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Yield production functions of irrigated sugarbeet in an arid climate

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ABSTRACT

Increased water demands and drought have resulted in the need to provide data to guide deficit water management decisions in irrigated sugarbeet (*Beta vulgaris* L.) production. The objective of this study was to quantify the yield response of sugarbeet to water input and actual crop evapotranspiration (ETa) on a soil type (silt loam) common to sugarbeet production in the Northwest U.S. These relationships are valuable to understanding sugarbeet response over a range of water availability and in developing tools to assess future production under water shortages. This paper consolidates data from three studies consisting of ten site-years from 2009 to 2016. The studies were at the USDA-Agricultural Research Service facility in Kimberly, ID on a Portneuf silt loam soil. Treatments consisted of varying levels of cumulative seasonal Kimberly-Penman ET model estimated crop evapotranspiration (ETc) rates ranging from rain-fed to 125% of ETc. Irrigation methods consisted of surface drip irrigation (3 site-years), linear/pivot overhead sprinkler (6 site-years), and solid-set sprinkler (1 site-year). Irrigation frequency was consistent for all studies with applications occurring 2–3 times per week depending on ETc demand. Estimated recoverable sucrose (ERS) yield and root yield were measured, and soil water contents were measured. Across all site-years, quantitative relationships between both actual crop ET (ETa) and water input, and sugarbeet yield and quality variables were developed. Significant (0.05 probability level) positive linear relationships were found between ETa and sugarbeet ERS and root yields ($r^2 = 0.78$). Estimated recoverable sucrose and root yields increased at rates of 19.4 kg ha^{-1} mm^{-1} ETa and 0.13 Mg ha^{-1} mm^{-1} ETa, respectively. When ETa depths of 719 and 729 mm were reached by the crop, root and ERS yields were maximized, respectively. When water input (irrigation + precipitation) depths of 598 and 605 mm were applied root and ERS yields were maximized, respectively. The quantitative relationships between both ETa and water input, and sugarbeet yields can be used to quantify sugarbeet production under deficit irrigation conditions (data derived from pivot/linear, drip, and solid set irrigation types), which may arise due to water shortage scenarios, or when drought occurs in non-irrigated areas.

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1. Introduction

Increased water demand from agriculture and non-agricultural sectors, variable regional and seasonal precipitation, and increased irrigation costs have resulted in concerns about water supplies and availability for irrigation in arid Northwestern U.S. regions. As a result, science is being relied on to determine how to allocate limited water supplies. Water stress negatively affects plant physiology and metabolism (Zhu, 2002). The severity of water stress on plant function can range from mild to severe depending on the degree and extent of the stress (Jaleel and Llorente, 2009). Water deficits can limit growth and influence a host of physiological functions in plants to a greater extent than any other environmental factor (Cattivelli et al., 2008; Jaleel and Llorente, 2009). Thus, considerable research effort has been undertaken to improve crop production under deficit water conditions (Wang et al., 2003; Cattivelli et al., 2008).

Determining quantitative relationships between sugarbeet yields, and water input and water use variables is vital to develop tools to evaluate and guide sugarbeet deficit irrigation management decisions. In recent years numerous research studies have focused on developing these relationships in other crops such as corn (*Zea mays* L.), alfalfa (*Medicago sativa* L.), potatoes (*Solanum tuberosum* L.), dry bean (*Phaseolus vulgaris* L.), and spring wheat (*Triticum aestivum* L.) (Robins and Domingo, 1953; Benoit et al., 1965; Hanks et al., 1976; Barrett and Skogerboe, 1978; Gilley et al., 1980; Hill et al., 1982); Schneekloth et al., 1991; Stone, 2003; Klocke et al., 2004; Payero et al., 2006; Payero et al., 2008). Several studies have evaluated various effects of deficit irrigation in sugarbeets

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Table 1
Selected experimental and cultural information for irrigation types.

Study	Site-Years	ETc[†] Treatments % ETc	Other Treatment[§]	Previous Crops	Seeding Rate plant ha^{-1}	Fertilizer Recommendations	Plot Size m^2	Plot Harvest Area m^2
Solid Set	2009	R-F, 25, 50, 75, 100, 125	–	Barley	128,000	University of Idaho/Amalgamated Sugar Co.	29.7	10.2
Drip	2011, 2012, 2016	R-F[‡], 35, 65, 100	–	Barley	128,000	University of Idaho/Amalgamated Sugar Co.	29.7	10.2
Linear	2012, 2013, 2015	25, 50, 75, 100	ST, CT	Barley	128,000	University of Idaho/Amalgamated Sugar Co.	275.4	84.7

[†] ETc = ET estimated from the Kimberly-Penman ET model (Wright, 1982).
[‡] R-F = Rain-fed.%ETc for R-F treatments ranged from 5 to 12%.
[§] Other treatment included in analysis; ST = Strip Tillage, CT = Conventional Tillage.

Table 2
Average daily values of alfalfa reference evapotranspiration (ETr), minimum air temperature (T_{min}), maximum air temperature (T_{max}), average air temperature (T_{avg}), solar radiation (Rs), relative humidity (RH), and wind speed at 2-m height (μ_2) during site-year growing seasons in Kimberly, ID.

Year	Month	ETr	T_{min}	T_{max}	T_{avg}	Rs	RH	μ_2
		mm d^{-1}	°C	°C	°C	MJ m^{-2} d^{-1}	%	m s^{-1}
2009	April	4.2	1.3	14.0	7.6	20.8	61.1	3.2
	May	6.2	6.0	21.7	14.1	25.8	54.8	2.6
	June	6.1	10.2	23.3	16.5	23.9	68.0	2.3
	July	8.6	13.3	30.9	22.0	29.2	52.3	2.2
	August	6.6	11.2	28.6	19.9	23.7	55.0	2.0
	September	5.7	8.9	26.9	17.8	19.7	48.1	2.3
	October	2.5	1.2	13.2	6.9	12.8	70.1	2.7
	Average	**5.7**	**7.5**	**22.7**	**15.0**	**22.3**	**58.5**	**2.5**
2011	April	3.5	0.4	11.6	5.8	17.9	66.0	3.4
	May	5.0	4.4	17.0	10.5	21.5	65.5	3.0
	June	7.4	8.2	23.2	15.8	27.9	55.7	2.8
	July	8.5	12.7	30.1	21.5	29.3	48.7	2.0
	August	7.4	12.7	31.3	21.9	24.8	45.7	1.9
	September	5.7	8.5	27.2	17.8	20.3	47.3	2.1
	October	2.7	3.7	17.1	10.1	12.0	63.8	2.4
	Average	**5.8**	**7.2**	**22.5**	**14.8**	**22.0**	**56.1**	**2.5**
2012	April	5.1	3.0	18.3	10.6	21.7	50.3	3.2
	May	6.7	5.5	20.7	13.2	26.5	47.9	3.0
	June	8.7	8.8	25.9	17.9	29.8	42.0	2.7
	July	8.3	15.1	31.8	23.2	25.4	48.7	2.1
	August	7.7	12.7	31.6	22.1	22.6	44.5	2.2
	September	5.7	7.7	26.9	17.2	19.0	44.0	2.2
	October	3.3	2.1	17.5	9.7	13.1	51.8	2.4
	Average	**6.5**	**7.8**	**24.7**	**16.3**	**22.6**	**47.0**	**2.6**
2013	April	4.5	1.0	14.8	8.0	18.3	53.1	3.8
	May	6.3	5.7	21.5	13.8	22.1	48.6	3.1
	June	8.0	9.8	27.3	19.1	25.0	45.1	2.7
	July	8.6	14.2	33.2	23.9	23.3	43.1	2.2
	August	7.6	13.0	32.1	22.7	21.5	42.4	2.3
	September	4.8	9.9	23.8	16.5	14.7	60.2	2.7
	October	2.9	0.5	15.6	7.7	11.8	57.8	2.6
	Average	**6.1**	**7.7**	**24.0**	**15.9**	**19.5**	**50.1**	**2.8**
2015	April	4.9	1.1	16.5	8.9	19.6	47.5	3.6
	May	5.1	6.9	21.0	13.6	19.8	63.7	2.7
	June	8.1	12.3	29.6	21.4	25.5	46.6	2.3
	July	7.5	12.8	29.3	21.0	22.4	52.7	2.3
	August	6.7	12.1	29.9	20.9	19.8	50.4	2.2
	September	5.0	7.7	25.8	16.6	17.1	49.9	2.1
	October	3.1	5.8	20.7	12.8	11.3	63.1	2.3
	Average	**5.8**	**8.4**	**24.7**	**16.4**	**19.4**	**53.4**	**2.5**
2016	April	4.5	3.8	18.5	11.1	18.2	58.1	3.2
	May	5.5	5.9	20.6	13.2	21.7	59.9	2.8
	June	8.1	10.4	28.5	19.7	25.2	46.5	2.5
	July	8.5	11.6	30.7	21.5	26.0	43.1	2.3
	August	7.4	10.5	30.1	20.5	22.3	42.4	2.2
	September	4.4	7.8	22.3	15.0	15.3	58.0	2.5
	October	2.8	4.3	18.2	10.6	9.8	68.0	2.5
	Average	**5.9**	**7.8**	**24.1**	**16.0**	**19.8**	**53.7**	**2.6**

(Erie and French 1968; Carter et al., 1980; Hang and Miller, 1986; Hills et al., 1990; Fabeiro et al., 2003; Yonts et al., 2003; Yonts, 2011). However, only a few have evaluated the relationships between sugarbeet yields and ETa and/or water input (Draycott and Messem, 1977; Hang and Miller, 1986; Davidoff and Hanks, 1989). Davidoff and Hanks (1989) conducted the only study in the U.S. (Logan, UT). Updated and additional research is needed to develop relationships between sugarbeet yields and water input and water use variables in the Northwest U.S. The Northwest U.S. is a major sugarbeet production area in the U.S. (30–40% of production) and relies on irrigation to optimize production for economically sustainable production (USDA-NASS, 2016).

The objective of this study was to quantify the yield response of sugarbeet to water input and actual crop evapotranspiration (ETa) on a soil type common to sugarbeet production in the Northwest U.S.

2. Materials and methods

Data from three studies consisting of ten site-years from 2009 to 2016 was utilized in this analysis (Table 1). All studies were conducted at the USDA-ARS Northwest Irrigation and Soils Research Laboratory in Kimberly, ID. Readers are referred to the original papers for detailed method descriptions (Tarkalson et al., 2014; Tarkalson and King, 2017a,b). A brief description of the studies is presented here; Table 1 contains selected study details.

The climate at Kimberly, ID is arid, with average annual precipitation and alfalfa-reference evapotranspiration of approximately 237 and 1443 mm, respectively (10-yr average). On average, about 36% (85 mm) of the annual precipitation occurs during the growing season, which extends from late April to mid-October (Bureau of Reclamation AgriMet System). The climatic data for each year of the study is located in Table 2. The soil at the experimental site is a Portneuf silt loam (coarse-silty, mixed, superactive, mesic Durinodic Xeric Haplocalcids). The soil at each study site had no restrictive root layer to a depth of at least 2.4 m. The soil profile was well drained with a saturated hydraulic conductivity of 3.2 cm h^{-1}. Available water holding capacity was 0.2 cm available water per cm soil depth (USDA, 2009).

The three studies differed based on irrigation system; surface drip, linear sprinkler, and solid set sprinkler. In each study water was applied to match various rates of estimated model evapotranspiration (ETc) (Table 1). The model utilized for ETc calculation was the Kimberly-Penman ET model (Wright, 1982). The model estimates ETc by modeling alfalfa-reference ET from measured data from a local 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, www.usbr.gov/pn/agrimet/cropcurves/BEETcc.html). The weather station is located within 3 miles of the research site. Rates of ETc were based on non-water stressed conditions. In all the studies, irrigation was applied to all treatments 2–3 times a week depending on ETc demand through the growing season and irrigation was adjusted to account for precipitation (precipitation was collected at the research site using calibrated rain gages).

Within each study, the irrigation treatments were replicated four times in randomized block designs, or split plot designs (refer to original publications for details: Tarkalson and King, 2017a,b; Tarkalson et al., 2014). All other cultural practices for each site-year were conducted based on accepted research protocols (soil sampling, fertilization, seed treatments, seeding rates, tillage, herbicide applications, pesticide applications, etc.). Sugarbeet were planted in late April to early May and harvested in early to mid-October. Plot sizes and harvest areas are listed in Table 1. The roots in the center two rows of each study plot were counted and harvested to determine root yield and estimated recoverable sucrose yield (ERS).

Actual seasonal crop evapotranspiration (ETa) was estimated based on seasonal soil water balances as (Evett et al., 2012):

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

Where, ΔS is the change in soil water storage in the soil profile (1.2 m) between sugarbeet emergence and harvest, P is cumulative precipitation, I is cumulative irrigation, R is the difference between runoff and run on, DP is water percolating below the root depth. All units are in mm. Precipitation was measured at the research site in each replication. For two years in the Linear Study (Tarkalson and King, 2017a), R was measured. Runoff was minimal and did not have a significant effect on ETa. Thus, R was estimated in the other site-years. 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.

The yield response factor (Ky) was established by FAO to assess the relative yield reduction in relation to the relative ET reduction (Smith and Steduto, 2012):

$$Ky = \frac{1 - Ya/Ym}{1 - ETa/ETm}$$

Where, Ky is the yield response factor. Ya is the actual root and ERS yield, Ym is the maximum root and ERS yield, ETa is the actual evapotranspiration, and ETm is the maximum evapotranspiration. In general, Ky values greater than 1 indicate that crop response in sensitive to water stress (larger proportional reductions in yield when water use is reduced), Ky values less than 1 indicate that crop response in not as sensitive to water stress (less proportional reductions in yield when water use is reduced), and Ky equal to 1 when reduction in yield is directly proportional to reduction in water use. Sugarbeet has a published average Ky book value of 1 (Smith and Steduto, 2012).

Soil water in the 0–0.3 m depth was continuously measured at 30 min intervals using time domain reflectometry (TDR) probes with factory calibration (TDR100, Campbell Scientific Inc. Logan, UT) and stored on a data logger (CR1000, Campbell Scientific Inc. Logan, UT). From 0.3–1.2 m, the neutron probe method (Evett and Steiner, 1995) was used to measure soil water content. The neutron probe (CPN Instrotek 503, Conord, CA) was calibrated to site soil with a R^2 of 0.89. Volumetric soil water measurements were multiplied by soil depth to obtain soil water depth. Plant available water was determined based on estimated water content at field capacity (0.32 m^3 m^{-3}) and water at permanent wilting point (0.14 m^3 m^{-3}). A management allowable depletion (MAD) level of 55% (0.1 m^3 m^{-3}) was set as the depletion level above which the crop would be water-stressed (Jensen et al., 1990).

Regression equations were developed in Sigma Plot 13.0 (Systat Software Inc.) to describe the response of the dependent variables (ERS and root yields) to independent variables (ETa and

Table 3
Estimated model crop evapotranspiration (ETc) and growing season precipitation for the study site years.

Year	ETc[†]	Growing Season Precipitation	Growing Season Precipitation/ETc
	mm	mm	%
2009	756	123	16
2011	816	57	7
2012	733	36	5
2016	759	72	10
2013	751	51	7
2015	681	68	10

irrigation + precipitation); and between dependent variables (ERS and root yield reductions) to independent variables (ETa and irrigation + precipitation). Yield reductions were determined by comparing treatment yields with maximum yield within each site-year study:

$$\%\text{Yield Reduction} = \text{Yield}/\text{Max Yield} \times 100 \tag{2}$$

3. Results and discussion

The average annual rainfall across study period growing seasons was 64 mm, while the average ETc for sugarbeet was 748 mm (Table 3). Precipitation during the growing season represented an average of 8.6% (64 mm) of sugarbeet ETc, highlighting the importance of irrigation in this arid production system.

Water production functions (WPF), i.e. the relationships between yields (ERS and root), and ETa and water inputs (irrigation + precipitation) across all site-years are shown in Fig. 1. The WPFs are defined in the paper as follows:

ERS-ETa WPF = ERS yield vs. ETa

RY-ETa WPF = Root Yield vs. ETa

ERS-IP WPF = ERS yield vs. water input (irrigation + precipitation)

RY-IP WPF = Root ERS yield vs. water input (irrigation + precipitation)

Water production functions (ERS-ETa WPF and RY-ETa WPF) were fit to linear regression models, and ERS-IP WPF and RY-IP WPF were fit to quadratic regression models. The results of the regression models are shown in Fig. 1. The data from all site-years were combined in the regression analysis because there were little visual differences between site-year WPFs. In order to obtain a robust average response across sources of variability (year, location, and irrigation type) the data – was combined across these sources of variability. All regression analyses were significant at the 0.05 probability level. The linear ERS-ETa WPF and RY-ETa WPF in sugarbeet were also observed by Davidoff and Hanks (1989) and Groves and Bailey, (1997) from studies conducted in Logan, Utah and Nottinghamshire, England, respectively. In our studies, year to year precipitation was not highly variable, so we were able to control total water input in the production system through irrigation. Thus, the year to year variability associated with ERS-ETa WPF and RY-ETa WPF was reduced. The r^2 values for ERS-ETa WPF

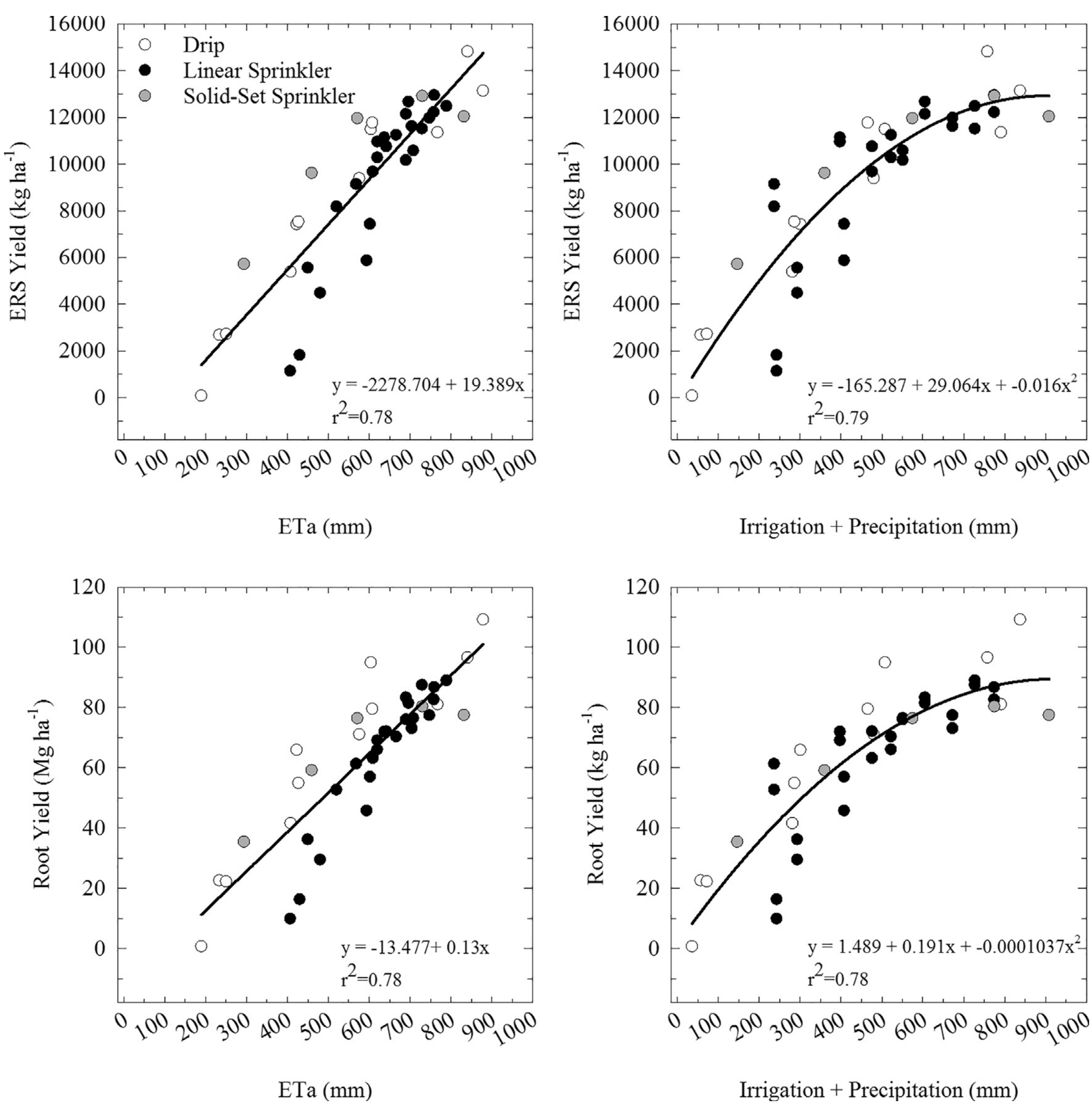

Fig. 1. Relationships between ERS and Root Yields, and water input for three studies (total of 7 site years). ETa is the actual measured crop evapotranspiration and Irrigation + Precipitation was measured as an accumulation over the growing season. Each value is the average of four treatment replications for a given year and study.

and RY-ETa WPF were both 0.78. The r^2 values for the quadratic ERS-IP WPF and RY-IP WPF were 0.79 and 0.78, respectively. Similar linear relationships with corn (*Zea mays* L.), alfalfa (*Medicago sativa* L.), potatoes (*Solanum tuberosum* L.), dry bean (*Phaseolus vulgaris* L.), and spring wheat (*Triticum aestivum* L.) have been observed (Robins and Domingo, 1953; Benoit et al., 1965; Hanks et al., 1976; Barrett and Skogerboe, 1978; Gilley et al., 1980; Hill et al., 1982); Schneekloth et al., 1991; Stone, 2003; Klocke et al., 2004; Payero et al., 2006; Payero et al., 2008). The ERS-IP WPF and RY-IP WPF resulted in a quadratic regression model fit with a downward curvature due to increasing inefficiencies of water application for plant transpiration as water input approaches the maximum yield point (Trout and DeLonge, 2015). On a field scale, water input inefficiencies are due to increasing water losses from canopy and soil evaporation, wind drift, deep percolation due to non-uniform water application, and decreasing utilization of precipitation and soil moisture (Evans and Sadler, 2008). In this study, the inefficiencies are largely due to wind drift and surface evaporation with the sprinkler systems, and decreased utilization of precipitation and soil moisture storage with increasing water input for all irrigation systems.

A measure of average water use efficiencies (WUE, yield/depth of water input or use) in the system can be observed from the slopes of the linear regression models; sugarbeet ERS increased by 19.4 kg ha^{-1} mm^{-1}, root yield increased by 0.13 Mg ha^{-1} mm^{-1} across the range of ETa in our studies (Fig. 1). The root yield increase of 0.13 Mg ha^{-1} mm^{-1} derived from our studies was over two times higher than that reported by Groves and Bailey (1997) who measured 0.058 Mg ha^{-1} mm^{-1}. However, Davidoff and Hanks (1989) calculated that ERS increased by an estimated 18–19 kg ha^{-1} mm^{-1}, which is similar to the WUE in our studies (19.4 kg ha^{-1} mm^{-1}). Based on the limited studies for sugarbeet, climate and cultivar may play an important role in the WUE of sugarbeet. These regression models can be used in system production models where sugarbeets are part of the system and water supplies are a factor.

For climate and soil of the study location, about 104 and 118 mm of ETa is required to obtain the first unit of root and ERS yield, respectively (Fig. 1). About 8 mm of water input is needed to

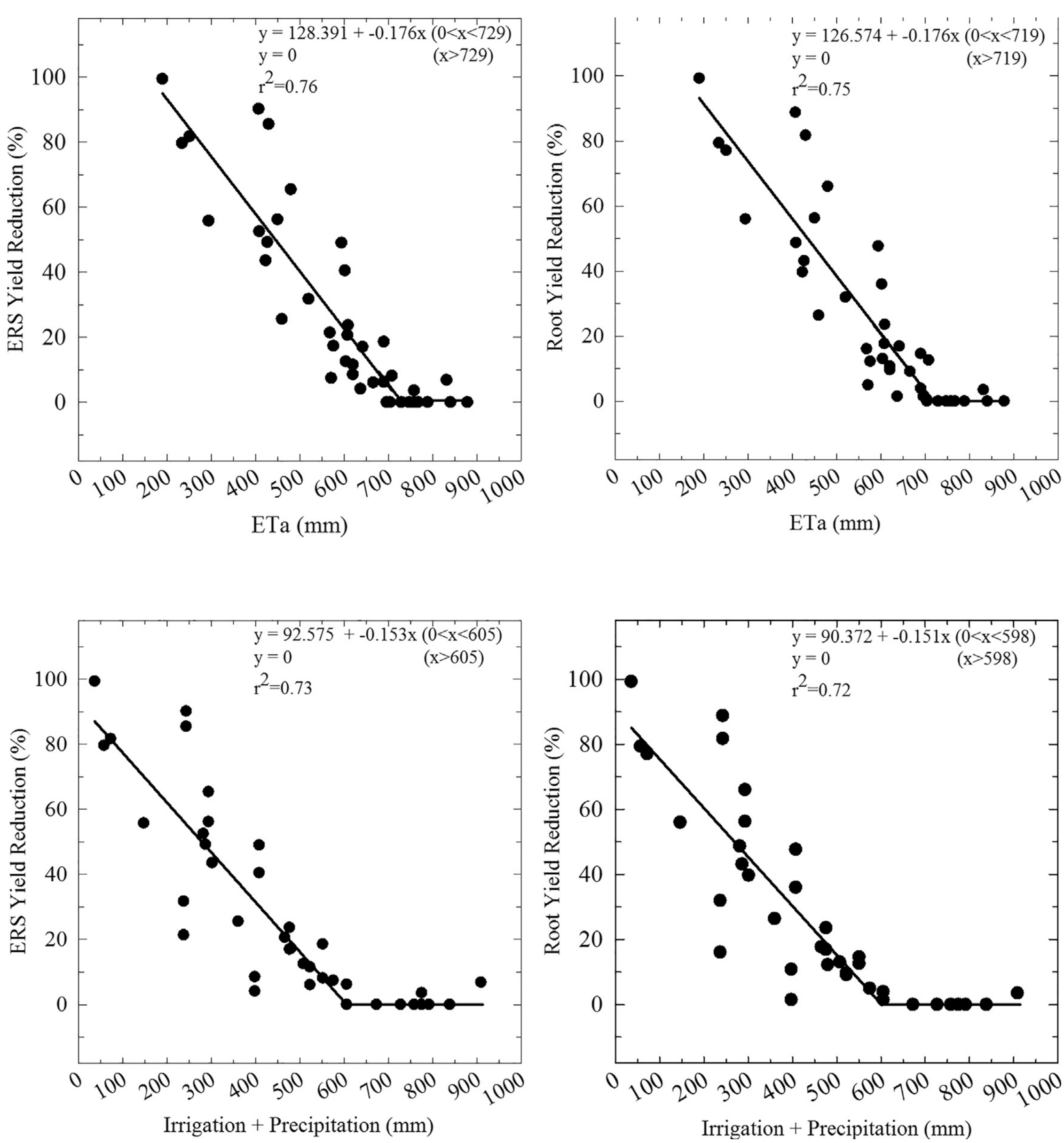

Fig. 2. Relationships between water use efficiency (WUE) and water input for three studies (total of 7 site years). ETa is the actual measured crop evapotranspiration and Irrigation + Precipitation was measured as an accumulation over the growing season. Each value is the average of four treatment replications for a given year and study.

obtain the first increment of root yield (Fig. 1). The negative value of water input indicates that initial stored soil moisture during those study years was sufficient to obtain the first unit of root yield if the crop germinates in the arid climate. About 6 mm of water input is needed to obtain the first increment of ERS yield. The slopes of the first 100 mm of water input for the ERS-IP and RY-IP WPFs (23.6 kg ha^{-1} mm^{-1} and 0.16 Mg ha^{-1} mm^{-1}) are greater than the slopes of the ERS-ETa and RY-ETa WPFs (19.4 kg ha^{-1} mm^{-1} and 0.13 Mg ha^{-1} mm^{-1}) indicating that initial water inputs are extremely important for crop establishment and good vegetative growth needed to obtain maximum crop production for any level of amount of water inputs. When water input is approximately 300 mm the slope of the RY-ETa and RY-IP WPFs, and the ERS-ETa and ERS-IP WPFs are about equal ($\approx$0.13 Mg RY ha^{-1} mm^{-1}, and 19 kg ERS ha^{-1} mm^{-1}, respectively) above which the slope of IP WPFs continually decreases to zero at maximum yield.

Other research has shown a higher degree of temporal variation for the relationship between yields and water input. Payero et al. (2006) described much of the year to year variability in their study with corn on differences in soil water content at emergence and the amount and distribution of in-season precipitation. In our study, growing season precipitation contributed less than 10 percent of crop ETa, limiting the variation precipitation between study years can have on yield. Additionally, in each study year the crop was sprinkler irrigated to ensure good emergence and initial vegetative growth further limiting the effect variable precipitation on

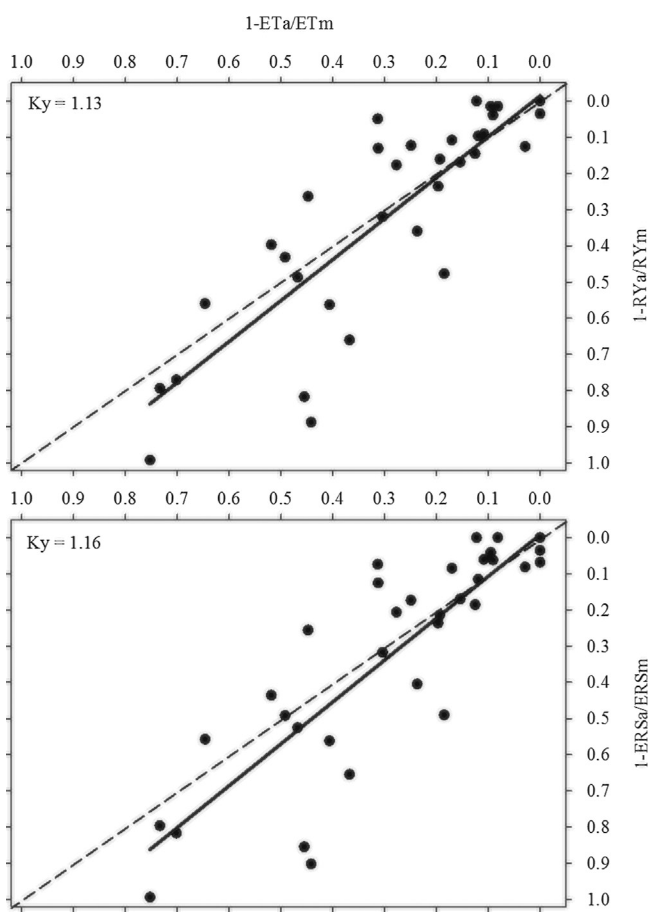

Fig. 3. Yield response factors (Ky) determined from the relationships between seasonal relative ET deficit (1-ETa/ETm) and relative root yield and ERS yield declines (1-Ya/Ym). The slope of the linear relationships (solid line) = Ky. The dashed line represents a Ky of 1, the FAO published Ky value for sugarbeet (Smith and Steduto, 2012).

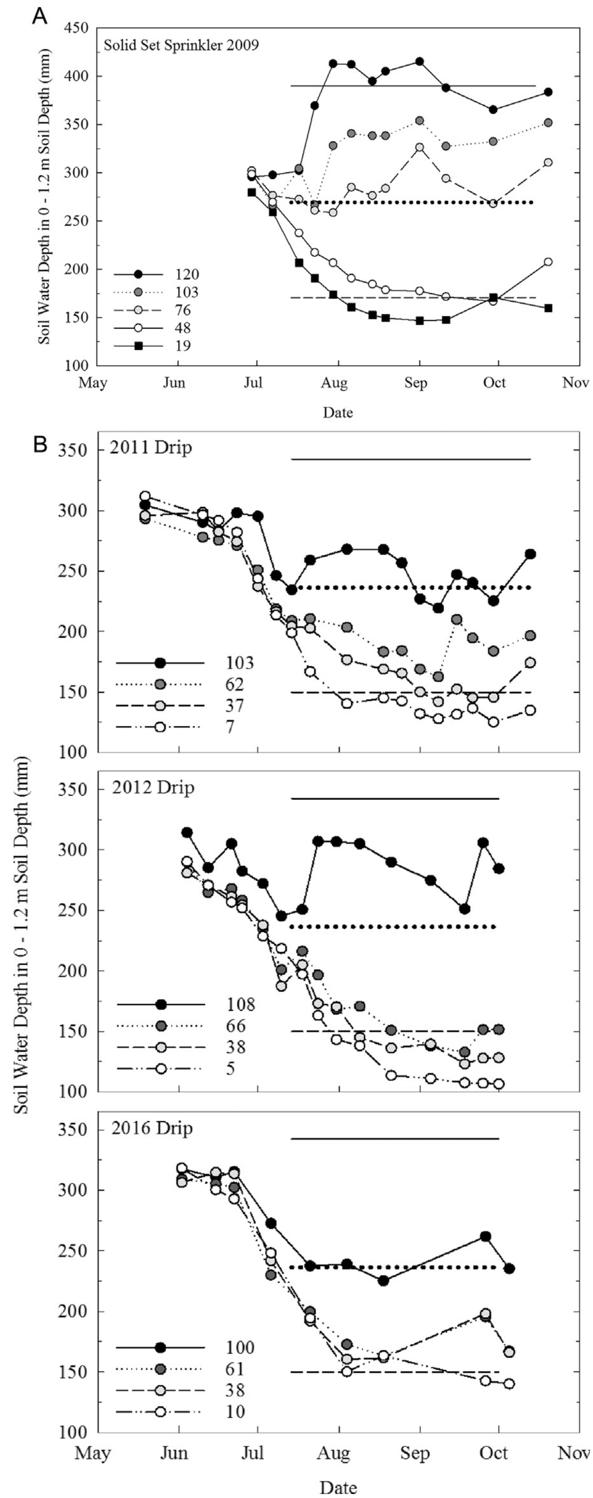

Fig. 4. a Soil water depth of irrigation treatments (Water Input/ETa) in the 0–1.2 m soil profile in the solid-Set sprinkler study. Each point is the average of two treatment replications. Horizontal lines represent field capacity (solid), permanent wilting point (dashed), and 55% depletion of available water (dotted) are shown from dates of approximate full 1.2 m rooting depth to harvest. b Soil water depth of irrigation treatments (Water Input/ETa) in the 0–1.2 m soil profile in the drip study. Each point is the average of two treatment replications. Horizontal lines represent field capacity (solid), permanent wilting point (dashed), and 55% depletion of available water (dotted) are shown from dates of approximate full 1.2 m rooting depth to harvest. c Soil water depth of irrigation treatments (Water Input/ETa) in the 0–1.2 m soil profile in the linear sprinkler study. Each point is the average of two treatment replications. Horizontal lines represent field capacity (solid), permanent wilting point (dashed), and 55% depletion of available water (dotted) are shown from dates of approximate full 1.2 m rooting depth to harvest.

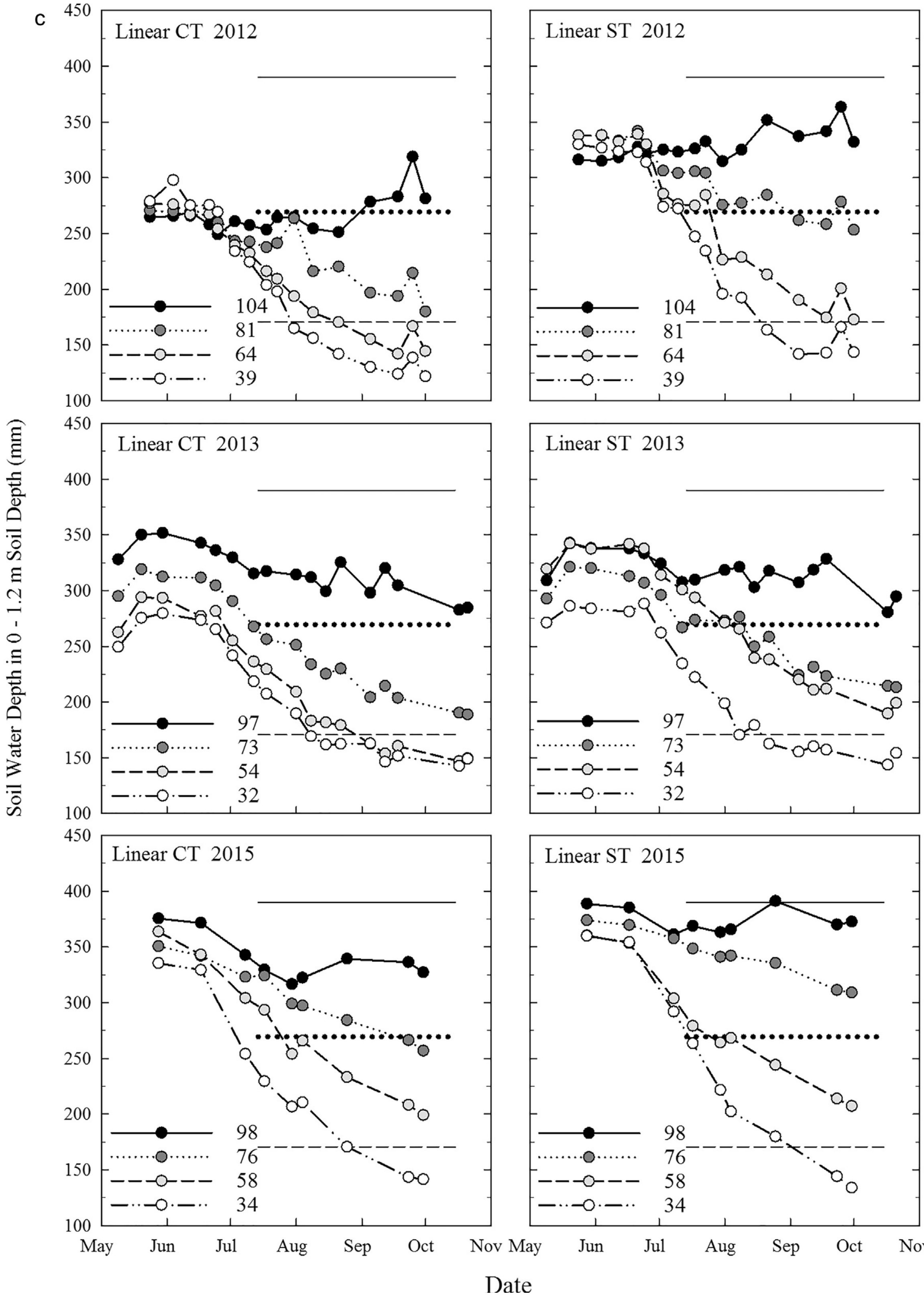

Fig. 4. (*Continued*)

crop yield. In our study, across all site years, the soil water content in the 0–1.2 m depths at emergence averaged 308 mm, with a range of 260–380 mm with a median depth of 304 mm. The range of water depth at emergence in the 1.2 m depth of the Portneuf silt loam was 249–388 mm (mean = 306 mm) (Fig. 4). Because most soil water depths at emergence were mostly in the range between field capacity and 55% of available water (269–390 mm) at emergence, relationships between yields at given water input rates across years for each study were similar (Fig. 1). In this study the relationships between yields, and ETa and water input were similar for the different irrigation systems (Fig. 1).

Relationships between reduction in yields (ERS and root), and ETa and water inputs across all site-years are shown in Fig. 2. The data were fit to linear plateau models. The r^2 values for the linear portion of the relationships between yields (ERS and root) and ETa were 0.76 and 0.75, respectively. The r^2 values for the linear portion of the relationships between yields (ERS and root) and water input were 0.73 and 0.72, respectively. Sugarbeet ERS yield was reduced at a rate of 0.18% mm^{-1} to an ETa of 729 mm, and root yield was reduced by the same 0.18% mm^{-1} to an ETa of 719 mm. ETa rates higher than 729 and 719 mm resulted in no further reduction in ERS and root yield, respectively. Sugarbeet ERS yield was reduced at a rate of 0.15% mm^{-1} to a water input of 605 mm, and root yield was reduced by the same 0.15% mm^{-1} to a water input of 598 mm (Fig. 2). Water inputs higher than 605 and 598 mm resulted in no further reduction in ERS and root yield, respectively. These limits in ETa and water input will give irrigation guidance to growers and to prevent over irrigation in areas with similar climate and soils.

The root and ERS response factors (Ky) of 1.13 and 1.16, respectively, were similar to the standard FAO Ky of 1 for sugarbeet (Fig. 3). The Ky factors were not significantly different than the standard FAO Ky value of 1 (the 95% confidence interval for the slope of the relationship included a Ky of 1). The r^2 values for the linear relationships were both 0.77. A Ky value of 1 indicated that sugarbeet yield reduction is proportional to the reduction in water use. The FAO Ky category descriptions indicate that sugarbeet are neither tolerant or excessively sensitive to water stress.

Soil water depths over time in the 0–1.2 m depth for all site-years are shown in Fig. 4a–c . The treatment keys for the figures are detailed in Table 4. Across all site years, soil water depth was related to water availability, the greater the water availability (greater water input) more soil water was present through the growing season. Water inputs closer to ETc resulted in less change in soil water over the growing seasons. In general, the soil water depth in plots where ETa and yield were at maximums remained between FC (field capacity) and 55% depletion of available water throughout the growing season. The greater reduction in water input, the greater difference in soil water over the season. During some years, water input/ETc at approximately 75% and greater remained between FC (field capacity) and 55% depletion of available water throughout the growing season. At lower water inputs and ETa (deficit irrigation), soil water depths were often below than the 55% depletion and in some cases below the permanent wilting point (PWP)

Table 4
Irrigation, precipitation, and crop water use data for irrigation studies.

Study	Year	Other Treatment†	Water Input/ETc‡	Irrigation + Precipitation	ETa§	ETa/ETc
			%	mm	mm	%
Solid Set	2009	–	120	909	832	110
			103	775	730	97
			76	575	571	76
			48	360	459	61
			19	147	294	39
Drip	2011	–	103	838	879	108
			62	507	604	74
			37	301	423	52
			7	57	234	29
	2012	–	108	791	767	105
			66	480	576	79
			38	281	408	56
			5	36	190	26
	2016	–	100	758	841	111
			61	466	608	80
			38	286	427	56
			10	72	251	33
Linear	2012	CT	104	775	758	102
			81	605	696	93
			64	476	609	82
			39	293	450	60
	2013	CT	97	727	729	97
			73	551	708	94
			54	408	594	79
			32	243	407	54
	2015	CT	98	673	747	108
			76	522	666	97
			58	398	620	90
			34	237	520	76
	2012	ST	104	775	759	102
			81	605	690	93
			64	476	642	86
			39	293	480	64
	2013	ST	97	727	789	105
			73	551	690	92
			54	408	602	80
			32	243	430	57
	2015	ST	98	673	704	102
			76	522	620	90
			58	398	637	93
			34	237	568	82

† CT = Conventional Tillage, ST = Strip Tillage.
‡ ETc = ET estimated from the Kimberly-Penman ET model (Wright, 1982). Values are listed in Table 3.
§ ETa = Actual measured crop evapotranspiration.

during much of the growing season after full cover. The general crop PWP of −1.5 MPa was assumed as the PWP for sugarbeet to establish the estimated plant available water range (Cabelguenne and Debaeke, 1998). However, the sugarbeet crop survived when soil water depth was below the PWP depth. Potential reasons for this result are that the sugarbeet crop was extracting water from a greater depth than measured and/or the general crop PWP is lower than the volumetric soil water content of 0.14 m^3 m^{-3}. The results indicate that the amount of available water in the soil at the beginning of the season greatly influences the response of sugarbeet to deficit irrigation inputs as sugarbeet can extract water to 2.4 m and soil water potentials below −1.5 MPa assumed permanent wilting point (unpublished data).

These results were based on sugarbeet growth in a deep silt loam soil with minimal precipitation during the growing season. Results could be different in sand based soils and shallow soils. Future research would be necessary to assess similar objectives in sandy and shallow soils.

4. Conclusions

For ten site-years of data on a common silt loam soil, there were strong linear relationships between root and ERS yields with ETa, and quadratic relationships between root and ERS yields with water input. Reductions in root and ERS yields leveled off after ETa depths of 719 and 729 mm, respectively. Reductions in root and ERS yields were leveled off after water input depths of 598 and 605 mm, respectively. Evidence suggests that sugarbeet can extract water from a greater depth than was measured and/or the PWP for sugarbeet is lower than for other crops. These results were based on sugarbeet growth in a deep silt loam soil. Results could be different in sand based soils and shallow soils. The quantitative relationships developed from this study can be used to develop tools to evaluate and guide sugarbeet irrigation management from full to deficit conditions.

References

Barrett, J.W.H., Skogerboe, G.V., 1978. Effect of irrigation regime on maize yields. J. Irrig. Drain. Div. 104, 179–194.

Benoit, G.R., Hatfield, A.L., Ragland, J.L., 1965. The growth and yield of corn. III. Soil moisture and temperature effects. Agron. J. 57, 223–226.

Cabelguenne, M., Debaeke, P., 1998. Experimental determination and modelling of the soil water extraction capacities of crops of maize sunflower, soya bean, sorghum and wheat. Plant Soil 202, 175–192.

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

Cattivelli, L., Rizza, F., Badeck, F.W., Mazzucotelli, E., Mastrangelo, A.M., Francia, E., Mare, C., Tondelli, A., Stanca, A.M., 2008. Drought tolerance improvement in crop plants: an integrated view from breeding to genomics. Field Crops Res. 105, 1–14.

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

Draycott, A.P., Messem, A.B., 1977. Response by sugar beet to irrigation, 1965–75. J. Agric. Sci. 89, 481–493.

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

Evans, R.G., Sadler, E.J., 2008. Methods and technologies to improve efficiency of water use. Water Resour. Res. 44, W00E04, http://dx.doi.org/10.1029/2007ER006200.

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

Evett, S.R., Schwartz, R.C., Casanova, J.J., Heng, L.K., 2012. Soil water sending for water balance, ET and WUE. Agric. Water Manag. 104, 1–9.

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

Gilley, J.R., Watts, D.G., Sullivan, C.Y., 1980. Management of Irrigation Agriculture with a Limited Water and Energy Supply. Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln, pp.168.

Groves, S.J., Bailey, R.J., 1997. The influence of sub-optimal irrigation and drought on crop yield, N uptake and risk of N leaching from sugarbeet. Soil Use Manag. 13, 190–195.

Hang, A.N., Miller, D.E., 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.

Hanks, R.J., Keller, J., Rasmussen, V.P., Wilson, G.D., 1976. Line source sprinkler for continuous variable irrigation-crop production studies. Soil Sci. Soc. Am. J. 40, 426–429.

Hill, R.W., Hanks, R.J., Wright, J.L., 1982. Crop Yield Models Adapted to Irrigation Scheduling Programs. Research Report 99. USDA-ARS and Utah State University, Logan, UT.

Hills, F.J., Winter, S.R., Henderson, D.W., 1990. Sugarbeet. In: Stewart, B.A., Nielsen, D.R. (Eds.), Irrigation of Agricultural Crops. Agronomy No. 30. American Society of Agronomy, Madison, WI, pp. 795–810.

Jaleel, C.A., Llorente, B.E., 2009. Drought stress in plants: a review on water relations. Biosci. Res. 6, 20–27.

Jensen, M.E., Burman, R.D., Allen, R.G., 1990. Evapotranspiration and irrigation water requirements. In: ASCE Manuals and Reports on Engineering Practices No. 70. American Society of Civil Engineers, New York, NY.

Klocke, N.L., Schneekloth, J.P., Melvin, S., Clark, R.T., Payero, J.O., 2004. Field scale limited irrigation scenarios for water policy strategies. Appl. Eng. Agric. 20, 623–631.

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

Payero, J.O., Tarkalson, D.D., Irmak, S., Davison, D., Petersen, J.L., 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. Agric. Water Manag. 95, 895–908.

Robins, J.S., Domingo, C.E., 1953. Some effects of severe soil moisture deficit at specific growth stages in corn. Agron. J. 45, 618–621.

Schneekloth, J.P., Klocke, N.L., Hergert, G.W., Martin, D.L., Clark, R.T., 1991. Crop rotations with full and limited irrigation and dryland management. Trans. ASAE 34, 2372–2380.

Smith, M., Steduto, P., 2012. Yield response to water: the original FAO water production function. In: Steduto, P., Hsiao, T.C., Fereres, E., Faes, D. (Eds.), Crop Yield Response to Water. Food and Agricultural Organization of the United Nations, Rome, Italy, pp. 6–13.

Stone, L.R., 2003. Crop water use requirements and water use efficiencies. In: Proceedings of the 15th Annual Central Plains Irrigation Conference and Exposition Colby, Kansas, February 4–5.

Tarkalson, D.D., King, B.A., 2017a. Effects of tillage and irrigation management on sugarbeet production. Agron. J. 109, 2396–2406.

Tarkalson, D.D., King, B.A., 2017b. Effect of deficit irrigation timing on sugarbeet. Agron. J. 109, 2119–2127.

Tarkalson, D.D., Eujayl, I., Beyer, W., King, B.A., 2014. Drought tolerance selection of sugarbeet hybrids. J. Sugar Beet Res. 51, 14–30.

Trout, T.J., DeLonge, K.C., 2015. Does deficit irrigation of field crops increase water productivity? In: ASABE/IA Symposium: Emerging Technologies for Sustainable Irrigation, Paper No. 152143372, St. Joseph, Mich, pp. 1–7, http://dx.doi.org/10.13031/irrig.20152143372.

USDA, 2009. Web Soil Survey, http://websoilsurvey.nrcs.usda.gov/app/ (Accessed 04 April 2017).

USDA-NASS, 2016 Online: https://www.nass.usda.gov/Quick_Stats/ (Accessed 20 September 2017).

Wang, W., Vinocur, B., Altman, A., 2003. Plant response to drought: salinity and extreme temperatures: towards genetic engineering for stress tolerance. Planta 218, 1–14.

Wright, J.L., 1982. New evapotranspiration crop coefficients. J. Irrig. Drain. Div. 108, 57–74.

Yonts, D.C., Palm, K.L., Reichert, D.L., 2003. Late season irrigation management for optimum sugarbeet production. J. Sugar Beet Res. 40, 11–28.

Yonts, D.C., 2011. Development of season long deficit irrigation strategies for sugarbeets. ASSBT Annual Meeting Proceedings, http://assbt-proceedings.org/ASSBT2011Proceedings/Agronomy/Yonts.pdf (Accessed 20 September 2017).

Zhu, J.K., 2002. Salt and drought stress signal transduction in plants. Ann. Rev. Plant Biol. 53, 247–273.