EVALUATION OF CANOPY TEMPERATURE BASED CROP WATER STRESS INDEX FOR DEFICIT IRRIGATION MANAGEMENT OF SUGAR BEET IN SEMI-ARID CLIMATE

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Research

HIGHLIGHTS

- Sugar beet irrigation scheduling was based on daily average crop water stress index between 13:00 and 16:00 hours.
- Three crop water stress index thresholds, 0.2, 0.35, and 0.55, were evaluated for irrigation scheduling.
- Season evapotranspiration decreased and soil water extraction increased as crop water stress threshold increased.
- There was no significant difference in root or sucrose yield between full irrigation and 0.2 crop water stress index, while seasonal irrigation depths were reduced from133 to 185 mm.

ABSTRACT. *Sugar beet is an economically important crop in the semi-arid Intermountain Western U.S., with seasonal water use ranging from 500 to 900 mm. Sugar beet is a deep-rooted crop (1.5-2 m) in unrestricted soil profiles that can utilize stored soil water to reduce seasonal irrigation requirements. Effective use of stored soil water below 0.6 m requires precise irrigation scheduling and knowledge of soil water availability below 0.6 m, which is usually unknown due to the labor and expense of soil water monitoring at deeper depths and uncertainty in effective rooting depth and soil water holding capacity. Deficit irrigation (DI) management of sugar beet using a thermal-based crop water stress index (CWSI) has the potential to overcome soil water monitoring limitations and facilitate the utilization of stored soil water to reduce seasonal irrigation requirements. The objective of the research summarized in this paper was to implement and evaluate the effect of automated DI scheduling of sugar beet using three daily average CWSI thresholds (0.2, 0.35, and 0.55) on seasonal irrigation requirement, crop evapotranspiration, seasonal soil water depletion, root yield, estimated recoverable sugar (ERS) yield, and water use efficiency compared to full irrigation. There were no significant differences in root and ERS yield between full irrigation and 0.2 CWSI DI treatment, while seasonal ET was significantly decreased, seasonal soil water extraction was significantly increased, and seasonal irrigation depths were reduced from 133 to 185 mm. Root and ERS yield water production functions were curvilinear with a downward concave. Root and ERS yield water use efficiencies were constant or increased slightly for crop evapotranspiration reductions up to 85% of full irrigation evapotranspiration. The results indicate that irrigating when the average daily CWSI sugar beet exceeds 0.2 is an effective means for mild deficit irrigation scheduling to reduce seasonal irrigation requirements with no significant effect on root and ERS yield.*

Keywords. *Crop water stress index, Evapotranspiration, Irrigation, Irrigation scheduling, Root yield, Sucrose yield, Sugar beet.*

Water resources in the western U.S. are experiencing unprecedented competitive demand from irrigated agriculture, growing urban populations, and environmental and ecosystem restoration. Groundwater levels in many areas have steadily decreased from historic levels and ground water use is approaching an unsustainable level. In addition, the western U.S. is experiencing the worst megadrought since 800 CE (Williams et al., 2022) leading to historically low water levels in many of the regions water reservoirs. Warmer winter temperatures due to climate change are predicted to reduce future mountain snowpack volume and duration (Mote et al., 2018; Marshall et al., 2019), which is the water source of early irrigation developments in much of the western U.S. The growing demand on surface and groundwater resources combined with climate change necessitates increased water resource stewardship and crop water productivity to meet food and fiber needs of a growing population.

Sugar beet is an economically important crop in the semi-arid Western U.S. (Calif., Colo., Idaho, Mont., Ore., and Wyo.) and comprises about 27% of the total U.S production, or 124,300 ha (USDA-NASS, 2017) with seasonal evapotranspiration (ET_c) ranging from 500 to 900 mm (U.S Bureau of Reclamation, https://www.usbr.gov/pn/agrimet/)

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depending upon growing season length. Sugar beet is a deep-rooted crop (1.5-2 m) in unrestricted soil profiles that can readily utilize stored soil water to reduce seasonal irrigation requirements (King et al., 2019). Additionally, sugar beet is a moderately drought-tolerant crop due to the capacity for osmotic adjustments within the plant and the long vegetative growth stage without a sensitive flowering period (Dunham, 1993; Martin et al., 2007). Water stress in sugar beet is first seen as leaf wilt during the highest evapotranspiration period of the day. If the period of leaf wilt is a relatively small portion of the entire day and the leaves fully hydrate at night, the effect on root yield is minimal, but when leaf wilt occurs over longer periods of the day, carbohydrate production in the leaves is reduced, which decreases the rate of root growth and sucrose storage (Martin et al., 2007).

Deficit irrigation (DI) is when the irrigation water applied to a crop is less than required to meet full crop water requirements, resulting in ET_c less than the maximum crop ET_c. For a few crops, irrigation is intentionally reduced to attain a desired plant response and/or yield product characteristic such as reduced vegetative growth, increased fruit quality and value, induce maturity, or facilitate harvest. This intentional reduction in irrigation is often referred to as regulated DI, or RDI (Chai et al., 2015). Regardless of the objective, DI usually results in reduced yield. Additionally, DI may occur due to unforeseen irrigation water delivery interruptions from system malfunctions or imposed by management due to regulatory seasonal irrigation water use restrictions or water availability under drought conditions. Knowledge of crop yield response to DI is required to realize the desired outcome from DI and make appropriate irrigation management decisions.

The crop water production function (WPF) defines the relationship between crop yield or value and the amount of water used or applied to a crop. The WPF varies with crop, variety, growth stage, climate, soil, and management practices (Trout et al., 2020). Another measure of crop water productivity, defined as either the yield or net income per unit of water used by the crop, is known as crop water use efficiency (CWUE). Like the WPF, CWUE varies with climate, crop, variety, soil, irrigation method, and water management practices but can also vary with crop input parameters, including fertilizer and chemicals (Djaman and Irmak, 2012). The WPF can be linear or a curvilinear concave downward function of yield versus water applied or ET_c (Trout and DeJonge, 2017). When the WPF is curvilinear, the unit of yield per unit of ET_c or water applied (CWUE) varies with the total amount of water applied, or ET_c. This causes CWUE to increase as the amount of water applied or ET_c decreases below full irrigation until the slope of the WPF is greater than one. This occurs because water application efficiency increases as water application decreases due to less deep percolation, runoff, evaporation losses from irrigation, and more effective use of precipitation. The increase in CWUE with less water application implies that DI may be a way to maximize net return per unit of irrigation water. When the WPF is linear, CWUE is constant, and there is no economic benefit from DI (Trout and DeJonge, 2017).

Effective irrigation water management requires optimum timing of water application and applying an amount of water that replaces ET_c or some fraction of ET_c when practicing DI. Conventional soil water balance-based irrigation scheduling relies on tracking estimated crop evapotranspiration, maintaining a continual numerical soil water balance, and irrigating when available soil water is forecasted to reach a predetermined lower limit based on crop characteristics or an established lower threshold for DI, known soil water holding capacity, and known effective crop root zone depth. Often, soil water holding capacity and crop root zone depth are unknown and estimated. Soil water content monitoring is necessary to periodically validate/adjust the numerical soil water balance to minimize calculation errors introduced by the use of generalized ET crop coefficients and estimated and variable water application inefficiency (Werner, 1993; Ashley et al., 1996; Jones, 2004; Melvin and Yonts, 2009).

Irrespective of the shape of the WPF, mild DI may increase the use of stored off-season precipitation and reduce seasonal irrigation water requirements. Effective use of stored soil water requires precise irrigation scheduling, considering available soil water below 0.6 m, especially for deep-rooted crops such as sugar beet. Soil water monitoring can be achieved using a variety of techniques, with various tradeoffs among them. Regardless of the selected technique, there will be a cost for the equipment, labor for installation, maintenance, and removal, and a cost in terms of the time required for the irrigation manager to interpret the data. Ultimately, the irrigation manager needs fundamental knowledge of soil-water-plant relationships to transform soil water content data into an effective DI scheduling decision. For example, the conversion of volumetric soil water content values into available soil water based on site-specific soil-water characteristics, crop effective rooting depth, and the critical soil water availability threshold of the crop. Most soil water measurement techniques have small sampling volumes (Muñoz-Carpena, 2004), which requires multiple soil water sampling sites to reliably quantify soil water content at the field scale for irrigation scheduling (Zotarelli et al., 2013; Li et al., 2020). However, equipment and labor costs limit the number of measurement sites in practice.

Many features of a plant's physiology respond directly to changes in water status in the plant tissues rather than to changes in the bulk soil water availability (Jones, 2004). For example, plant canopy temperature increases when solar radiation is absorbed and cools when water is evaporated (transpiration) within the leaf structure. A water-stressed plant canopy will reduce transpiration and have a higher temperature than a non-stressed canopy (Raschke, 1960; Tanner, 1963). Infrared radiometers have been used to measure plant canopy temperature under field conditions to estimate evapotranspiration and drought stress in many crops (Idso et al., 1981; Jackson et al., 1981; Hatfield, 1983; Maes and Steppe, 2012). Infrared thermometry is nondestructive, can be measured continuously, can be mounted on mobile platforms for spatial and temporal monitoring (Sadler et al., 2002; Nayak, 2005), and can be less expensive (Mahan and Yeater, 2008) than soil water sensing. Plant canopy temperature can be influenced by abiotic factors other than soil water availability as well as biotic factors such as disease (DeJonge et al., 2015), which can lead to elevated canopy temperature and potential errors in irrigation scheduling from incorrect interpretation of elevated canopy temperature. A wet canopy and/or low solar radiation mask the link between soil water availability and canopy temperature, precluding appropriate irrigation scheduling when the canopy is wet from irrigation, or rainfall, or cloudy conditions (Jones, 1999; Jones, 2004; Bockhold et al., 2011). Thus, canopy temperature measurement for irrigation scheduling is likely best suited for arid and semi-arid climates (Jones, 1999).

Canopy temperature measurement for irrigation scheduling was expressed as a simple empirical relationship called the crop water stress index (CWSI) nearly 40 years ago by Idso et al. (1981) and Jackson et al. (1981). The CWSI is a simple linear scale ranging from 0, when under identical climatic conditions measured canopy temperature (T_c) is equal to the well-watered canopy temperature, and 1 when T_c is equal to the non-transpiring canopy temperature. Canopy temperatures corresponding to well-watered and non-transpiring at the same atmospheric conditions as measured T_c are known as the lower and upper reference temperatures and used to normalize the 0 to 1 range of the CWSI. Normalizing is used to account for the effects of atmospheric conditions (air temperature, relative humidity, solar radiation, wind speed, etc.) on transpiration and canopy temperature. Practical application of the CWSI has been limited by the difficulty of estimating the reference temperatures (Maes and Steppe, 2012). Theoretical determination of crop-specific constants for the reference temperature relative to ambient air temperature has not been fruitful due to the poorly understood and complex influences of canopy architecture and environmental conditions on the soil-plant-air continuum (Idso et al., 1981; Jones, 1999; Jones, 2004; Payero and Irmak, 2006). In the original development and application of the CWSI concept, the reference temperatures were experimentally determined from field measurements, and the difference between canopy and air temperature was linearly correlated with the vapor pressure deficit to account for major climatic effects confounding T_c measurements (Idso, 1982). In the initial development and application of CWSI, canopy temperature measurements were restricted to times near solar noon on cloudless days to limit the effect of variable solar radiation on canopy temperature and stomatal conductance. Ideally, in the application of CWSI, companion plots of the crop under well-watered and non-transpiring conditions would be available for direct measurement of reference temperatures. In commercial agriculture, use of companion plots is not feasible, nor is it possible to maintain a crop canopy under non-transpiring conditions. Alternative methods of estimating reference temperature have been investigated, including artificial wet and dry reference surfaces (Jones, 1999; Jones et al., 2002; Leinonen and Jones, 2004; Cohen et al., 2005; Alchanatis et al., 2010; O'Shaughnessy et al., 2011; Pou et al., 2014), physical models (Jackson et al., 1981; O'Toole and Real, 1986), and data-driven empirical models (Payero and Irmak, 2006; King and Shellie, 2016; King et al., 2020; Kumar et al., 2021) for specific crops. King et al. (2021) used a combination of data-driven models to estimate the reference temperatures of sugar beet in southern Idaho with good results.

Deficit irrigation management of sugar beet based on plant canopy temperature has the potential to overcome soil water monitoring limitations, facilitate DI to increase utilization of stored soil water, and reduce seasonal irrigation requirements. The objective of the research summarized in this paper was to implement and evaluate the effect of automated DI scheduling of sugar beet using three CWSI thresholds on irrigation use, crop evapotranspiration, seasonal soil water depletion, root yield, estimated recoverable sugar (ERS) yield, and water use efficiency compared to full irrigation.

METHODS AND MATERIALS

SITE DESCRIPTION

A field study was conducted in 2019, 2021, and 2022 at the USDA-ARS Northwest Irrigation and Soil Laboratory near Kimberly, Idaho. The climate is borderline arid-semi-arid, where the 20-y average annual precipitation and alfalfa-reference evapotranspiration (ET_r) are approximately 253 and 1479 mm, respectively. Approximately 45% of annual precipitation and 83% of annual ET_r occur from April through mid-October. The soil at the study site is a Portneuf silt loam (coarse-silty mixed mesic Durixerollic Calciorthid). The soil profile is classified as very deep and well drained, with weak silica cementation ranging from 30 to 45 cm deep that can restrict root growth (USDA, 1998).

EXPERIMENTAL DESIGN

The field study utilized a randomized block experimental design to evaluate four irrigation treatments with four replications. The four irrigation treatments were fully irrigated (FIT) and DI irrigation when the daily average CWSI exceeded three threshold values designated as CWSI1, CWSI2, and CWSI3. Irrigation treatment plots were 4.6 m wide by 21.3 m long. The FIT represents the condition where the crop was irrigated one to three times a week with a cumulative depth equal to the weekly cumulative estimated sugar beet evapotranspiration (ET_c). Water was applied using a solid-set sprinkler system with an irrigation event duration of 2 h and 25 mm of water applied.

CULTURAL AND HARVEST PRACTICES

In each study year, tillage consisted of four tillage passes: moldboard plow, tandem disk, roller harrow, and bedding in the spring prior to planting. The experimental plots were in different physical locations each year, and the previous crop was either spring barley or oats. Tillage practices were based on farmer practices for sugar beet production for suitable seedbed preparation to achieve good soil-seed contact for acceptable germination. The experimental site was reservoir-tilled to prevent runoff and subsequent run-on between and within plots.

Several soil cores were taken across the experimental site to a depth of 60 cm each year prior to planting. The cores were split into two sampling depths of 0 to 30 cm and 30 to 60 cm. The soil samples were composited by depth increment. The soil samples were analyzed for nitrate N (NO_3-N) and ammonium N (NH_4-N) after extraction with 2 M KCL (Mulvaney, 1996) using a flow injection analyzer (Lachat Instruments, Loveland, Colo.). The 0 to 30 cm soil samples were tested for sodium bicarbonate extractable P and exchangeable K concentrations (Olson et al., 1954). The study sites were fertilized uniformly based on University of Idaho recommendations (Walsh et al., 2009) prior to planting.

Sugar beet was planted on 3 May 2019, 3 May 2021, and 10 May 2022 (cultivar Crystal A404NT MP) with a row spacing of 0.56 m. In all study years, seed was treated with the insecticide Pancho Beta (60 g a.i. per 100,000 seeds) and the fungicides Allegiance and Thiram (Bayer AG Crop Science Division, Monheim am Rhein, Germany). Seeding rates in all study years were 128,000 plants ha^{-1}. As a rule, 60% of planted seeds survive to harvest, and plant populations between 47,000 and 120,000 plants per ha^{-1} produce acceptable yields (Grower Guide Amalgamated Sugar Co., Twin Falls, Idaho, 2018). Full emergence was achieved on 30 May 2019, 2 June 2021, and 12 June 2022. Glyphosate was applied multiple times each study year to all plots as at maximum labeled rates to control weeds. Fungicide Quadris (Syngenta US, Greensboro, N.C.) was applied once at the maximum label rate in 2022 to control powdery mildew (*Erysiphe polygoni*) due to its presence in 2021 plots.

The harvest area within each plot was 1.1 m (2 rows) by 18.3 m centered in the plot to avoid non-uniform application due to sprinkler pattern edge effects and adjacent plot sprinkler overlap. Roots in the center two rows of each plot were harvested on 11 October 2019, 7 October 2021, and 6 October 2022. Total root yield was determined from each plot using a load cell-equipped scale on a two-row plot harvester. From each plot root sample, four to eight roots were collected and sent to the Amalgamated Sugar Co. (Paul, Idaho) tare lab for analysis of percent sucrose and impurities. Percent sucrose was determined using an Autopol 880 polarimeter (Rudolph Research Analytical, Hackettstown, N.J.), a half-normal weight sample dilution, and the aluminum sulfate clarification method [ICUMSA Method GS6-3 1994](ICUMSA, 2005). Brei conductivity was measured using a Foxboro conductivity meter Model 871EC (Foxboro, Foxboro, Mass.) and brei nitrate was measured using a multimeter Model 250 (Denver Instruments, Denver, Colo.) with Orion probes 900200 and 9300 BNWP (Krackler Scientific, Inc., Albany, N.Y.). Brei extractable sucrose was determined using an equation developed by the Amalgamated Sugar Co. (Twin Falls, Idaho) tare lab to account for the effect brie impurities have on sucrose extraction efficiency as:

$$Ex = \frac{250 + \left(1255.2 \bullet Ec - 15000 \bullet Sugar - 6185\right)}{\left(Sugar \bullet \left(98.66 - 7.845 \bullet Ec\right)\right)} \tag{1}$$

where

Ex = percent extractable sucrose

Ec = brei conductivity (dS m^{-1})

$Sugar$ = brei percent sucrose.

Estimated recoverable sugar was computed as:

$$ERS = \frac{Ex \bullet RY \bullet Sugar}{10000} \tag{2}$$

where

ERS = estimated recoverable sugar (kg ha^{-1})

RY = root yield (kg ha^{-1}).

IRRIGATION SYSTEM

Each year, the experimental site was irrigated with a solid-set sprinkler system installed immediately after planting and reservoir tillage. The sprinkler system used Nelson MP2000 90-210 landscape sprinklers (Nelson Irrigation Corp., Walla Walla, Wash.) arranged on a 4.6 m square spacing mounted 70 cm above ground level. Each sprinkler was equipped with a Nelson 241 kPa pressure regulator to ensure uniform sprinkler pressure and flow across the experimental site. Each treatment water supply line was equipped with a Rain Bird 100-DV-NPT 24 VAC solenoid actuated valve (Rain Bird Corp., Azusa, Calif.). The water supply was filtered using an Amiad Filtomat M102C filter (Amiad U.S.A. Inc., Mooresville, N.C.) equipped with a 130 µm screen. The water supply was pressured using a Paco 10707 LC pump (Grundfos Pumps Corp., Brookshire Tex.). The FIT irrigation events were manually controlled, and irrigation events for treatments CWSI1, CWSI2, and CWSI3 were automatic based on the daily CWSI computed by the irrigation system control data logger (CR6, Campbell Scientific, Logan, Utah). Irrigations occurred after 20:00 MDT to minimize the effects of evaporation and wind on irrigation uniformity and efficiency. Rain gauges designed for minimum evaporation loss (All-Weather Rain Gauge, Forestry Suppliers, Jackson, Miss.) were used in each plot to verify water application and rainfall amounts.

IRRIGATION SCHEDULING AND SOIL WATER MEASUREMENT

Irrigation scheduling for the FIT was based on a weekly soil water balance to ensure soil water content remained above 40% available and did not appreciably increase or decrease throughout the growing season. The estimated daily sugar beet ET$_c$ was based on the ASCE standardized reference evapotranspiration equation (Allen et al., 2005) and daily crop coefficients (Wright, 1982) obtained from an AgriMet (U.S Bureau of Reclamation, https://www.usbr.gov/pn/agrimet/) weather station located within 100 m of the study site. Daily precipitation was also obtained from the AgriMet weather station. Irrigation for the FIT treatment was applied 1 to 3 times a week, depending on the weekly soil water balance.

Irrigation scheduling for the DI treatments CWSI1, CWSI2, and CWSI3 was based on a daily crop water stress index beginning the second week of July, with prior irrigations being identical to the FIT treatment. A 25-mm irrigation was trigged each day the daily CWSI exceeded the designated threshold for the irrigation treatment. The 25-mm irrigation depth was selected to mimic center pivot irrigation depths common in the region. Irrigation treatment replications were irrigated identically. The daily CWSI was computed as the average 15-min CWSI of all replications of a DI treatment between 13:00 and 16:00 MST. In 2019, irrigation to treatment CWSI1 was scheduled when daily CWSI exceeded 0.2, irrigation to treatment CWSI2 was scheduled when daily CWSI exceeded 0.3, and irrigation to treatment CWSI3 was scheduled when daily CWSI exceeded 0.35. The DI irrigation treatments were initiated the second week in July in each study year. By the first week of August in 2019, it was apparent that there was little difference in the irrigation schedules of the DI treatments. Subsequently, the DI irrigation treatments CWSI1, CWSI2, and CWSI3 were modified to occur when the daily crop water stress index exceeded 0.2, 0.35, and 0.55, respectively. These redefined daily CWSI thresholds for the DI treatments were used in study years 2021 and 2022.

The 15-min CWSI was computed using the empirical formula (Idso et al., 1981; Jackson et al., 1981):

$$CWSI = \frac{\left(T_c - T_{LL}\right)}{\left(T_{UL} - T_{LL}\right)} \tag{3}$$

where

T_c = 15-min average measured canopy temperature of fully sunlit leaves (°C)

T_{LL} = canopy temperature when the crop is well-watered

T_{UL} = canopy temperature of water-stressed non-transpiring crop.

Temperatures T_{LL} and T_{UL} are the lower and upper baselines used to normalize CWSI for the effects of atmospheric conditions (air temperature, relative humidity, solar radiation, wind speed, etc.) on transpiration and canopy temperature. Ideally, CWSI ranges from 0 to 1, where 0 represents a well-watered condition and 1 represents a non-transpiring, severely water-stressed condition.

The T_{LL} reference temperature was estimated using a neural network model (King and Shellie, 2016; King et al., 2020; King et al., 2021). Inputs to the neural network model were 15-min averaged values of measured solar radiation (R_s, w m^{-2}), air temperature (T_a, °C), relative humidity (RH,%), and wind speed (WS, m s^{-1}). The T_{UL} reference temperature (°C) was estimated using the energy balance-based equation of Jackson et al. (1981) as:

$$T_{UL} - T_a = \frac{r_a R_n}{\rho c_p} \tag{4}$$

where

r_a = aerodynamic resistance (s m^{-1})

R_n = net radiation (W m^{-2})

c_p = heat capacity of air (J kg^{-1} °C^{-1})

ρ = density of air (kg m^{-3}).

Aerodynamic resistance was estimated using the approach of O'Toole and Real (1986) as described by Shellie and King (2020) for sugar beet at the experimental site. The value used for r_a was 25.4 s m^{-1}, and R_n was estimated as $R_n = 0.65R_s + 14.7$ (King et al., 2020). A spreadsheet demonstrating the calculation of CWSI using equations 3 and 4 and the neural network model for estimating T_{LL} is available at: https://doi.org/10.13031/24076602

Soil water content was measured at 10 to 14 d intervals in 0.15 m depth increments from 0.15 to 2.3 m midway along the center row of each plot using a neutron probe calibrated to the experimental site soil using the methods of Hignett and Evett (2002). The soil water content of the 0 to 0.15 m soil depth was measured at 30 min intervals using time domain reflectometery (TDR) (TDR 100, Campbell Scientific Co., Logan, Utah) with two probes in the center crop row of a treatment plot.

The fraction of available soil water (*fASW*) was calculated as:

$$fASW = \frac{\sum_{i=1}^{n} \frac{\left(\theta_i - \theta_{pwpi}\right)}{\left(\theta_{fci} - \theta_{pwpi}\right)}}{n} \tag{5}$$

where

θ_i = measured volumetric soil water content for depth i

θ_{pwpi} = estimated volumetric soil water content at permanent wilting point for depth i

θ_{fci} = estimated volumetric soil water content at field capacity at depth i

n = the number of 15 cm soil water content measurement depths considered.

Field capacity (FC) for each 15 cm soil depth was estimated from neutron probe measurements of soil water content in a 1.5 × 1.5 m basin that received weekly water application depths of 100 to 150 mm over a six-week period. The basin was continuously covered with a waterproof tarp to prevent soil evaporation. A neutron probe access tube was installed, and soil water content was measured 48 h after the last water application. The permanent wilting point (PWP) for each soil depth was estimated at 50% of FC, or the minimum soil water content measured if less than 50% of FC.

FIELD MEASUREMENTS AND INSTRUMENTATION HARDWARE AND SOFTWARE

Canopy temperature was measured using infrared radiometers (SI-121, Apogee Instruments, Logan, Utah) with a 36° field of view and one radiometer in each replication of the irrigation treatments. The infrared radiometers were positioned approximately 0.6 m above the canopy and oriented northeasterly, approximately 45° from nadir, with the sensor view aimed at the sunlit canopy surface. The infrared radiometers were installed when the sugar beet crop neared full cover, usually the first week of July. Climatic parameters R_s (SP-110 pyranometer, Apogee Instruments, Logan, Utah), T_a, RH (HMP50 temperature and humidity probe, Campbell Scientific, Logan, Utah), and WS (034B, Met One Instruments, Inc., Grants Pass, Ore.) were measured at a height of 2 m at the experimental site. Canopy temperature and TDR measurements were measured and recorded by four data loggers (CR1000, Campbell Scientific, Logan, Utah). Canopy temperature was measured at 1-min intervals and recorded as 15-min averages. Climatic parameters were also measured at 1-min intervals and recorded as 15-min averages by a master data logger (CR6, Campbell Scientific, Logan, Utah) that performed real-time CWSI calculations using equations 3, 4, and the neural network model for estimating T_{LL} coded on the data logger and controlled irrigation for each irrigation treatment. Each data logger was equipped with a wireless transmitter (RF401a, Campbell Scientific, Logan, Utah) to transfer canopy temperature measurements to the master data logger. The master data logger was also equipped with a machine-to-machine cellular modem (Cell200 series, Campbell Scientific Inc., Logan, Utah) to allow remote access to recorded data and daily irrigation schedule. Study personnel accessed sensor data in real-time using datalogger management software (LoggerNet 4.5, Campbell Scientific Inc., Logan, Utah). The FIT irrigations were scheduled manually via wireless connectivity to the master data logger. All the DI irrigation treatments were scheduled automatically according to the computed daily CWSI. All equipment was removed immediately prior to harvest, usually in late September each year.

SEASONAL EVAPOTRANSPIRATION

Seasonal sugar beet ET_c (mm) was calculated using a soil water balance between emergence and harvest as:

$$ET_c = \Delta S + P + I + U - DP - R \tag{6}$$

where

ΔS = the change in soil water storage in the soil profile between emergence and harvest (mm)

P = cumulative precipitation between emergence and harvest (mm)

I = cumulative irrigation applied between emergence and harvest (mm)

R = the difference between plot runoff and run-on (mm)

U = upward soil water flux (mm)

DP = cumulative water percolating below the root depth between emergence and harvest (mm).

Deep percolation was assumed to be zero based on soil water content in the lower depths of the 2.2 m soil profile remaining less than field capacity and constant or decreasing from emergence to harvest. Runoff was assumed to be zero as all plots had reservoir tillage to prevent surface water movement within and between plots, as visually confirmed over the season. Upward soil water flux was assumed to be zero as the ground water table was more than 5 m below the surface.

ROOT YIELD AND ESTIMATED RECOVERABLE SUGAR WATER USE EFFICIENCY

Water use efficiency was calculated as the ratio of yield to water used by the crop. Sugar beet root yield water use efficiency (Mg ha^{-1} mm^{-1}) was calculated as:

$$RYWUE = \frac{RY}{ET_c \bullet 1000} \tag{7}$$

Estimated recoverable sucrose yield water use efficiency (kg ha^{-1} mm^{-1}) was calculated as:

$$SYWUE = \frac{ERS}{ET_c} \tag{8}$$

NORMALIZED WATER PRODUCTION FUNCTION

Treatment differences in measured yield values between study years can sometimes be minimized by normalizing measured values relative to the maximum value measured in a study year (Doorenbos and Kassam, 1979). In this study, relative values of ET_c, sugar beet root yield, and ERS yield were normalized in each study year by dividing the value for each treatment by the maximum measured value from the FIT treatment.

STATISTICAL ANALYSIS

Data reduction and analysis were conducted in MS Excel spreadsheets. Statistical data analysis was conducted using PROC MIXED in SAS (SAS 9.4, SAS Institute Inc., Cary, N.C.) to test for treatment differences. Irrigation treatments were designated as fixed effects and replication and year as random effects. Least square means (LSMEANS) was used to differentiate the significance of treatment and interaction effects. Treatment differences and interactions were considered significant at $p = 0.05$, unless otherwise noted. Residual diagnostics were conducted to evaluate the assumptions of ANOVA and determine the need for data transformations. Graphical presentations were generated using SigmaPlot 14 (Systat Software, San Jose, Calif.).

RESULTS

CLIMATIC CONDITIONS

May through September monthly average air temperature, solar radiation, relative humidity, wind speed, and monthly and growing season (May through September) total rainfall and alfalfa reference evapotranspiration (ET_r) in each study year along with 20-year averages are given in table 1. Monthly and growing season average wind speeds were similar in all three study years as well as the 20-year average. Monthly average air temperatures were similar for all three study years except for September 2022, which was higher compared to 2019 and 2021 and the 20-year average. Average monthly relative humidity was higher in 2019 compared to 2021, 2022, and the 20-year average. This resulted in season total ET_r about 100 mm less in 2019 compared to 2021, 2022, and the 20-year average. Monthly rainfall was variable between years, but growing season and 20-year average totals were similar.

CUMULATIVE WATER APPLICATION

The cumulative estimated ET_c and water application (rainfall + irrigation) for each irrigation treatment in each study year are shown in figure 1. Cumulative water application exceeded the estimated ET_c of FIT all season and the DI treatments prior to start of automated DI to account for water application inefficiencies and maintain soil water depletions below 60% (>40% available soil water). Water applications to the irrigation treatments started to diverge in mid-July, immediately after DI irrigation scheduling based on daily CWSI began. Seasonal rainfall and irrigation amounts applied to each irrigation treatment in each study year are given in table 2. Irrigation application to the DI treatments decreased as the daily average CWSI threshold value required to trigger irrigation increased.

SOIL WATER TRENDS

Water content of the soil profiles in each irrigation treatment near emergence and prior to harvest is depicted in figures 2-4 for study years 2019, 2021, and 2022, respectively. The soil water content of the soil profile at emergence in each irrigation treatment was greatest in 2021 compared to 2019 and 2022.

Water content of the soil profiles in the four irrigation treatments was very similar at emergence in each study year.

Table 1. Monthly average and growing season average ($\bar{x}$) daily mean air temperature, daily solar radiation, daily mean relative humidity, and daily mean wind speed, and monthly and growing season total (Σ) rainfall and alfalfa reference crop evapotranspiration (ET_r) in each study year and 20-yr average (1998-2018).

Year	Month	Air Temperature (°C)	Solar Radiation (MJ m^{-2} d^{-1})	Relative Humidity (%)	Wind Speed (m sec^{-1})	Rainfall (mm)	Alfalfa Reference ET_r (mm)
2019	May	12.2	20.3	66.8	2.7	60	131
	June	17.4	29.3	51.8	2.7	0	238
	July	21.3	24.9	55.8	2.2	2	238
	August	21.1	24.5	51.5	2.2	7	230
	September	15.5	18.0	62.4	2.5	20	146
	Season Summary	$\bar{x}$ = 17.5	$\bar{x}$ = 23.4	$\bar{x}$ = 57.7	$\bar{x}$ = 2.5	Σ = 89	Σ = 983
2021	May	13.8	24.4	56.4	3.1	23	196
	June	21.7	28.1	42.1	2.9	1	279
	July	24.4	23.1	48.4	1.9	2	249
	August	20.1	20.1	50.5	2.0	14	197
	September	16.2	18.2	46.1	2.2	7	162
	Season Summary	$\bar{x}$ = 19.2	$\bar{x}$ = 22.8	$\bar{x}$ = 48.7	$\bar{x}$ = 2.5	Σ = 47	Σ = 1083
2022	May	11.0	19.9	60.1	3.4	44	163
	June	17.5	23.9	52.1	2.8	5	222
	July	23.9	26.7	42.3	2.2	1	277
	August	23.7	20.9	46.7	2.1	3	226
	September	18.5	17.3	44.6	2.4	1	178
	Season Summary	$\bar{x}$ = 18.9	$\bar{x}$ = 21.7	$\bar{x}$ = 49.1	$\bar{x}$ = 2.6	Σ = 54	Σ = 1066
1999 thru 2018	May	13.2	23.9	55.8	2.9	29	183
	June	18.0	27.0	50.3	2.7	13	234
	July	22.5	26.8	46.8	2.1	5	265
	August	20.8	23.1	48.4	2.1	11	221
	September	15.9	18.6	50.5	2.3	11	155
	Season Summary	$\bar{x}$ = 18.1	$\bar{x}$ = 23.9	$\bar{x}$ = 50.4	$\bar{x}$ = 2.4	Σ = 69	Σ = 1058

There was no significant difference in soil profile water contents at emergence and prior to harvest for the FIT treatment in 2019 and 2022. There was slightly less soil water in the soil profile prior to harvest compared to emergence in 2021. Soil water content of the soil profile in each study year was well above 40% available for the FIT treatment, indicating that the irrigation amount applied in each year sufficiently replaced ET_c and prevented yield-reducing plant water stress. The soil water content of the soil profiles between emergence and prior to harvest was significantly different for the three DI treatments in each year. Soil water content at emergence was greater in 2021 compared to 2019 and 2022.

Seasonal soil water extraction between emergence and prior to harvest is shown in table 2. There was a highly significant difference ($p < 0.001$) in seasonal soil water extraction between irrigation treatments in each study year. Seasonal soil water extraction increased as the CWSI value threshold to trigger irrigation increased. Study year had a highly significant effect ($p < 0.001$) on seasonal soil water extraction, and there was a significant irrigation by year interaction. There was no significant difference in seasonal soil water extraction between the CWSI2 and CWSI3 treatments in any study year. Seasonal soil water extraction in each irrigation treatment was less in 2022 compared to 2019 and 2021 (table 2, figs. 2-4) due to less water stored in the soil profile at emergence, particularly below 1 m.

Table 2. Season average daily crop water stress index between mid-July and harvest, rainfall, irrigation, soil water extraction, and soil water balanced based sugar beet evapotranspiration (ET_c) between crop emergence and harvest, and root yield, estimated recoverable sugar, root yield water use efficiency and recoverable sugar water use efficiency in each study year.[a]

Year	Irrigation Regime	Season Average Daily Crop Water Stress Index	Irrigation (mm)	Rain Fall (mm)	Soil Water Extraction (mm)	ET_c (mm)	Root Yield (Mg ha^{-1})	Estimated Recoverable Sugar (kg ha^{-1})	Root Yield Water Use Efficiency (Mg ha^{-1} mm^{-1})	Recoverable Sugar Water Use Efficiency (kg ha^{-1} mm^{-1})
2019	100% ET	0.08a	526	20.3	74a	620a	85.1a	13420a	0.14a	21.4a
	CWSI = 0.2	0.12ab	393	20.3	211b	624a	78.1a	12222ab	0.13ab	19.7ab
	CWSI = 0.35	0.19b	353	20.3	228bc	601a	67.0b	10463b	0.11b	17.5ab
	CWSI = 0.55	0.31c	213	20.3	285c	518b	53.1c	8131c	0.11b	16.4b
2021	100% ET	0.10a	612	34.8	118a	764a	88.8a	13748a	0.12a	19.2a
	CWSI = 0.2	0.15ab	448	34.8	174b	657b	81.4a	11913a	0.13a	18.6a
	CWSI = 0.35	0.22b	314	34.8	241c	590bc	68.6b	10060b	0.12a	17.0a
	CWSI = 0.55	0.33c	254	34.8	243c	532c	61.9c	8903b	0.11a	16.1a
2022	100% ET	0.11a	739	9.6	2a	751a	103.2a	15042a	0.14a	20.1a
	CWSI = 0.2	0.16ab	554	9.6	80b	644b	96.0a	13999a	0.15a	21.8a
	CWSI = 0.35	0.25b	465	9.6	100bc	574c	75.1b	10770b	0.13a	18.3a
	CWSI = 0.55	0.39c	285	9.6	132c	427d	43.0c	5752c	0.10b	13.5b

[a] Values followed by the same letter in a study year are not significantly different ($p \le 0.05$).

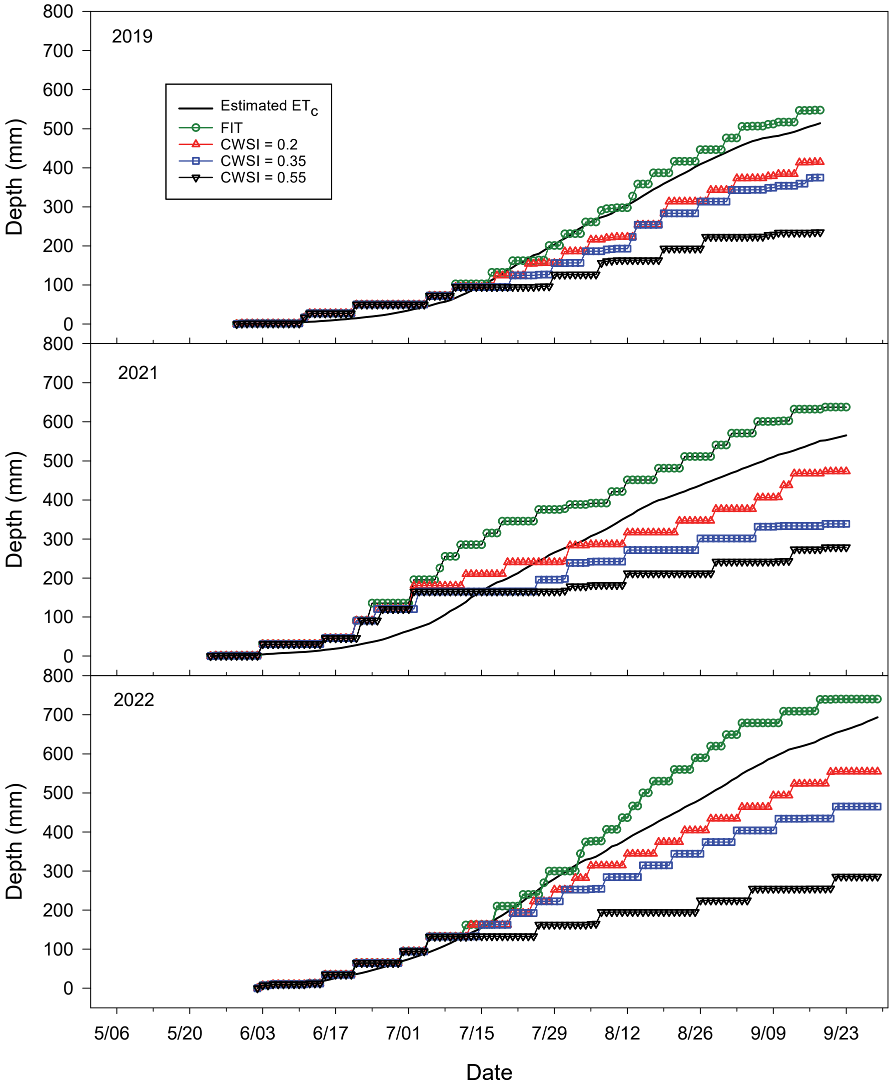

Figure 1. Estimated sugar beet evapotranspiration (ET_c) and cumulative rainfall and irrigation applied to each irrigation treatment, full irrigation (FIT), CWSI=0.2, CWSI=0.35, and CWSI=0.55, in each study year.

AVERAGE DAILY CROP WATER STRESS INDEX

Daily CWSI throughout each study year for each irrigation treatment is shown in figure 5. Daily CWSI values were greatest throughout the season for the CWSI3 treatment. Daily CWSI values were very similar between irrigation treatments in September 2021 due to the high incidence of powdery mildew (*Erysiphe polygoni*) in the crop. The fungal disease imparts a white color to the leaves, which apparently interferes with infrared canopy temperature measurement. The development of the disease late in the growing season has minimal effect on sugar beet yield (Sugar Beet Grower Guide, Amalgamated Sugar Co., Twin Falls, Idaho). Daily CWSI averaged over the season was significantly different between irrigation treatments (table 2) in each study year. There was a significant difference in season average daily CWSI between irrigation treatments CWSI2 and CWSI 3. There was no significant difference in season average daily CWSI between irrigation treatments FIT and CWSI1 in any study year. There was a significant difference in season average CWSI between study years, but the interaction between irrigation treatment and study year was not significant. The season average daily CWSI of DI treatments was greater in 2022 compared to 2019 and 2021. This may be due to less soil water stored in the soil profile at emergence in 2022 compared to 2019 and 2021 (figs. 2-4).

EVAPOTRANSPIRATION

Soil water balance based on ET_c in each irrigation treatment in each study year is given in table 2. There were highly significant differences ($p < 0.001$) in ET_c between irrigation treatments in each study year. The study year and the interaction between irrigation treatment and study year were also significant. There was no significant difference in ET_c between the FIT, CWSI1, and CWSI2 irrigation treatments in 2019. This is likely due to the delayed implementation of the higher CWSI irrigation thresholds in 2019 and extraction of up to 228 mm soil water, replacing reduced irrigation water application to the DI irrigation treatments. There was a significant difference in ET_c between the FIT and CWSI1 irrigation treatments in 2021, but no significant difference between the CWSI2 and CWSI3 treatments. There were

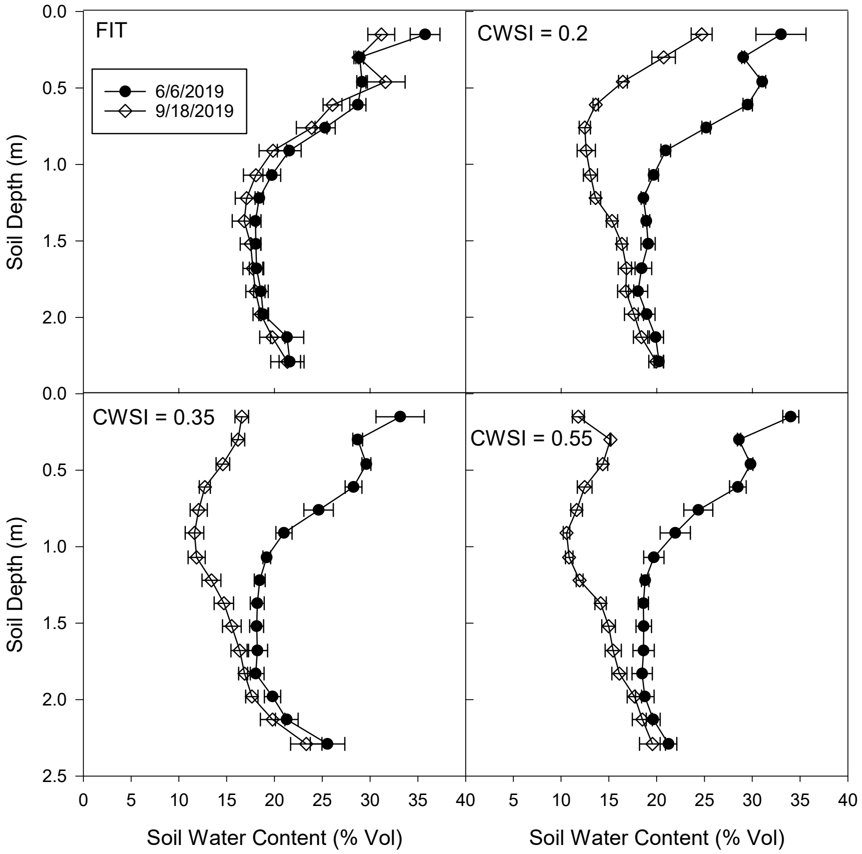

Figure 2. Soil water content profiles for four irrigation treatments, full irrigation (FIT), CWSI=0.2, CWSI=0.35, and CWSI=0.55, at emergence (6 June) and prior to harvest (18 September) in study year 2019. Bars represent the standard error of the measurements.

significant differences in ET_c between all four irrigation treatments in 2022. Soil water balance based ET_c was lower in 2019 for the FIT and CWSI1 irrigation treatments than in 2021 and 2022. This is likely due to ET_r being less in 2019 than in 2021 and 2022 (table 1).

SUGAR BEET YIELD

There were highly significant differences in sugar beet root yield ($p < 0.001$) between irrigation treatments in each study year (table 2). Study year and the interaction between irrigation treatment and study year were also significant. There were no significant differences in root yield between the FIT and CWSI1 treatment in any study year. There were significant differences in root yield between each of the DI treatments in each study year. Root yield for the FIT, CWSI1, and CWSI2 irrigation treatments was highest in 2022, which likely resulted in a significant difference between the study year.

There were significant differences in ERS yield ($p < 0.001$) between irrigation treatments in each study year. Study year was not significant, but the interaction between irrigation treatment and study year was significant. There was no significant difference in ERS yield between the FIT and CWSI1 treatment in any study year. There were significant differences in ERS yield between each of the DI treatments in 2021 and 2022. The lack of a significant difference between the CWSI1 and CWSI2 treatments in 2019 is likely due to little difference in ET_c between treatments.

WATER USE EFFICIENCY

There were highly significant differences in RYWUE ($p < 0.001$) between irrigation treatments, and the interaction between irrigation treatment and study year was significant, but study year was not significant. There was no significant difference in RYWUE between the FIT and CWSI1 irrigation treatments in any study year. In 2021 and 2022, RYWUE was numerically greater for the CWIS1 treatment than the FIT treatment. There were no significant differences in RYWUE between the irrigation treatments in 2021. Only in 2022 was RYWUE significantly different between the CWIS3 and CWIS2 treatments.

There were highly significant differences in *SYWUE* ($p < 0.001$) between irrigation treatments, and the interaction between irrigation treatment and study year was significant, but study year was not significant. There was no significant difference in *SYWUE* between the FIT and CWSI1 irrigation treatments in any study year. There were no significant differences in *SYWUE* between the irrigation treatments in 2021. Only in 2022 was *SYWUE* significantly different between the CWIS3 and CWIS2 treatments.

FRACTION AVAILABLE SOIL WATER

The *fASW* for each irrigation treatment in each study year is shown in figure 6. There was no significant difference in *fASW* between irrigation treatments in any study year prior to mid-July when the DI treatments were initiated. In 2019 and 2021, the *fASW* of the FIT treatment was well above the

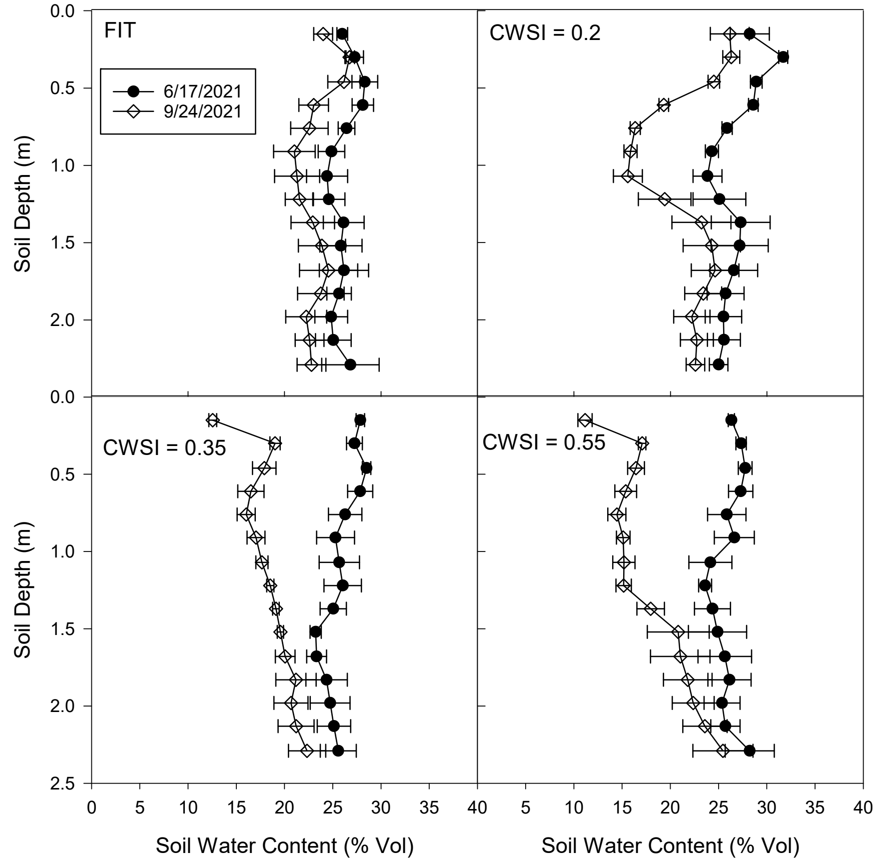

Figure 3. Soil water content profiles for four irrigation treatments, full irrigation (FIT), CWSI=0.2, CWSI=0.35 and CWSI=0.55, at emergence (17 June) and prior to harvest (24 September) in study year 2021. Bars represent the standard error of the measurements.

sugar beet water stress threshold of 0.4 throughout the season. In 2022, *fASW* of the FIT treatment at emergence was much less than in other study years and decreased to the 0.4 threshold in mid-July despite irrigation applications exceeding the estimated ET$_c$ (fig. 1). The decrease in *fASW* was apparent by a daily CWSI of the FIT greater than 0.2 the last week in July (fig. 5). Irrigation frequency for the FIT was increased (fig. 1) to raise the *fASW* above the 0.4 threshold throughout the remainder of the season. Generally, the relative values of *fASW* at the end of the season in each study coincided inversely with the daily CWSI irrigation threshold of each DI treatment.

NORMALIZED WATER PRODUCTION FUNCTION

The WPFs for sugar beet root yield and estimated recoverable sugar are shown in figure 7 for all study years combined. Both WPFs were best represented by a higher coefficient of determination (R^2) by curvilinear concave downward functions than linear functions. Yields for study year 2022 (CWSI = 0.55 treatment) were the lowest measured in the study. These low yields are largely the reason for curvilinear concave downward functions providing a higher R^2 than linear functions. The lowest yields measured in 2022 resulted from the soil water content at emergence being considerably lower than in other study years. This resulted in *fASW* of the CWSI3 treatment in 2022 less than in any other study year and the correspondingly lowest soil water balanced ET$_c$.

DISCUSSION

The use of different levels of daily CWSI to control three DI treatments with equal irrigation application depths of 25 mm per irrigation resulted in three distinct DI treatment regimes, especially in 2021 and 2022. There were only two days during the 3-year study where CWSI thresholds were not used to automatically schedule irrigations due to solar radiation being less than 200 W m^{-2} between 13:00 and 16:00 MDT. There were significant irrigation treatment differences in ET$_c$, soil water extraction, *fASW*, season average daily CWSI, sugar beet root yield, ERS yield, and water use efficiencies in each study year. The number of irrigations applied decreased as the daily CWSI threshold for irrigation increased. In 2019, the number of irrigations was 21, 16, 14, and 8, in 2021, there were 24, 18, 12, and 10 irrigations; and in 2022, there were 30, 26, 20, and 17 irrigations for the FIT, CWSI1, CWSI2, and CWSI3 irrigation treatments, respectively. The substantially greater number of irrigations in 2022 was the result of only about 50% available soil water in the profile at emergence (fig. 6). In 2019 and 2021, soil water extractions for the CWSI3 treatment were similar and nearly equivalent to the irrigation amounts applied (table 2). In contrast, soil water extraction for the CWSI3 treatments was only 132 mm in 2022 due to limited soil water availability at emergence and throughout the season (fig. 6).

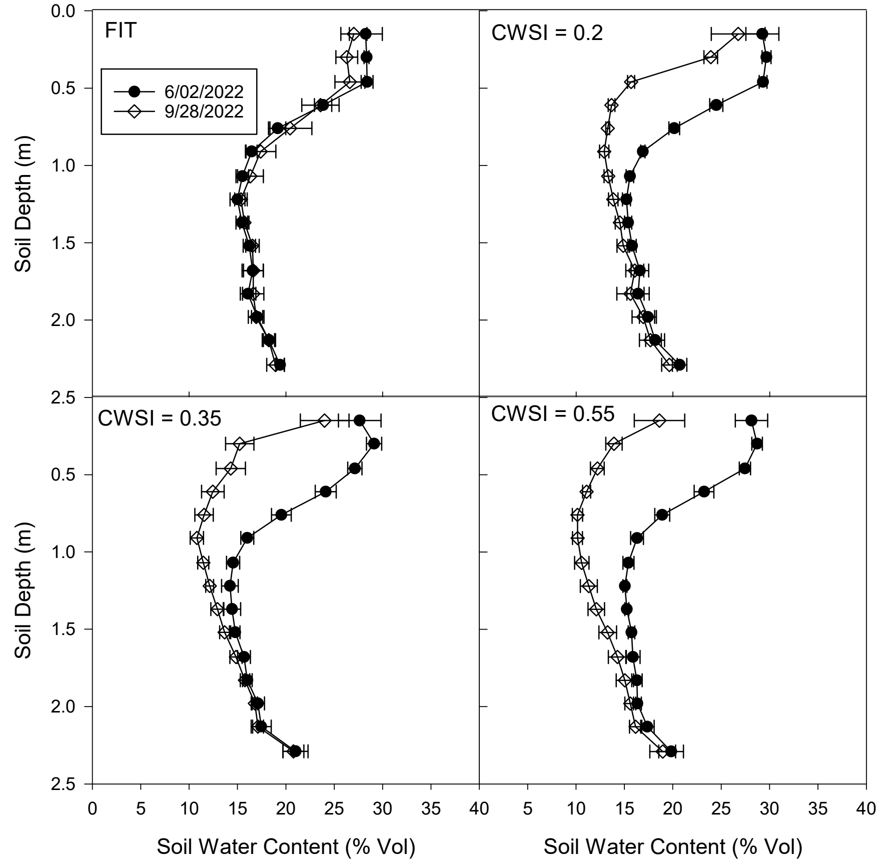

Figure 4. Soil water content profiles for four irrigation treatments, full irrigation (FIT), CWSI=0.2, CWSI=0.35 and CWSI=0.55, at emergence (2 June) and prior to harvest (28 September) in study year 2022. Bars represent the standard error of the measurements.

Soil water balanced-based ET_c for the FIT was about 100 mm less in 2019 compared to 2021 and 2022 (table 2). This was likely largely due to ET_r (table 1) being about 100 mm less in 2019 compared to 2021 and 2022. Despite substantial differences in ET_r and *fASW* at emergence between the study years, ET_c of the CWSI1 treatment was very similar in each study year. This outcome highlights the consistency and accuracy of scheduling sugar beet irrigation based on a CWSI = 0.2 (CWSI1), regardless of seasonal differences in ET_r and soil water availability.

In each study year, irrigation depth was less for the CWSI1 treatment compared to the FIT. Irrigation depth was 133, 154, and 185 mm less for the CWSI1 treatment in 2019, 2021, and 2022, respectively, compared to the FIT treatment without a significant difference in RY or ERS yield. This outcome highlights the ability of mild DI to reduce irrigation requirements of sugar beet at the study site. The soil at the study site had a relatively high water holding capacity, allowing stored soil water to be effectively substituted for irrigation under mild DI in this study. Reductions in irrigation depth will likely be less for locations with less soil water holding capacity.

Neither the RY nor the estimated ERS yield of the CWSI1 treatment was significantly different from the FIT in any study year. Additionally, *RYWUE* and *SYWUE* were not significantly different between the CWSI1 and FIT treatments in any study year. This outcome underscores the feasibility of using canopy temperature-based DI irrigation scheduling for sugar beet to reduce seasonal irrigation requirements by utilizing available soil water storage and maximizing root, ERS yield, and water use efficiencies. Additionally, deficit irrigation scheduling based on CWSI could reduce over-irrigating without installing soil water sensors or tracking irrigation amounts and ET_c. One practical application would be to place a radial line of canopy temperature sensors in a center pivot irrigated field forward and adjacent to where the center pivot system is usually stopped between irrigations, with one or more sensors for each span length. The canopy temperature data could be collected via wireless technology by a master controller to calculate the daily average CWSI for each span and send the producer a text via cellular connectivity that displays the daily CWSI and denotes that irrigation is needed when the CWSI exceeds 0.2. This approach could also be used to automate the center pivot irrigation of sugar beets in much the same manner as it was used to automate DI treatments in this research study.

Comparing figures 5 and 6, greater CWSI values correspond with lower *fASW* values in general. However, *fASW* only depends upon soil water content, while CWSI depends upon *fASW,* evaporative demand, and other environmental factors such as temperature, solar radiation, wind, etc. Thus, *fASW* can correspond to a range of CWSI values, depending upon evaporative demand. For this reason, simple functional relationships between CWSI and *fASW* measured in this study have low R^2 values (data not shown). Hence, daily CWSI is not a good indicator of *fASW,* but it is a reliable and

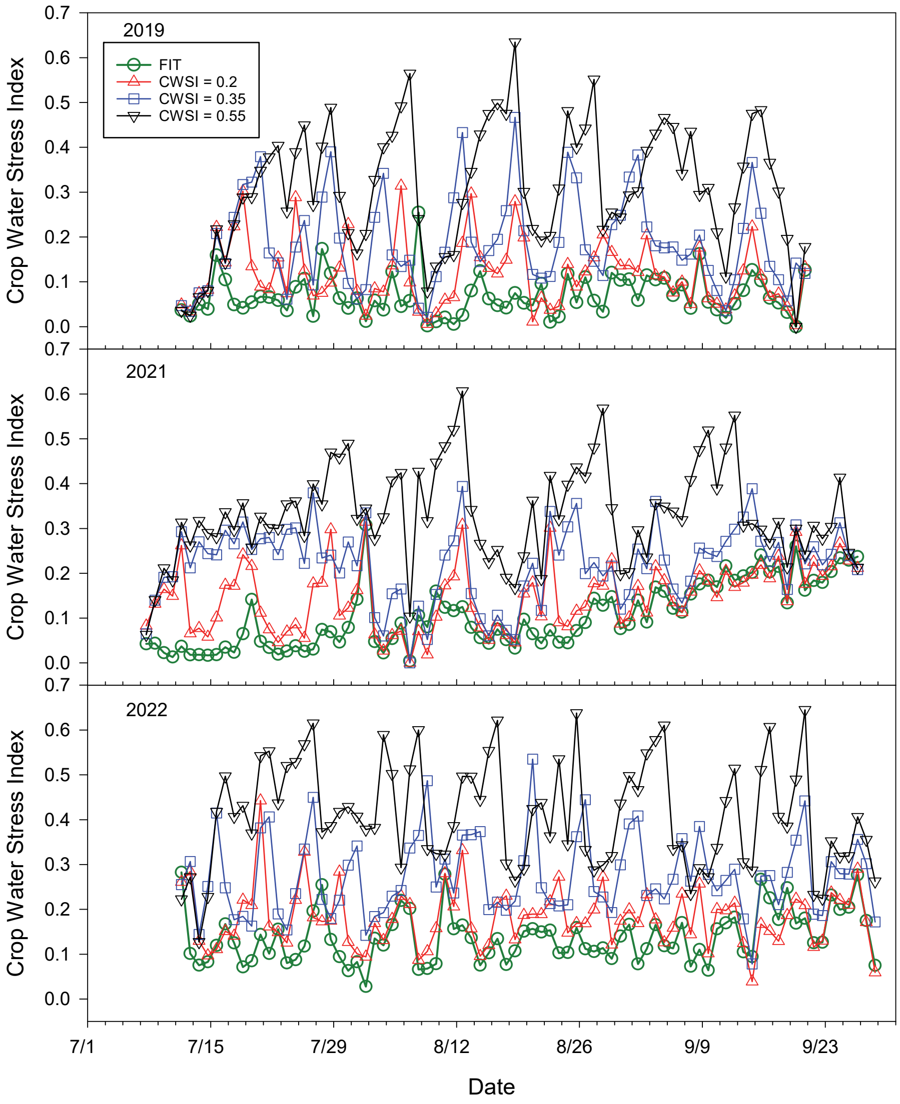

Figure 5. Daily average crop water stress index for each irrigation treatment, full irrigation (FIT), CWSI=0.2, CWSI=0.35, and CWSI=0.55, in each study year.

repeatable basis for implementing DI of sugar beet, as demonstrated in this study.

WATER PRODUCTION FUNCTIONS AND WATER USE EFFICIENCIES

The relationships between relative ET_c, relative RY, and relative ERS yield were found to be curvilinear concave downward in this study. Thus, the marginal productivity of water for sugar beet varies with ET_c and increases with decreasing ET_c. The WPFs of this study are like those reported by Tarkalson et al. (2018) for sugar beet at the same study site. They found that a quadratic relationship between ET_c and RY and ERS yield provided a slightly better R^2 than a linear relationship. Davidoff and Hanks (1989) and Hanks et al. (1982) reported linear WPFs for sugar beet for multiple study sites in the Intermountain Western U.S., as did Groves and Bailey (1997) in the UK. However, the data presented by Davidoff and Hanks (1989) clearly showed a numerical increase in root and sucrose yields with up to a 15% reduction in ET_c. Tarkalson et al. (2018) used linear relationships between relative ET_c, relative RY, and relative ERS yield to represent WPFs measured under drip, solid-set sprinkler and lateral-move sprinkler irrigation combined. However, a decreasing piece-wise linear plateau function of ET_c was used to represent the relationship between ET_c and RY and ERS yield reduction. These relationships predicted a zero percent RY or ERS yield reduction for ET_c of 719 and 729 mm (~85% ET_c) and greater. These relationships are like the curvilinear concave downward WPFs used in this study, as often no yield loss occurs for small ET_c reductions (<15% ET_c). The curvilinear concave downward sugar beet WPF behavior explains why there were no significant differences in RY or ERS yield between the FIT and CWSI1 irrigation treatments in this study.

Since the WPFs developed in this study are curvilinear concave downward, RYWUE and ERSWUE initially increase, then decrease as ET_c decreases from full irrigation. There was no significant difference in RYWUE between the FIT and CWSI1 irrigation treatments in any study year (table 2). In 2021 and 2022, RYWUE was numerically greater for the CWSI1 treatment compared to the other irrigation treatments, characteristic of a curvilinear concave downward

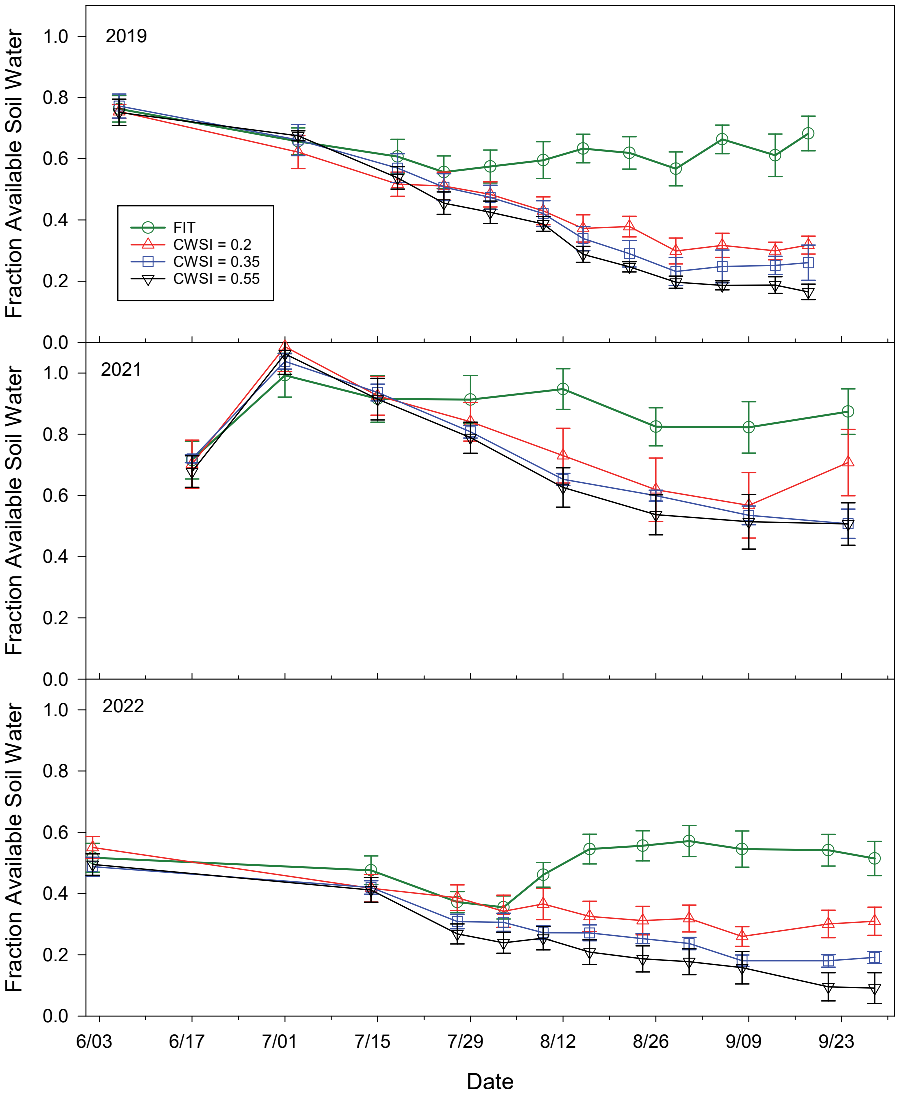

Figure 6. Fraction available soil water for each irrigation treatment, full irrigation (FIT), CWSI=0.2, CWSI=0.35, and CWSI=0.55, in each study year.

WPF. There was no significant difference in ERSWUE between the FIT, CWSI1 and CWSI2 irrigation treatments in any study year (table 2). Only in 2022 was ERSWUE numerically greater for the CWSI1 compared to the other irrigation treatments. Yearly variability in measured yield response to ET_c masked the initial increase in water use efficiency with decreasing ET_c in the 2019 and 2021 study years.

The range in RYWUE measured in this study (0.14 to 0.15 Mg ha^{-1} mm^{-1}) are consistent with that reported by Tarkalson et al. (2018). The RYWUE of previous studies range from 0.053 Mg ha^{-1} mm^{-1} (Winter, 1980) to 0.096 Mg ha^{-1} mm^{-1} (Ehlig and LeMert, 1979) under full irrigation. Root yield water use efficiency of data presented by Winter (1980) and Ehlig and LeMert (1979) of fall planted sugar beet was greater under reduced irrigation compared to adequate irrigation, consistent with a curvilinear concave downward WPF and results of this study. Maximum root yield water use efficiency measured in every year of this study equals or exceeds the values of these studies. The range in SYWUE measured in this study (19.0 to 21.8 kg ha^{-1} mm^{-1}) are consistent with that reported by Tarkalson et al. (2018) and King et al. (2019). The SYWUE of previous studies range from 7.4 to 15.9 kg ha^{-1} mm^{-1} (Hanks et al., 1982; Hang and Miller, 1986; Howell et al., 1987; Davidoff and Hanks, 1989) under full irrigation. Most of the previous studies did not report an increase in sugar yield water use efficiency with deficit irrigation, with the exception of Winter (1988). However, data presented by Davidoff and Hanks (1989) clearly showed an increase in RYWUE and SYWUE with up to 15% reduction in ET_c. The reason water use efficiencies of sugar beet in earlier studies were less than measured in this study is likely due to an increase in sugar beet root yields since 2006 (King and Tarkalson, 2017) without a corresponding increase in ET_c. The results of this study demonstrate that mild DI will likely increase the water use efficiency of sugar beet.

SEASONAL CROP WATER STRESS INDEX AND SEASONAL EVAPOTRANSPIRATION RELATION

The crop water stress index is a measure of crop evapotranspiration expressed as (Jackson et al., 1981):

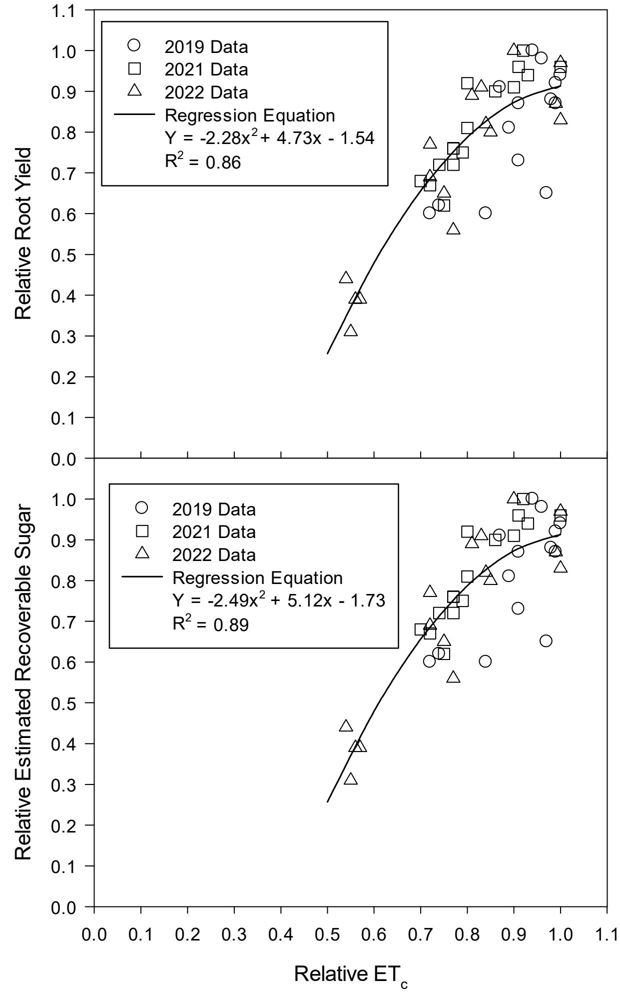

Figure 7. Relationship between relative seasonal sugar beet evapotranspiration and relative root yield and relative estimated recoverable sugar yield for all irrigation treatments and study years.

$$CWSI = 1 - \frac{ET_a}{ET_p} \tag{9}$$

where

ET_a = instantaneous evapotranspiration of crop canopy (mm)

ET_p = maximum instantaneous evapotranspiration of non-water stressed canopy (mm).

The crop water stress index (eq. 3) was measured when evaporative demand was at the diurnal maximum, and assuming the instantaneous evapotranspiration ratio during the maximum diurnal atmospheric demand is similar to the daily ratio of ET_a to non-water stressed crop evapotranspiration (Jackson, 1982), CWSI can be expected to be representative of daily, weekly, or seasonal ratios.

Assuming the seasonal measured value of ET_c under the FIT treatment is representative of non-water-stressed canopy evapotranspiration, then the ratio of seasonal measured ET_c under the DI treatments to that of the FIT treatment needs to follow equation 9 if baseline temperatures T_{LL} and T_{UL} are accurately estimated.

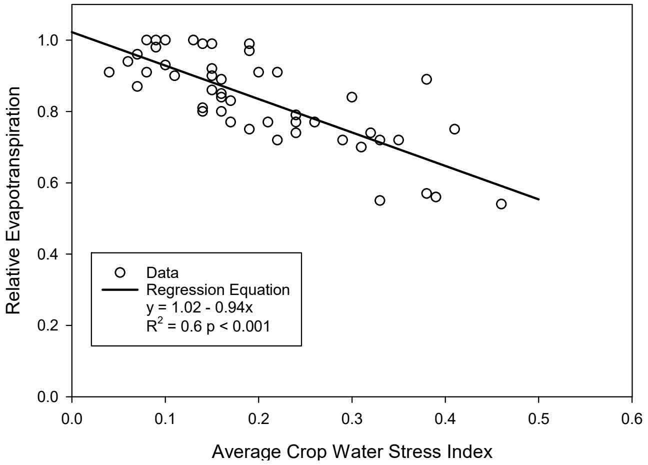

Figure 8. Relationship between seasonal average daily crop water stress index and relative seasonal sugar beet evapotranspiration for all irrigation treatments and study years.

The linear relationship between seasonal CWSI and the ratio of each irrigation treatment measured ET_c to FIT ET_c (table 2) in each study year combined is shown in figure 8. Equation 9 has a slope of -1 and an intercept of one. The linear regression relationship shown in figure 8 is highly significant ($p<0.001$) with a slope of -0.94 and an intercept of 1.02. The slope was not significantly different ($p<0.05$) from -1 and the intercept was not significantly different ($p<0.05$) from 1. Thus, the daily average CWSI calculated in this study accurately represented the ratio of actual to non-water-stressed evapotranspiration seasonal values, implying the 15-min baseline temperatures T_{LL} and T_{UL} were reliably estimated.

CONCLUSIONS

Seasonal evapotranspiration, root yield, and ERS yield of sugar beet under four irrigation treatments, full irrigation and three automated DI treatments based on three thermal CWSI thresholds, were measured in a three-year field study in southcentral Idaho. The automated DI treatments applied 25 mm of water when the daily average CWSI reached 0.2, 0.35, and 0.55 thresholds. There were significant irrigation treatment differences in seasonal evapotranspiration, soil water extraction, seasonal average CWSI, root yield, ERS yield, and water use efficiencies.

Seasonal soil water extraction for the full irrigation treatment was significantly less than for the DI treatments in all study years. In 2021 and 2022, soil water balanced-based evapotranspiration was significantly less for the DI treatments compared to the full irrigation treatment. However, there was no significant difference in root yield, ERS yield, or water use efficiencies between the full irrigation treatment and irrigating when daily CWSI exceeded 0.2 in any study year. Despite substantial differences in ET_r and *fASW* at emergence between the study years, the ET_c of the CWSI1 treatment was very similar in each study year. This result highlights the consistency and accuracy of irrigation scheduling for sugar beet based on a CWSI = 0.2 (CWSI1) regardless of differences in ET_r and soil water availability.

Water production functions were curvilinear, with a downward concave for both root yield and ERS yield. Based on these water production functions, water use efficiencies are constant or increase slightly for seasonal evapotranspiration, which decreases up to 15% of full irrigation. Deficit irrigation of up to 15% of full evapotranspiration can be used to reduce seasonal water use and promote the use of stored soil water. Deficit irrigation based on irrigating when the daily average CWSI exceeds 0.2 was an effective means of implementing consistent mild water stress throughout the season.

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