. 62:215–227. doi:10.1016/S0378-3774(03)00097-0

Hang, A.N., and D.E. Miller. 1986. Responses of sugarbeet to deficit, high frequency sprinkler irrigation. I. sucrose accumulation, and top and root dry matter production. Agron. J. 78:10–14. doi:10.2134/agronj1986.00021962007800010003x

Hills, F.J., S.R. Winter, and D.W. Henderson. 1990. Sugarbeet. In: B.A. Stewart and D.R. Nielsen, editors, Irrigation of agricultural crops. Agron. Monogr. 30. ASA, Madison, WI. p. 795–810.

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

Kang, S., W. Shi, and J. Zhang. 2000. An improved water-use efficiency for maize grown under regulated deficit irrigation. Field Crops Res. 67:207–214. doi:10.1016/S0378-4290(00)00095-2

Mulvaney, R.L. 1996. Nitrogen-inorganic forms. In: D.L. Sparks, editor, Methods of soil analysis. Part 3. Chemical methods. SSSA and ASA, Madison, WI. p. 1123–1184.

Olson, S.R., C.V. Cole, F.S. Watanabe, and L.A. Dean. 1954. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. USDA Circular 939:1–19. U.S. Gov. Print. Office, Washington, DC.

O'Neill, P.M., J.F. Shanahan, J.S. Schepers, and N. Caldwell. 2004. Agronomic responses of corn hybrids from different eras to deficit and adequate levels of water and nitrogen. Agron. J. 96:1660–1667. doi:10.2134/agronj2004.1660

Payero, J.O., S.R. Melvin, S. Irmak, and D. Tarkalson. 2006. Yield response of corn to deficit irrigation in a semiarid climate. Ag. Water Manage. 84:101–112. doi:10.1016/j.agwat.2006.01.009

Payero, J.O., D.D. Tarkalson, S. Irmak, D. Davison, and J.L. Petersen. 2008. Effect of irrigation amounts applied with subsurface drip irrigation on corn evapotranspiration, yield, water use efficiency, and dry matter production in a semiarid climate. Ag. Water Manage. 95:895–908. doi:10.1016/j.agwat.2008.02.015

Pettigrew, W.T. 2004. Moisture deficit effects on cotton lint yield, yield components, and boll distribution. Agron. J. 96:377–383. doi:10.2134/agronj2004.0377

Tang, L., Y. Li, and J. Zhang. 2005. Physiological and yield responses of cotton under partial rootzone irrigation. Field Crops Res. 94:214–223. doi:10.1016/j.fcr.2005.01.005

U.S. Bureau of Reclamation. 2017. Pacific Northwest Region AgriMet crop coefficients: Beets. U.S. Bureau of Reclamation. www.usbr.gov/pn/agrimet/cropcurves/BEETcc.html (accessed 19 June 2017).

Wen, Y., D.L. Rowland, G. Piccinni, J.T. Cothren, D.I. Leskovar, A.R. Kemanian, and J.D. Woodard. 2013. Lint yield, lint quality, and economic returns of cotton production under tranditional and regulated deficit irrigation schemes in Southwest Texas. J. Cotton Sci. 17:10–22.

Wright, J.L. 1982. New evapotranspiration crop coefficients. Journal of Irrigation and Drainage Division. Proc. of the Am. Soc. of Civil Eng. J. Irr. Drain. Div. 108:57–74.

Yonts, D.C., K.L. Palm, and D.L. Reichert. 2003. Late season irrigation management for optimum sugarbeet production. J. Sugar Beet Res. 40:11–28. doi:10.5274/jsbr.40.1.11

Yonts, D.C. 2011. Development of season long deficit irrigation strategies for sugarbeets. Am. Soc. of Sugar Beet Technologists Annual Meeting Proceedings. http://assbt-proceedings.org/ASSBT2011Proceedings/Agronomy/Yonts.pdf (accessed 19 June 2017). doi:10.5274/ASSBT.2011.14

Zhang, B., F.-M. Li, G. Huang, Z. Cheng, and Y. Zhang. 2006. Yield performance of spring wheat improved by regulated deficit irrigation in an arid yield. Agric. Water Manage. 79:28–42. doi:10.1016/j.agwat.2005.02.007