Soil Water Extraction Patterns and Water Use Efficiency of Irrigated Sugarbeet under Full and Limited Irrigation in an Arid Climate

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ABSTRACT

The effects of full and limited irrigation sugarbeet production practices on soil water extraction and evapotranspiration water use efficiency were investigated in 2015, 2016, and 2017 near Kimberly, Idaho. Four irrigation regimes (fully irrigated (FIT), 75% FIT, 50% FIT and 25% FIT) were studied in 2015 and 2017 and three irrigation regimes (fully irrigated, 60% FIT, 30% FIT and rainfed) were studied 2016. Soil water was extracted from all layers of the 2.25 m soil profile and the pattern of extraction was impacted by irrigation regime. In general, net soil water depleted from the 2.25 m soil profile between emergence and harvest and seasonal average soil water extraction decreased with depth and irrigation amount. For all irrigation treatments and all study years, 70 to 90% of soil water extraction was from the 0 to 1.2 m soil profile and 4 to 10% of soil water extraction was from the 1.8 to 2.25 m soil profile. Water use efficiency increased under limited irrigation. Root yield water use efficiency was greatest for the 50% FIT, 60% FIT, and 75% FIT treatments in 2015, 2016, and 2017, respectively. Estimated recoverable sucrose water use efficiency was greatest for the 50% FIT, 60% FIT, and 50% FIT treatments in 2015, 2016, and 2017, respectively. Root yield water use efficiency was greater and estimated recoverable sugar water use efficiency was equal or greater than reported in other studies.

Additional Key words: rooting depth, root yield, sucrose yield, evapotranspiration

INTRODUCTION

Increased water demand for agricultural and non-agricultural uses and increasing variability in regional and local precipitation has resulted in concerns over water supplies for irrigation in the western U.S. Irrigated sugarbeet production in the western U.S. (CA, CO, ID, MT, OR, WY) comprises about 27% of the total U.S production or 124,300 ha (USDA, 2016). Production in the arid region of eastern Oregon and southern Idaho is approximately 72,000 ha or 15% of total U.S. production. Average seasonal evapotranspiration (ET_a) from irrigated sugarbeet in the eastern Oregon and southern Idaho region ranges from 740 to 890 mm, depending upon growing location season length. Optimum irrigation management practices need to be developed and evaluated for crops like sugarbeet to minimize yield and producer revenue reductions during drought years, minimize irrigation costs, and reduce seasonal water use. With irrigated agriculture being the largest water consumer in the region, it is vital that irrigated agriculture adopt new methods and management practices that increase water use efficiency while sustaining profitable farm enterprises.

One key element of optimum irrigation management is accurate estimation of crop rooting depth and how the amount of soil water used by the crop varies over the rooting profile. Understanding these factors is necessary to quantify crop soil water availability for optimum irrigation timing and amounts to avoid deep percolation losses and crop water stress. The rooting depth of sugarbeet cited in the irrigation management literature ranges from 0.7 to 2.0 m (Jensen et al., 1990; James 1988; Withers and Vipond 1980; Martin et al., 2007, Dunham 1993). Sugarbeet, a biennial crop for seed production and annual crop for sugar production, is known to have a deep root system resulting from its long vegetative growth stage with the depth of the root system increasing up to 15 mm d^{-1} (Dunham, 1993). Erie and French (1968) reported sugarbeet soil water extraction to a depth of 1.5 m with nearly 90 percent from the top 1 m of soil. Sugarbeet has been found to utilized soil water at deeper depths (> 1.7 m) under water stress compared to the irrigated control (< 1.5 m) (Brown et al., 1987). In the absence of soil depth limitations and depending on soil water holding capacity, sugarbeet can access a large soil water reservoir that can buffer yield reductions under deficit irrigation. Winter (1980) reported soil water extraction to permanent wilting point to a depth of 3 m across ten irrigation treatments. Rooting depth and soil water holding capacity have a significant impact on the effect of late season deficit irrigation on sugarbeet root and sucrose yield. For example, Carter et al. (1980) found that cutoff of irrigation up to eight weeks prior to harvest for a silt loam soil at field capacity to a depth of 1.6 m had minimal effect on sucrose yield while reducing irrigation by 30%. Similarly, Howell et al., (1987) found that irrigation cut-off up to 7 weeks before harvest for a deep (~2.5 m) clay loam soil at field capacity had minimal effect on sucrose yield while increasing water use efficiency. Miller and Hang (1980) found that irrigation rates of 35 to 50% of estimated ET_a on a deep loam soil did not reduce sugar yields, but irrigation rates up to 100% estimated ET_a increased sugar yields on a sandy soil with a shallow rooting depth. Similarly, Yonts et al., (2003) found that irrigation cutoff 8 to 10 weeks before harvest on a very fine sandy loam soil significantly reduced sucrose yield. However, Yonts (2011) found that season long deficit irrigation at rates greater than 50% of ET_a rate or deficit irrigation after mid-August at rates greater than 25% ET_a did not significantly decrease sucrose yield on the same very fine sandy loam soil. Hills et al. (1990) found that imposing water stress during August-September reduced sugar beet root and sucrose yield. These studies demonstrate that knowledge of sugarbeet rooting depth is essential to avoid crop water stress while reducing irrigation amounts to conserve water.

Sugarbeet grown for sucrose is considered a moderately drought tolerant crop due to its deep rooting pattern, 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 sugarbeet is first seen as leaf wilt during the highest ET_a 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 effects 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). Early season water stress has been found to be more detrimental to root and sucrose yield than late season water stress because early season effects on canopy and root growth cannot be overcome after water stress is alleviated (Brown et al., 1987; Tarkalson and King, 2017b). Erie and French (1968) proposed scheduling irrigation when 70% of available soil water in the top 0.9 m of the soil was extracted and discontinuing irrigation 3 to 4 weeks before harvest for conserving water after observing the sugarbeet plant's ability to utilize deep soil moisture with minimal effect on sugar yield. Multiple studies have reported increased water use efficiency for sucrose yield of sugarbeet under deficit irrigation (Winter, 1980; Miller and Hang, 1980; Howell et al., 1987; Winter, 1988). Sugarbeet root yield in southern Idaho and eastern Oregon has historically increased about 0.5 Mg ha^{-1} yr^{-1} (Tarkalson et al., 2016) and at a greater rate since 2006 (King and Tarkalson, 2017), which may be due to nearly 100% adoption of glyphosate resistant varieties, improved genetics, and new or improved pesticides. This increase in yields may have increased water use efficiency, if ET_a has not increased accordingly. Water use efficiency response of current sugarbeet production systems to deficit irrigation in the region have not been evaluated.

The objective of this study was to investigate soil water extraction patterns and water use efficiency under full and limited irrigation of sugarbeet production under the arid climatic conditions and silt loam soil type common to southern Idaho and eastern Oregon.

MATERIALS AND METHODS

Site Description

Three field studies were conducted during 2015, 2016, and 2017 at the USDA-ARS Northwest Irrigation and Soils Research Laboratory near Kimberly, Idaho. The climate is arid where the 20-yr (1997-2016) average annual precipitation and alfalfa-reference ET are approximately 253 and 1479 mm, respectively, requiring irrigation for economical agricultural crop production. Approximately 45% of annual precipitation and 83% of annual alfalfa-reference ET occurs during April through mid-October. Climatic data for each year of the study are summarized in Table 1. 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, 2009).

Table 1. Average climatic conditions during each study year and long-term (1998-2017) average values measured at the research site in Kimberly, Idaho. Values shown are average daily minimum air temperature (T_{min}), average daily maximum air temperature (T_{max}), average daily mean air temperature (T_{avg}), average daily relative humidity (RH_{avg}), average daily wind speed, average daily solar radiation (R_s), total rainfall and total alfalfa reference crop evapotranspiration (ET_r).

Year	Month	T_{min} (°C)	T_{max} (°C)	T_{avg} (°C)	RH_{avg} (%)	Wind Speed (m s^{-1})	R_s MJ m^{-2} d^{-1}	Total Rainfall (mm)	ETr (mm)
2015	May	6.9	21.0	13.6	63.7	2.7	19.7	66.5	159.0
	June	12.3	29.6	21.4	46.6	2.3	25.5	9.7	241.6
	July	12.8	29.3	21.0	52.7	2.3	22.4	2.0	231.6
	Aug.	12.1	29.9	20.9	50.3	2.2	19.8	5.3	208.5
	Sept.	7.7	22.3	16.6	49.9	2.1	17.1	7.1	150.4
2016	May	5.9	20.6	13.2	59.9	2.8	21.7	39.1	169.9
	June	10.4	28.5	19.7	46.5	2.5	25.2	4.6	241.6
	July	11.6	30.7	21.5	43.1	2.3	26.0	6.3	264.4
	Aug.	10.5	30.1	20.5	42.4	2.2	22.3	0.8	228.3
	Sept.	7.8	11.3	15.0	58.0	2.5	15.3	59.4	132.1
2017	May	5.3	20.9	13.3	57.3	3.0	23.3	29.2	182.4
	June	10.2	26.2	18.5	51.7	3.0	24.8	11.9	237.0
	July	13.8	33.3	23.8	46.7	2.1	24.3	3.0	262.4
	Aug.	12.5	30.8	21.7	47.1	2.2	20.8	0.8	221.2
	Sept.	7.8	23.5	15.6	54.9	2.4	16.1	14.7	144.0
1998-2017 average	May	5.6	20.4	13.1	55.4	2.9	24.1	28.0	184.7
	June	9.7	25.9	18.0	50.7	2.7	26.9	13.1	233.7
	July	13.6	31.5	22.6	47.6	2.1	26.6	5.7	262.9
	Aug.	11.9	29.9	20.8	48.6	2.1	23.2	12.8	220.7
	Sept.	7.5	24.7	16.0	51.8	2.2	18.5	12.3	183.4

Experimental Design

2015

The field study utilized a strip plot randomized complete block design to evaluate two tillage treatments and four irrigation treatments with four replications. Only one tillage treatment, conventional tillage, was utilized in the results reported in this manuscript. The four irrigation treatments were fully irrigated (FIT), 75% FIT, 50% FIT, and 25% FIT. The fully irrigated treatment represented the conditions where the crop was irrigated two or three times a week with a cumulative depth equal to weekly cumulative estimated ET, and soil water content was monitored to ensure that soil water depletion in the FIT plots remained above 45% of the total available water to avoid potential water stress impact on crop yield. Water was applied with a lateral move irrigation system, where each replicated block was separated by a 33 m wide strip of barley where the irrigation system was stopped, and sprinkler nozzles changed to achieve randomized water treatment amounts using different sized sprinkler nozzles. Each experimental plot was 6.7 m wide (12 rows) by 41.1 m long, which was the length of the lateral move irrigation system span. The harvest area within each plot was 3.7 m (2 rows) by 22.9 m centered in the plot to avoid the effect of sprinkler overlap from adjacent lateral move spans and non-uniform application caused by the lateral move irrigation system structural elements. All treatments were irrigated at the same time with different irrigation depths for each treatment. Additional details of the overall experimental plan are provided by Tarkalson and King (2017a).

2016

The field study utilized a randomized complete block design to evaluate eight irrigation treatments with four replications. Only four irrigation treatments were used in the results reported in this manuscript. The four irrigation treatments were fully irrigated (FIT) as previously described for year 2015, 60% FIT, 35% FIT and rainfed. Irrigation for the FIT, 60% FIT, and 35% FIT treatments was applied using a surface drip irrigation system. A single drip line was placed adjacent to the plants along each crop row. The entire plot area was sprinkler irrigated prior to emergence to ensure good germination and stand establishment across all treatments. The surface drip irrigation system was installed and used for all irrigations after 100% emergence. The experimental plots were 2.2 m wide (4 rows) by 12.2 m long with the center two rows harvested for yield sampling. The different amounts of irrigation water applied to the treatments was achieved by controlling irrigation set time in proportion to target irrigation treatment amount. All treatments were irrigated at the same time with different irrigation depths for each treatment. Complete details of the overall experimental plan and irrigation treatments are provided by Tarkalson and King (2017b).

2017

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) as described for year 2015, 75% FIT, 50% FIT, and 25% FIT. Irrigation was applied using landscape sprinklers arranged on a 4.6 m square spacing at a height of 70 cm above ground level. The experimental plots were 4.6 m wide (8 rows) and 18.3 m long with the center two rows harvested for yield sampling. The different amounts of irrigation water applied to the treatments was achieved by controlling irrigation set time in proportion to target irrigation treatment amount. All treatments were irrigated at the same time with different irrigation depths for each treatment.

Cultural Practices

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, CO). 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 (Moore et al., 2009). In the 2015 study, N fertilizer was applied through the lateral move irrigation system when the sugarbeet crop reached the four-leaf stage, prior to the start of significant crop N uptake (Amalgamated Sugar Co., 2010). In the 2016 and 2017 studies, N fertilizer was applied prior to planting.

In each study year tillage consisted of four tillage passes: moldboard plow, tandem disk, roller harrow and bedding in the spring prior to planting. In 2015 and 2017, the study sites were plowed in the previous fall. The previous crop was spring barley in 2015 and 2016 and corn in 2017. Tillage practices were based on commercial practices for sugarbeet production for suitable seedbed preparation to achieve good soil-seed contact for acceptable germination. In 2017, the experimental site was dammer-diked to prevent runoff and subsequent run-on between plots.

Sugarbeet was planted on 5 May 2015 (cultivar Betaseed 27RR20), 6 May in 2016 (cultivar Betaseed 27RR10), and on 8 May 2017 (cultivar Crystal A404NT MP) with a row spacing of 0.56 m. In all study years seed was treated with the insecticide Poncho Beta (60 g a.i. clothianidin [1-(2-Chloro-1,3-thiazol-5-ylmethyl)-3-methyl-2-nitroguanidine] and 8 g a.i. -cyfluthrin {[(R)-cyano-[4-fluoro-3-(phenoxy)phenyl]methyl] (1R,3R)-3-(2,2-dichloroethenyl)-2,2-dimethylcyclopropane-1-carboxylate} per 100,000 seeds) and the fungicides Allegiance and Thiram (Bayer AG Crop Science Division, Monheim am Rhein, Germany). Seeding rates in all study years were 128,000 plants ha^{-1}. In 2016 the entire study area was thinned by hand to a plant population of approximately 88,070 plants ha^{-1}.

Irrigation Systems

2015

The 2015 experimental site was irrigated with a lateral move irrigation system that traveled perpendicular to the tillage treatment strips. The irrigation system was equipped with Nelson S3000 sprinklers (Nelson Irrigation Corp., Walla Walla, WA) attached to Nelson 138 kPa pressure regulators. The irrigation treatments were achieved by using sprinkler nozzles with flow rates in proportion to the desired relative irrigation treatment amounts. The FIT treatment used nozzles with a flow rate of 24.71 L min^{-1} (#29) and the 75% FIT, 50% FIT, and 25% FIT treatments used nozzles with flow rates of 28.24 (#25), 12.71 (#21), and 6.58 (#15) L min^{-1}, respectively. The lateral-move lateral consisted of six 41.4 m long spans with only the middle four spans used as the experimental area. Each span was equipped with one size of sprinkler nozzle corresponding to the desired irrigation treatment; the lateral move then traversed one experimental block and the irrigation system was stopped in an area between experimental blocks and the sprinkler nozzles were manually changed to achieve randomization of the irrigation treatments. This process was repeated for each experimental block to complete an irrigation event. A catch can was used in each plot to verify water application amounts to each irrigation treatment.

2016

The 2016 experimental site used surface drip irrigation installed immediately after crop emergence with one lateral positioned adjacent to the crop row (within 10 cm). Irrigation water was applied prior to emergence by a solid-set irrigation system to ensure reliable and uniform germination across all irrigation treatments. The drip laterals had emitters spaced every 15 cm and an inside diameter of 1.6 cm (T-Tape 508-15-500, Rivulis Irrigation Inc., San Diego, CA) with a flow rate of 0.75 L h^{-1} at a nominal pressure of 55 kPa. Fixed 70 kPa pressure regulators (Nelson Irrigation Corp., Walla Walla, WA) were installed in each submain of each replicated block to ensure uniform pressure and emitter flow rate across the experimental plot. The irrigation water supply was filtered using an automated hydraulic turbine self-cleaning filter (Filtomat M100-750, Amaid Filtration Systems, Oxnard, CA). Each treatment lateral was equipped with a manual valve and volumetric flow meter. Irrigation amounts were obtained by manually controlling the irrigation time to each treatment.

2017

The 2017 experimental site was irrigated with a solid-set sprinkler system installed immediately after planting and dammer-diking. The sprinkler system used Nelson MP2000 90-210 landscape sprinklers (Nelson Irrigation Corp., Walla Walla, WA) arranged on a 4.6 m square spacing and mounted 70 cm above ground level. Each sprinkler was equipped with a Nelson 241 kPa pressure regulator to ensure uniform pressure and flow across the experimental site. Each treatment water supply line was equipped with a filter (Rusco Spin-Down, Rusco Inc., Brooksville, FL) and a manual valve. A catch can was used in each plot to verify water application amounts to each treatment. Irrigation treatment amounts were obtained by manually controlling the irrigation time of each irrigation treatment.

Irrigation Scheduling

In each study year, irrigation scheduling for the fully irrigated treatment was based on balancing estimated cumulative weekly crop ET_a with the weekly cumulative irrigation and precipitation. Estimated crop ET_a was based on 1982 Kimberly-Penman alfalfa reference evapotranspiration (ET_r) model and daily crop coefficients (Wright, 1982) using daily climatic data from an Agrimet (U.S. Bureau of Reclamation, Boise, ID) weather station located within 4.5 km from the study site. Irrigation was applied 1 to 3 times a week depending upon weekly ET_a rate, less frequent at beginning and end of growing season. The deficit irrigation treatments were started after the four-leaf growth stage to ensure crop establishment and root zone development. Soil water content was measured in 0.15 m depth increments from 0.15 to 2.25 m using neutron probe calibrated to the experimental site soil using the methods of Hignett and Evett (2002). Soil water content in the 0 to 0.15 m depth was continuously monitored using time domain reflectometery (TDR) (TDR 100, Campbell Scientific Co., Logan, UT) with two probes in the crop row. Soil water content was monitored in two replicated blocks in 2015 and 2016 and in all four replicated blocks in 2017. Soil water content was measured at crop emergence and a few days prior to harvest to capture the change in soil water content over the season. Soil water content was also measured periodically throughout the growing season to avoid water stress in the fully irrigated treatments by ensuring that available soil water content remained greater than 45% of total available moisture (Jensen et al., 1990).

Seasonal Evapotranspiration

Seasonal actual crop evapotranspiration (ET_a, mm) was calculated using a soil water balance from sugarbeet emergence to harvest:

$$ET_a = \Delta S + P + I - DP - R \qquad [1]$$

where ΔS is the change in soil water storage in the soil profile (mm), P is cumulative precipitation (mm), I is cumulative irrigation (mm), R is the difference between runoff and run-on (mm), and DP is water percolating below the root depth (mm). Precipitation was recorded in catch cans and used to verify amounts measured in the rain gauge at the Agrimet weather station site. Deep percolation was assumed to be zero based on soil water content in the lower depths of the 2.25 m soil profile remaining less than field capacity from emergence to harvest. In 2015, R was estimated for each irrigation and precipitation event in the FIT and 75% FIT treatments by measuring runoff from an area of 1.4

m^2 using runoff collection frames that emptied into a buried collector. Runoff was not measured in the 50% and 35% FIT treatments as ponding and runoff was not visible under the lower water application rates and depths of these treatments. In the 2016 drip irrigated study, R was assumed to be zero as the plot borders were diked to prevent inter-plot runoff and run-on, and the application rate was low enough to limit ponding and surface water movement within a plot based on visual observation. In the 2017 sprinkler irrigated study, R was assumed to be zero as the plots were dammer-diked to prevent surface water movement within and between plots.

Crop Water Use Efficiency

Sugarbeet crop water use efficiency was calculated in terms of root yield ($CWUE_r$, Mg ha^{-1} m^{-3}) and sucrose yield ($CWUE_s$, kg ha^{-1} m^{-3}) as:

$$CWUE_r = Y_r/ET_a \quad [2]$$

$$CWUE_s = Y_s/ET_a \quad [3]$$

where Y_r (Mg ha^{-1}) and Y_s (Kg ha^{-1}) are root and sucrose yield, respectively.

Soil Profile Water Extraction

Soil water extraction in this study represents soil water extracted by the sugarbeet crop for ET_a and was calculated as the decrease in soil water between successive soil water measurement dates plus water added by irrigation and precipitation during the period. Determination of water extraction from individual soil layers requires estimation of the distribution of water inputs to each soil layer. The distribution of applied irrigation and precipitation in 0.15 m soil profile layers was modeled as a top down cascade process. First, the soil water deficit of each layer was calculated based on the difference in average soil water content between two soil water measurement dates and field capacity of the layer (Djaman and Irmak, 2012; Lenka et al., 2009). Any irrigation or rainfall occurring between the two soil water measurement dates that was greater than the soil water deficit of the above 0.15 m layer was assumed to move to the next lower soil layer. The amount of water available to the next layer is the sum of irrigation and precipitation minus calculated soil water deficit of the above layer(s). This calculation process was repeated for all layers down to 2.25 m. The sum of the change in soil moisture of a layer between soil water measurement dates and stored irrigation and/or precipitation water represents the water extracted from the layer between the measurement dates. Water extraction of each layer is reported as a percentage of the total extraction from the 2.25 m soil profile as a means of normalizing the data for treatment differences in ET_a between soil water measurement periods.

Harvest

Roots in the center two rows of each plot were harvested on 6 Oct. 2015, 6 Oct. 2016, and 5 Oct. 2017. 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, ID) tare lab for analysis of percent sucrose and impurities. Percent sucrose was determined using an Autopol 880 polarimeter (Rudolph Research Analytical, Hackettstown, NJ), a half-normal weight sample dilution, and aluminum sulfate clarification method [ICUMSA Method GS6-3 1994] (Bartens, 2005). Conductivity was measured using a Foxboro conductivity meter Model 871EC (Foxboro, Foxboro, MA) and brei nitrate was measured using a multimeter Model 250 (Denver Instruments, Denver, CO) with Orion probes 900200 and 9300 BNWP (Krackler Scientific, Inc., Albany, NY). Recoverable sucrose yield per metric ton of roots was determined by Amalgamated Sugar Co. (Twin Falls, ID) tare lab as described by Tarkalson and King (2017b). Recoverable sucrose yield per metric ton of roots was multiplied by root yield to obtain estimated recoverable sucrose (ERS) yield (kg ha^{-1}).

Statistical Analysis

Data were analyzed using PROC MIXED in SAS (SAS Institute, 2013) to test for treatment differences. Treatment was designated as a fixed effect and replication as a random effect. Each year was analyzed separately as treatments differed between years as well as irrigation systems. Soil water content sampling date was used as a repeated measure in PROC MIXED for ANOVA of soil water extraction at each measurement depth. Least squares means (LSMEANS) was used to differentiate significance of treatment and interaction effects ($p \leq 0.05$). Residual diagnostics were conducted to evaluate the assumptions of ANOVA and determine the need for data transformations. The soil water extraction data for a given depth was often log transformed to obtain approximately normally distributed residuals. The soil water extraction data were analyzed as cumulative extraction from soil surface to depth of concern to overcome the presence of numerous zero extraction values in the data set, particularly at deeper depths. This prevented statistical comparison of soil water extraction at the 2.25 m depth but allowed statistical analysis of cumulative soil water extraction data for all other depth ranges.

RESULTS AND DISCUSSION

Climatic Conditions During Study Years

Climatic conditions (Table 1) were near the 20-yr averages for the three study years except for rainfall, which exceeded twice the 20-yr average in May 2015 and Sept. 2016. Alfalfa ET_r was below the 20-yr average in May and Sept. of 2015 and Sept. 2017, but not of sufficient magnitude relative to irrigation amount to substantially impact yield of irrigated treatments. May through September cumulative ET_r was 991, 1036, 1047 mm in 2015, 2016, 2017, respectively, but below the 20-year average of 1085 mm in all study years.

Soil Water Status

Soil water contents at emergence and prior to harvest are depicted in Figs. 1-3 for study years 2015, 2016, and 2017, respectively. Soil water content below 1.8 m at emergence in 2015 was greater than in 2016 and 2017. In 2016, soil water content of the 2.25 m profile at emergence was lower than in 2015 and 2017. In 2015 and 2017, there was minimal difference in soil water contents of the 2.25 m profile for the fully irrigated treatment between emergence and harvest. The difference between soil water contents at emergence and harvest represents net water removed from the soil profile over the growing season. The amount of net soil water removed from each soil layer and the 2.25 m profile for each treatment and study year is shown in Table 2. With exception of the rainfed treatment in 2016, net amount of soil water removed from the 2.25 m profile decreased as seasonal irrigation amount increased. In 2016, the rainfed treatment extracted less soil water from the profile than the 35% FIT treatment. This is likely the result of severe water stress limiting root growth impairing soil water extraction at depths greater than 1.5 m and less soil water in the soil profile at emergence (Fig. 2) compared to the 35% FIT treatment.

Table 2. Soil profile water depletions (mm) per 0.15 m soil depth increment and total soil profile water depletions from sugarbeet emergence to harvest under full and various levels of limited irrigation in each of the three study years. Negative values indicate that the soil water depth was greater at the end of the season than at emergence.

Soil Depth (m)	2015				2016				2017			
	25% FIT	50% FIT	75% FIT	FIT	Rainfed	35% FIT	60% FIT	FIT	25% FIT	50% FIT	75% FIT	FIT
0-0.15	25	21	-9	2	27	21	21	4	30	22	14	8
0.15-0.3	18	12	6	-2	4	10	1	-1	27	12	11	9
0.3-0.45	22	17	10	1	18	16	12	4	21	16	5	1
0.45-0.6	30	26	19	4	29	28	23	10	20	20	9	-1
0.6-0.75	30	26	17	3	36	32	28	14	20	18	14	-2
0.75-0.9	25	22	9	3	28	25	26	17	19	19	15	-2
0.9-1.05	21	15	13	2	23	22	25	16	17	17	12	-2
1.05-1.2	19	11	10	5	19	21	22	13	17	15	5	-2
1.2-1.35	20	9	12	5	19	20	15	12	17	11	3	0
1.35-1.5	20	10	15	4	17	22	14	11	12	8	3	1
1.5-1.65	15	9	12	6	15	22	14	12	9	7	6	1
1.65-1.8	14	6	12	4	13	20	12	10	7	6	8	1
1.8-1.95	10	3	7	3	11	27	9	9	5	5	9	1
1.95-2.1	3	4	0	3	7	14	7	7	3	5	4	1
2.1-2.25	4	1	7	1	8	13	6	5	5	5	3	2
0-2.25	276	194	139	46	273	303	234	144	228	187	121	13

Soil water removed from the 2.25 m profile for the FIT treatments in 2015 and 2017 was 46 and 13 mm, respectively. These minimal seasonal soil water extractions indicate that FIT treatment irrigation amounts adequately replaced seasonal ET_a without deep percolation throughout the season (data not shown). Soil water contents at the end of the season in 2016 were lower than in other years and are likely the result of lower soil water contents at emergence. With exception of the 35% FIT in 2016, net soil water removed below 1.95 m was less than 10 mm per 15 cm depth increment, indicating that the 2.25 m soil water monitoring depth exceeded the effective root zone of sugarbeet at the study site. In general, net soil water extraction below 1 m increased as seasonal irrigation amount decreased.

Nominal field capacity and permanent field capacity for the Portneuf silt loam soil at the study site is 32% and 14% by volume as determined in the laboratory using a pressure plate apparatus (Dole et al., 1974). In this manuscript, field capacity and permanent wilting point were taken as the maximum and minimum soil water contents measured by neutron probe over the three-year study period, which generally occurred at the beginning and end of the season (Figs. 1-3). In this manner, field capacity and permanent wilting point were 36% and 9%, respectively. The real behavior of crops often reveals that soil water can be extracted below the classical limit of -1.5 MPa (Cabelguenne and Debaeke, 1998). Based on observed values field capacity and permanent wilting point, maintaining 45% available soil water to avoid crop water stress corresponds to 21% soil water content. In all study years, a portion of the soil water profile in FIT treatments remained greater than 21% soil water content at the end of the season (Figs. 1-3) and throughout the season (data not shown), also indicating that FIT treatment irrigation amounts adequately replaced seasonal ET_a and avoided plant water stress.

Seasonal Soil Water Balance

Soil water balance (Eqn. 1) components (DP=0) for each irrigation treatment and study year are shown in Table 3. Sugarbeet ET_a for the FIT treatments varied by more than 100 mm between study years with 2015 being the least and 2016 the greatest. Irrigation amounts also varied between study years by nearly 100 mm, with 2015 being the least and 2017 being the greatest, corresponding with May through September ET_r (Table 1). Sugarbeet ET_a of the rainfed treatment in 2015 was the least over the study years, but still represented 38% of FIT ET_a due to 273 mm of soil water extraction.

Soil Water Extraction

The proportion of soil water extracted for each soil layer over the growing season under each irrigation treatment in 2015, 2016 and 2017 is shown in figures 4, 5, and 6, respectively. Cumulative seasonal soil water extraction (mm) for each soil layer and the 2.25 m soil profile under each irrigation treatment and study year is presented in Table 4. In general,

Table 3. Growing season soil water balance components for each treatment and study year. Inputs are soil moisture depletion over growing season (emergence – harvest), rainfall, irrigation and the only loss is runoff in 2015. Crop ET is the soil water balance residual and represents evaporation and transpiration that occurred in producing the crop.

Year	Treatment	Soil Moisture Depletion (mm)	Rainfall (mm)	Irrigation (mm)	Runoff (mm)	Crop ET (mm)
2015	FIT	46	51	592	26	663
	75% FIT	139	51	442	16	616
	50% FIT	194	51	317	0	562
	25% FIT	276	51	155	0	482
2016	FIT	144	72	686	0	902
	60% FIT	234	72	394	0	700
	35% FIT	303	72	213	0	588
	rainfed	273	72	0	0	345
2017	FIT	13	30	757	0	800
	75% FIT	121	30	536	0	687
	50% FIT	187	30	386	0	603
	25% FIT	228	30	248	0	506

Table 4. Pattern of soil water extraction (mm) per 0.15 m soil depth and soil profile total water extraction for each study year and irrigation treatment.

Soil Depth (m)	2015				2016				2017			
	25% FIT	50% FIT	75% FIT	FIT	Rainfed	35% FIT	60% FIT	FIT	25% FIT	50% FIT	75% FIT	FIT
0-0.15	213	205	151	144	69	198	223	111	183	253	223	131
0.15-0.3	38	162	136	152	37	82	153	140	50	62	145	128
0.3-0.45	33	73	79	72	31	62	99	116	47	45	63	146
0.45-0.6	36	35	60	34	38	35	76	118	34	49	42	97
0.6-0.75	36	34	64	29	30	30	28	103	33	35	37	61
0.75-0.9	37	31	42	42	25	26	28	95	24	25	33	52
0.9-1.05	33	28	34	37	20	24	25	84	22	23	27	37
1.05-1.2	24	26	26	42	19	26	17	43	20	15	16	28
1.2-1.35	24	16	18	45	19	25	15	42	16	15	15	12
1.35-1.5	25	16	25	40	16	26	17	24	14	12	13	9
1.5-1.65	21	16	21	25	15	26	19	18	12	13	16	9
1.65-1.8	19	13	24	24	15	24	16	16	10	13	16	7
1.8-1.95	23	11	19	22	16	18	16	15	10	12	10	12
1.95-2.1	17	13	10	12	12	19	14	12	10	12	12	12
2.1-2.25	11	11	18	10	11	18	16	12	10	7	11	8
0 – 2.25	590	689	728	741	373	638	763	948	496	591	678	747

the soil water extraction decreased with soil depth. Soil profile water extraction varied from 590 to 741 mm in 2015, 373 to 948 mm in 2016, and 496 to 747 in 2017 and was comparable to ET_a, which varied from 482 to 663 mm in 2015, 345 to 902 mm in 2016, and 506 to 800 mm in 2017. Computed soil water extraction often exceeded ET_a due to modeling infiltration using the cascading method and errors in soil water measurements between consecutive readings. This outcome is consistent with results reported by Djaman and Irmak (2012) where computed soil water extraction from a 1.8 m soil profile with limited and full irrigation exceeded crop evapotranspiration. The errors are consistent across all treatments and years allowing comparison of relative differences in extraction between irrigation treatments. In each study year the greatest amount of soil water extraction from the 2.25 m soil profile occurred under the fully irrigated treatment; the treatment with the smallest irrigation amount had the smallest soil water extraction, consistent with the conventional logic that less water available results in less soil water extraction. With exception of the rainfed treatment in 2016, irrigation treatments with the greatest soil water extraction from the 2.25 m soil profile correspond to treatments with the least difference in soil water depletions between emergence and harvest (Table 2). In general, soil water extraction over the 0 to 1.2 m soil depth varied substantially between irrigation treatments, especially for the full irrigation treatment in 2016. Conversely, soil water extractions over the 1.2 to 2.25 m soil depth were very similar across irrigation treatments. In all study years, with exception of the rainfed treatment in 2016, the fully irrigated treatment had the least soil water extraction from the 0 to 0.15 m soil layer compared to the other irrigation treatments, whereas Djaman and Irmak (2012) reported the greatest soil water extraction from the 0 to 0.3 m soil layer for corn under full irrigation, which they attributed to a high root mass in the zone and soil evaporation. In 2016, the percentage of soil water extraction from the 0 to 0.15 m depth was less than in 2015 or 2017 and the percentage of soil water extraction from the 0.3 to 1.5 m soil depth was greater in 2016 than 2015 or 2017. This may be due to the low application rate and longer irrigation times associated with use of drip irrigation in 2016 compared to sprinkler irrigation in 2015 and 2017. For all irrigation treatments and all study years, 70 to 90% of soil water extraction was from the 0 to 1.2 m soil profile. In contrast, 4 to 10% of soil water extraction was from the 1.8 to 2.25 m soil profile.

Significant irrigation treatment, sampling date, and interaction between irrigation treatment and sampling date differences in cumulative percent soil water extraction were present in each year of the study (Table 5) over multiple inclusive depths. The presence of a significant interaction term is expected as cumulative percent soil water extraction will differ between irrigation treatments throughout the season as the soil water profile is depleted at different rates according to irrigation treatment amounts, and irrigation amounts between

Table 5. Analysis of variance probability values (P > F) of fixed effects (I=irrigation, DOY = sampling date, I x DOY = interaction between irrigation and sampling date) for cumulative percent soil water depletion of each inclusive 0.15 m layer in the soil profile depth. Bolded values represent significance at the 0.05 probability level.

Soil Depth (m)	2015			2016			2017		
	I	DOY	I x DOY	I	DOY	I x DOY	I	DOY	I x DOY
0-0.15	**0.026**	**<.001**	**.002**	**<.001**	**<.001**	**<.001**	**<.001**	**<.001**	**<.001**
0.15-0.3	**0.033**	**<.001**	**0.005**	**<.001**	**<.001**	**<.001**	**<.001**	**<.001**	**<.001**
0.3-0.45	**0.041**	**0.001**	**0.006**	**<.001**	**<.001**	**0.001**	**<.001**	**<.001**	**<.001**
0.45-0.6	**0.044**	**0.002**	**0.004**	**<.001**	**<.001**	**0.006**	**<.001**	**<.001**	**<.001**
0.6-0.75	0.094	**0.001**	**0.002**	**<.001**	**<.001**	**0.005**	**<.001**	**<.001**	**<.001**
0.75-0.9	0.240	**0.005**	**0.004**	**<.001**	**<.001**	**0.001**	**<.001**	**<.001**	**<.001**
0.9-1.05	0.170	**0.005**	**0.006**	**<.001**	**<.001**	**0.015**	**<.001**	**<.001**	**<.001**
1.05-1.2	0.083	**0.006**	**0.012**	**0.001**	**0.001**	**0.045**	**0.004**	**<.001**	**0.005**
1.2-1.35	0.080	**0.002**	**0.007**	**0.002**	**0.007**	0.092	**0.006**	**<.001**	**0.031**
1.35-1.5	0.107	**0.004**	**0.031**	**0.003**	**0.010**	0.106	**0.032**	**<.001**	0.061
1.5-1.65	0.143	**0.018**	0.098	**0.006**	0.063	0.185	0.088	**<.001**	0.244
1.65-1.8	0.108	0.069	0.117	**0.002**	0.068	0.198	0.158	**<.001**	0.288
1.8-1.95	0.125	0.076	0.208	0.128	**0.005**	0.163	0.168	**<.001**	0.675
1.95-2.1	0.279	0.170	0.234	0.096	0.096	0.277	0.053	**<.001**	0.643

treatments were different with every irrigation. For example, soil water of the 25% FIT or rainfed treatment will be depleted first, followed by the 35% or 50% FIT treatment, then the 60 or 75% FIT treatments. Thus, a significant interaction between irrigation treatment and sampling date on cumulative percent soil water extraction is expected.

In 2015, sampling date was significant for inclusive soil depths up to 1.65 m and the interaction between irrigation treatment and sampling date was significant up to 1.5 m soil depth (Table 5). In 2015, significant irrigation treatment differences in season cumulative percent soil water extraction were present for inclusive soil depths up to 0.6 m (Table 5). Cumulative soil water extraction for the 0 to 0.15 m soil depth was significantly less for the full irrigation treatment compared to the other irrigation treatments (Figure 4). Cumulative percent soil water extraction for the 0 to 0.3 m soil profile depth was significantly greater for the 50% and 75% FITs. This is likely a result of limited infiltration depth of small irrigation amounts that were quickly extracted for ET_a. Cumulative percent soil water extraction from the 0 to 0.3 m soil profile for the 25% FIT was significantly less than for the 50% and 75% FITs. This is likely due to seasonal irrigation amount being less than soil water extraction from the soil profile over the season (Table 3), limiting extraction of water from irrigation relative to the total water extracted from the 0 to 2.25 m soil profile. Similarly, cumulative percent soil water extraction from the 0 to 0.45 m soil profile for the 25% FIT was significantly less than for the 50% and 75% FITs. Cumulative percent soil water extraction from the 0 to 0.6 m soil profile was significantly different between the 25% FIT and 75% FIT. This is likely due to seasonal irrigation amount of the 25% FIT being only 35% of the irrigation amount to the 75% FIT (Table 3). Cumulative percent soil water extraction of the fully irrigated treatment was numerically less than the other irrigation treatments between the 0 to 0.75 m to the 0 to 1.2 m soil profile depths. This is consistent with minimal differences in soil water extraction amounts below a depth of 1.5 m (Table 4).

In 2016, sampling date was significant for inclusive soil depths up to 1.5 m and the 0 to 1.95 m soil depth (Table 5), and the interaction between irrigation treatment and sampling date was significant for inclusive depths up to the 1.2 m. In 2016, significant irrigation treatment differences in season cumulative percent soil water extraction were present for inclusive soil depths up to 1.8 m (Table 5). Cumulative soil water extraction for the 0 to 0.15 m soil depth was significantly less for the full irrigation treatment compared to the 35% and 60% FITs (Figure 5). Cumulative soil water extraction for the 0 to 0.3 m, 0 to 0.45 m, and 0 to 0.75 m soil depths were significantly greater for the 35% FIT and 60% FIT compared to the rainfed and fully irrigated treatments. Analogous to 2015, this is likely due to limited irrigation amounts of the 35% FIT and 60% FIT being quickly extracted for ET_a in contrast to the rainfed treatment with zero irrigation water to extract and the fully irrigated treatment that extracted a substantial amount of soil water below the 0.75 m soil depth in 2016 (Table 4). Cumulative soil water extraction for the 0 to 0.75 m, 0 to 0.9 m, and 0 to 1.05 m soil depths were significantly less for the rainfed treatment compared to the irrigated treatments (Figure 5). This is due to only 72 mm of precipitation (Table 3) available over the growing season resulting in soil water extraction from deeper soil depths comprising a larger portion of cumulative soil water extraction. Limited soil water availability of the rainfed treatment at shallow soil depths due to limited precipitation also resulted in cumulative soil water extraction for 0 to 1.2 m, 0 to 1.35 m, 0 to 1.5 m, 0 to 1.65 m, and 0 to 1.8 m soil depths being significantly less than for the fully irrigated treatment.

In 2017, sampling date was significant for all soil depths (Table 5), and the interaction between irrigation treatment and sampling date was significant up to the 1.35 m soil depth. In 2017, significant irrigation treatment differences in season cumulative percent soil water extraction were present for inclusive soil depths up to 1.5 m (Table 5). Cumulative soil water extraction for the 0 to 0.15 m and 0 to 0.3 m soil depths was significantly less for the fully irrigated treatment compared to the other irrigation treatments (Figure 6). Cumulative percent soil water extraction for the 0 to 0.6 m through 0 to 1.05 m soil depths was significantly less for the 25% FIT compared to the other irrigation treatments. This is likely due to the other irrigation treatments receiving more irrigation water that was extracted from the 0 to 1.05 m soil profile, whereas irrigation water of the 25% treatment is nearly equal to the amount of soil water extracted from the 2.25 m soil profile over the season (Table 3), reducing the proportion of water extracted from the 0 to 1.05 m soil profile.

In general, the 25% FIT or rainfed treatments tended to have less percent cumulative extraction from the 0 to 0.9 m soil profile than the 50% FIT to 75% FIT treatments due to less water available relative to water extracted from the 0.9 to 2.25 m soil profile. The fully irrigated treatments tended to have less percent cumulative extraction from the 0 to 0.6 m soil profile than the 50% FIT to 75% FIT treatments due to deeper infiltration depth of irrigation water resulting in a smaller fraction of extraction, whereas smaller irrigation amounts of the 50% FIT to 75% FIT treatments did not infiltrate beyond 0.6 m and were rapidly extracted for ET_a. This result differs from Djaman and Irmak (2012) where the 0 to 0.3 m soil layer of fully irrigated corn had the greatest soil water extraction relative to deficit irrigated treatments. This difference may be due to rooting characteristic differences between corn and sugarbeet, and differences in frequency and amounts of water inputs from primarily irrigation (>80% of ET_a) in this study versus primarily precipitation (>70% ET_a) for Djaman and Irmak (2012). Over the 3-year study, 90% or more of soil water extraction under the fully irrigated treatment was from the 0 to 1.5 m soil profile. Over the 3-year period, 90% or more of soil water extraction under all irrigation treatments was from the 0 to 1.8 m soil profile. Water extraction was measured to a depth of 2.25 m in all treatments, but there was no indication of deep rooting preference of sugarbeet under seasonal water deficit conditions, consistent with the results of Hao et al (2015) for maize. However, limited irrigation had a significant effect on proportion of water extraction from different soil layers.

Root and ERS Yield

There was a significant irrigation treatment effect on root and ERS yield in each study year (Table 6). In 2015, root yield and sucrose yield were not significantly different for the FIT, 75% FIT and 50% FIT treatments. However, in 2017 these irrigation treatments were all significantly different. In 2015 there was only 101 mm ET_a difference between the 50% FIT and fully irrigated treatment while in 2017 the ET_a difference was double the amount at 197 mm (Table 3). The lack of an irrigation treatment effect in 2015 is the result of lower root yield of the FIT, 75% FIT and 50% FIT treatments in 2015 compared to 2017, coincident with lower ET_a in 2015 compared to 2017. The reason for the lower ET_a and yields in 2015 is unknown, although different sugarbeet varieties were used in each study year representing one possible explanation. In contrast, ERS was greater in 2015 than 2017 for all irrigation treatments due to greater root sucrose concentration in 2015 (Table 6). Root and ERS yield were greater in 2016 for the 60% FIT and fully irrigated treatment compared to the 75% FIT and fully irrigated treatments in either 2015 or 2017. The ET_a of the FIT and 60% FIT in 2016 were also greater than ET_a for the FIT and 75% FIT in 2015 and 2017 (Table 3). The greater yields and ET_a in 2016 suggest better sugarbeet growing conditions in 2016 despite the lack of obvious differences in climatic conditions between study years (Table 1) and growing season lengths. Average root yields of the fully irrigated treatments in 2016 and 2017 were 30% greater than yields for the same area reported by Carter et al., (1980) and root yields reported by Yonts et al., (2003) for western Nebraska, reflecting the increase in sugarbeet yields of the region since about 2006.

Several irrigation studies on sugarbeet have reported an increase in root sucrose concentration with late season water stress (Loomis and Worker, 1963; Erie and French, 1968; Carter et al., 1980a; Miller and Hang, 1980; Carter, 1982; Brown et al., 1987; Howell et al., 1987). In contrast, a significant increase in root sucrose concentration with water stress was reported in only one of seven years by Winter (1988) and zero of three years by Yonts et al., (2003), and the trend with ET_a varied positive to negative between years in both studies. Growing season climatic conditions affect root sucrose concentration (Carter, 1982; King and Tarkalson, 2017). Root sucrose concentrations were lower in 2017 compared to 2015 or 2016, which may be due to growing season climatic conditions or possibly variety differences since a different variety was

Table 6. Root yield, estimated recoverable sucrose (ERS) yield, root sucrose concentration, root yield water use efficiency and estimated recoverable sucrose yield water use efficiency.

Year	Treatment	Root Yield ($Mg\ ha^{-1}$)	ERS ($kg\ ha^{-1}$)	Sucrose (%)	Root Yield Water Use Efficiency ($Mg\ m^{-3}$)	ERS Water Use Efficiency ($kg\ m^{-3}$)
2015	FIT	77.4[a*]	11972[a]	18.0[a]	0.0095	1.469
	75% FIT	70.3[a]	11246[a]	18.5[a]	0.0114	1.826
	50% FIT	69.0[a]	10954[a]	18.5[a]	0.0123	1.949
	25% FIT	52.7[b]	8174[b]	18.2[a]	0.0109	1.696
2016	FIT	96.6[a]	14819[a]	18.1[a]	0.0107	1.643
	60% FIT	79.5[b]	11764[b]	17.6[a]	0.0114	1.681
	35% FIT	54.9[c]	7531[c]	16.3[b]	0.0093	1.281
	rainfed	22.2[d]	2719[d]	14.7[c]	0.0064	0.788
2017	FIT	86.7[a]	11015[a]	16.5[a]	0.0108	1.377
	75% FIT	77.1[b]	9897[ab]	16.5[a]	0.0112	1.441
	50% FIT	65.9[c]	9016[b]	17.2[a]	0.0109	1.495
	25% FIT	42.5[d]	5888[c]	17.4[a]	0.0084	1.164

* Values with the same letter in each year are not significantly different ($p \leq 0.5$).

used each year. In 2015 and 2017, root sucrose concentration increased as ET_a decreased, consistent with other studies but not statistically significant (Table 6). In 2016, there was a significant irrigation treatment effect on root sucrose concentration, but root sucrose concentration decreased as ET_a decreased, contrary to most other studies, but consistent with trends reported by Winter (1988) and Yonts et al. (2003).

Most research studies have reported sugar yield as root yield multiplied by root sucrose content, neglecting the impact water stress induced impurities in juice may have on sucrose recovery in the refining process. Juice impurity is not usually improved by water stress (Hills et al., 1990). Carter (1982) found that root sucrose concentration increased under late season water stress due to root dehydration, but sugar yield remained constant. Comparable results were reported by Loomis and Worker (1963), Erie and French (1968) and Ehlig and LeMert (1979). In contrast, Howell et al., (1987) reported a significant increase in sugar yield with increasing late season water stress while Winter (1988) found a significant decrease in sugar yield with seasonal water stress. In this study, seasonal water stress significantly reduced ERS yield every year (Table 6). The reduction in root yield from water stress dominated any increase in root sucrose concentration in 2015 or 2017, resulting in significantly reduced ERS yield. The significant reduction in root sucrose concentration and root yield by water stress in 2016 combined to overwhelmingly reduced ERS yield. Compared to the results of Carter et al., (1980b), root sucrose concentration has remained relatively unchanged but ERS yield of the fully irrigated treatments in 2016 and 2017 was 18% greater than sugar yield reported for the same area due to higher root yield.

Water Use Efficiency

In this study root yield and ERS water use efficiency were greatest for deficit irrigation treatments in each study year (Table 6). Root yield water use efficiency was greatest for the 50% FIT, 60% FIT and 75% FIT treatments in 2015, 2016, and 2017, respectively. Estimated recoverable sucrose water use efficiency was greatest for the 50% FIT, 60% FIT, and 50% FIT treatments in 2015, 2016, and 2017, respectively. A quadratic relationship between root yield or ERS water use efficiency and the ratio of actual crop ET_a to 100% FIT treatment ET_a (ET_{amax}) in each study year provided a good representation of deficit irrigation effect on sugar beet water use efficiency (Figure 7). Based on the quadratic regression equation both root yield and ERS water use efficiency are maximum near ETa/ETamax of 0.6. A similar quadratic relationship between root yield and ERS water use efficiency and irrigation depth indicates that for the study site conditions, a seasonal irrigation depth of about 450 mm will maximize sugarbeet water use efficiencies. The irrigation depth that maximizes water use efficiencies is highly dependent on soil water holding capacity, spring soil water content, and rooting depth. Depletion of soil water storage over the growing season in the rainfed treatment of 2016 provided about 40% of ET_{amax} (Figure 4). Production sites with soils of lower water holding capacity and/or shallower rooting depth would require greater seasonal irrigation depths to maximize water use efficiencies. The R^2 values for the quadratic water use efficiency relationships are better for root yield than ERS due to uncontrolled experimental conditions such as early season climatic effect on sugarbeet sucrose content (King and Tarkalson, 2015).

Root yield water use efficiency of previous studies ranges from 0.0053 Mg m^{-3} (Winter, 1980) to 0.0096 Mg m^{-3} (Ehlig and LeMert, 1979) under full irrigation. Root yield water use efficiency of data presented by Winter (1988) and Ehlig and LeMert (1979) of fall planted sugarbeet was greater under reduced irrigation compared to adequate irrigation, consistent with the results of this study. Maximum root yield water use efficiency measured in every year of this study equals or exceeds values of previous studies. This is likely due to the increase in sugarbeet root yields since 2006 (King and Tarkalson, 2015) without a corresponding increase in ET_a. Sugar yield water use efficiency of previous studies ranges from 0.74 kg m^{-3} (Howell et al., 1987) to 1.59 kg m^{-3} (Hang and Miller, 1986) under full irrigation. Most of the previous studies did not find an increase in sugar yield water use efficiency with deficit irrigation, with exception of Winter (1988). In 2015 and 2016, ERS water use efficiency of this study was equal to or greater than sugar yield water use efficiency of previous studies. Estimated recoverable sucrose water use efficiency was less in 2017, due to lower root sucrose concentrations compared to 2015 and 2016. The results of this study indicate that reduced irrigation up to 25% of ET_a during water short years will result in reduced ERS yields but not catastrophic economic losses.

CONCLUSIONS

Soil water depletion from each 0.15 m soil layer and seasonal total soil water extraction patterns of a 2.25 m soil profile for fully irrigated and limited irrigation sugarbeet production were quantified. Irrigation regime significantly impacted soil water extraction pattern. In general, net soil water depleted from the 2.25 m soil profile between emergence and harvest decreased with depth and seasonal irrigation amount. Similarly, seasonal soil water extraction decreased with depth and irrigation amount. Soil water extraction from the 0 to 0.15 m top soil layer of the fully irrigated treatment was less than the limited irrigation treatments, except rainfed, which was the likely due to limited growing season precipitation. For all irrigation treatments and all study years, 70 to 90% of soil water extraction was from the 0 to 1.2 m soil profile. In contrast, 4 to 10% of soil water extraction was from the 1.8 to 2.25 m soil profile. Quadratic relationships between root yield water use efficiency and estimated recoverable sucrose water use efficiency versus sugarbeet ET_a and applied irrigation water were statistically significant ($p \leq 0.05$) for southern Idaho climatic conditions. Water use efficiency increased under limited irrigation. Root yield water use efficiency was greatest for the 50% FIT, 60% FIT and 75% FIT treatments in 2015, 2016, and 2017, respectively. Estimated recoverable sucrose water use efficiency was greatest for the 50% FIT, 60% FIT, and 50% FIT treatments in 2015, 2016, and 2017, respectively. Root yield water use efficiency was greater than in previous reported studies, which is likely due to an increase in sugarbeet yields of the region over the past decade. Estimated recoverable sugar water use efficiency was equal to or greater than found in previous reported studies.

ACKNOWLEDGEMENTS

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Figure 1. Soil water contents measured at emergence (DOY 133) and prior to harvest (DOY 273) in 2015 in each of the four irrigation treatments. Bars represent standard error of the measurements.

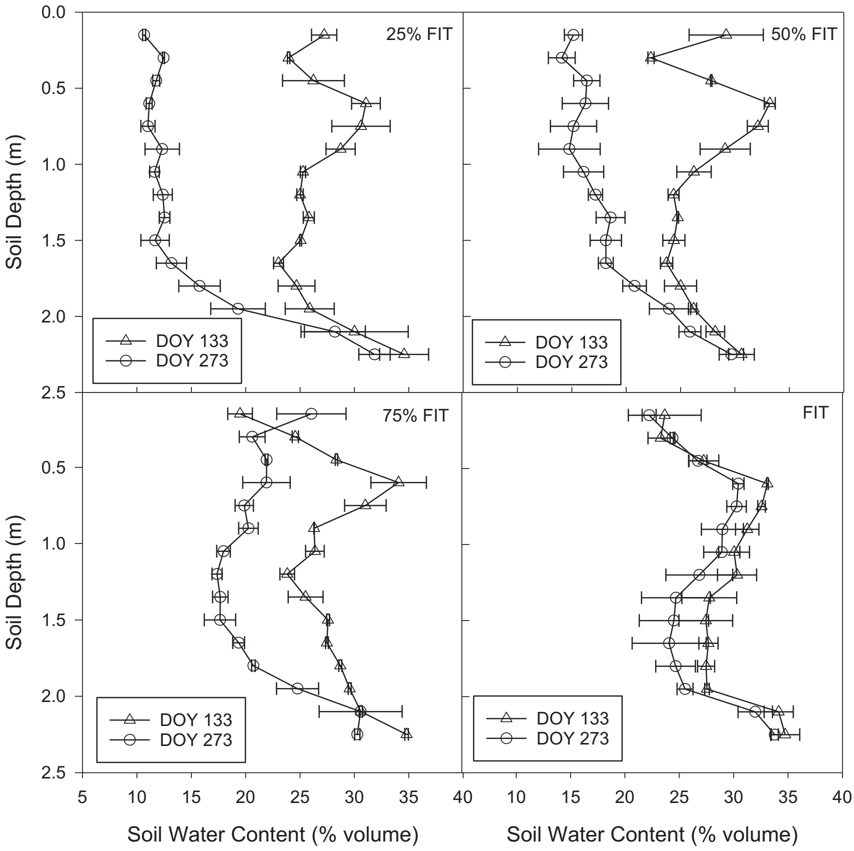


Figure 2. Soil water contents measured at emergence (DOY 154) and prior to harvest (DOY 279) in 2016 in each of the four irrigation treatments. Bars represent standard error of the measurements.

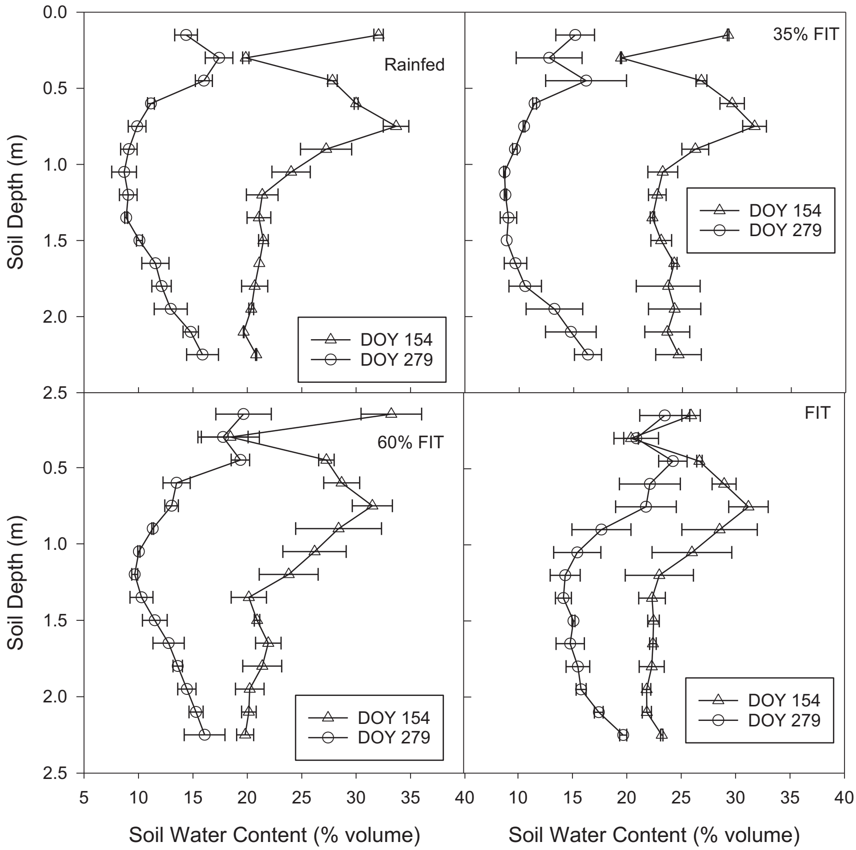


Figure 3. Soil water contents measured at emergence (DOY 152) and prior to harvest (DOY 269) in 2017 in each of the four irrigation treatments. Bars represent standard error of the measurements.

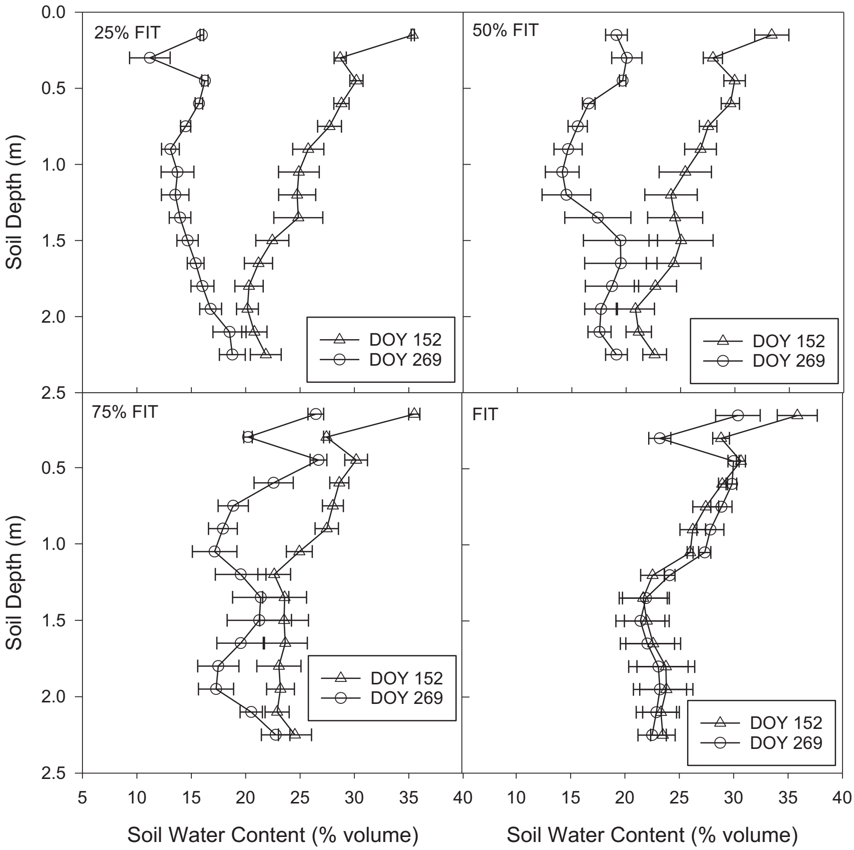


Figure 4. Seasonal average percent soil water extraction by depth (top) and seasonal average cumulative soil water extraction by depth (bottom) for each irrigation treatment in 2015. Different letters above a set of bars represent significant difference ($p \leq 0.5$) between treatments for a given soil profile depth.

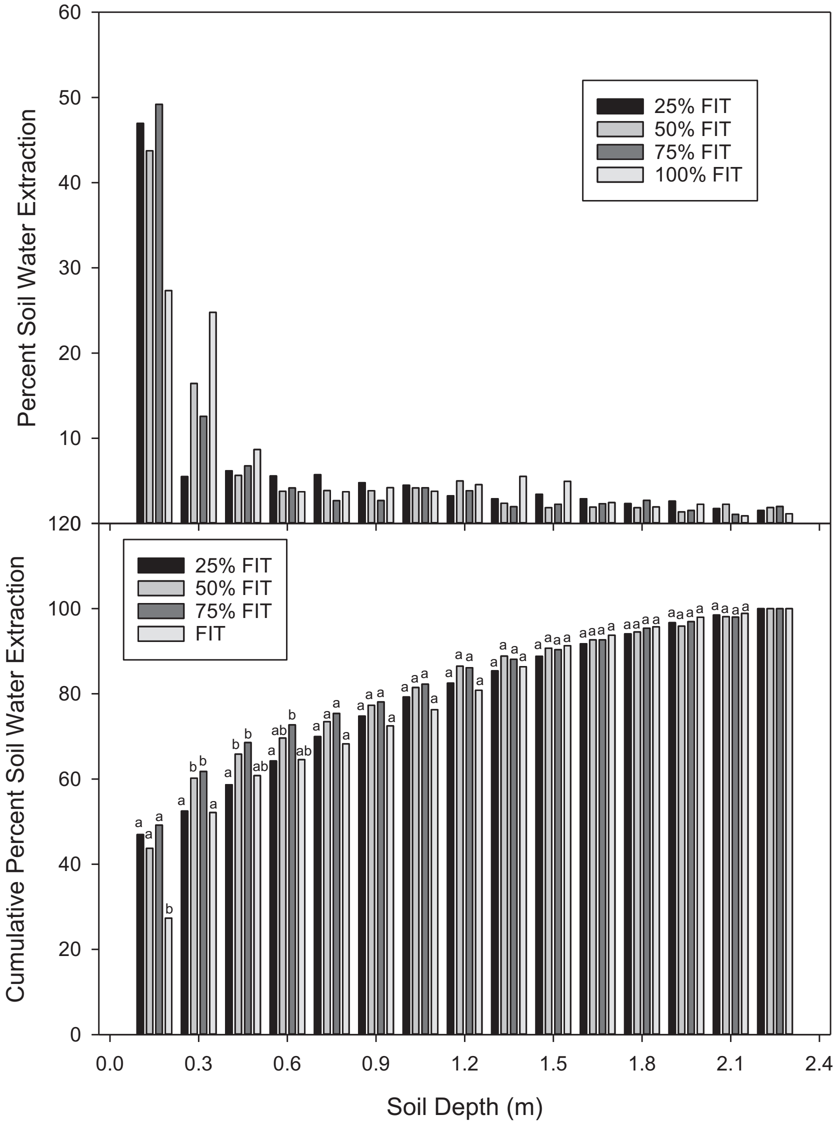


Figure 5. Seasonal average percent soil water extraction by depth (top) and seasonal average cumulative soil water extraction by depth (bottom) for each irrigation treatment in 2016. Different letters above a set of bars represent significant difference ($p \leq 0.5$) between treatments for a given soil profile depth.

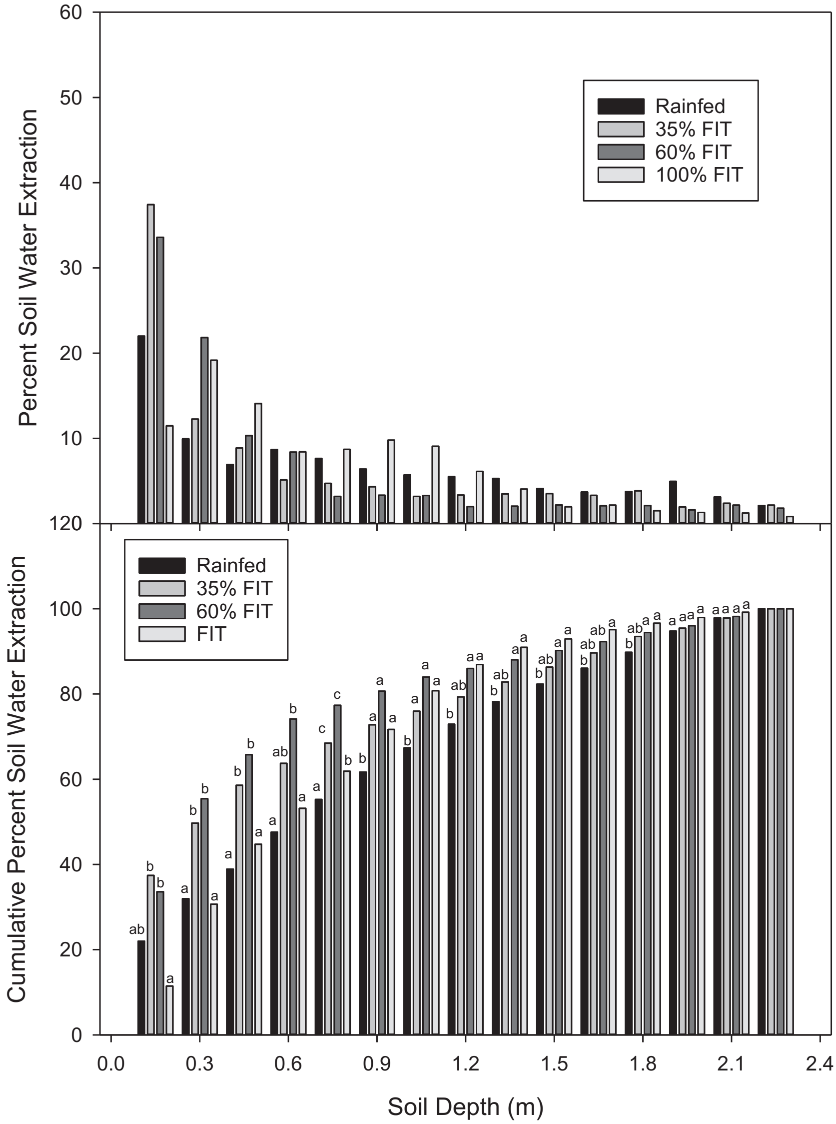


Figure 6. Seasonal average percent soil water extraction by depth (top) and seasonal average cumulative soil water extraction by depth (bottom) for each irrigation treatment in 2017. Different letters above a set of bars represent significant difference ($p \leq 0.5$) between treatments for a given soil profile depth.

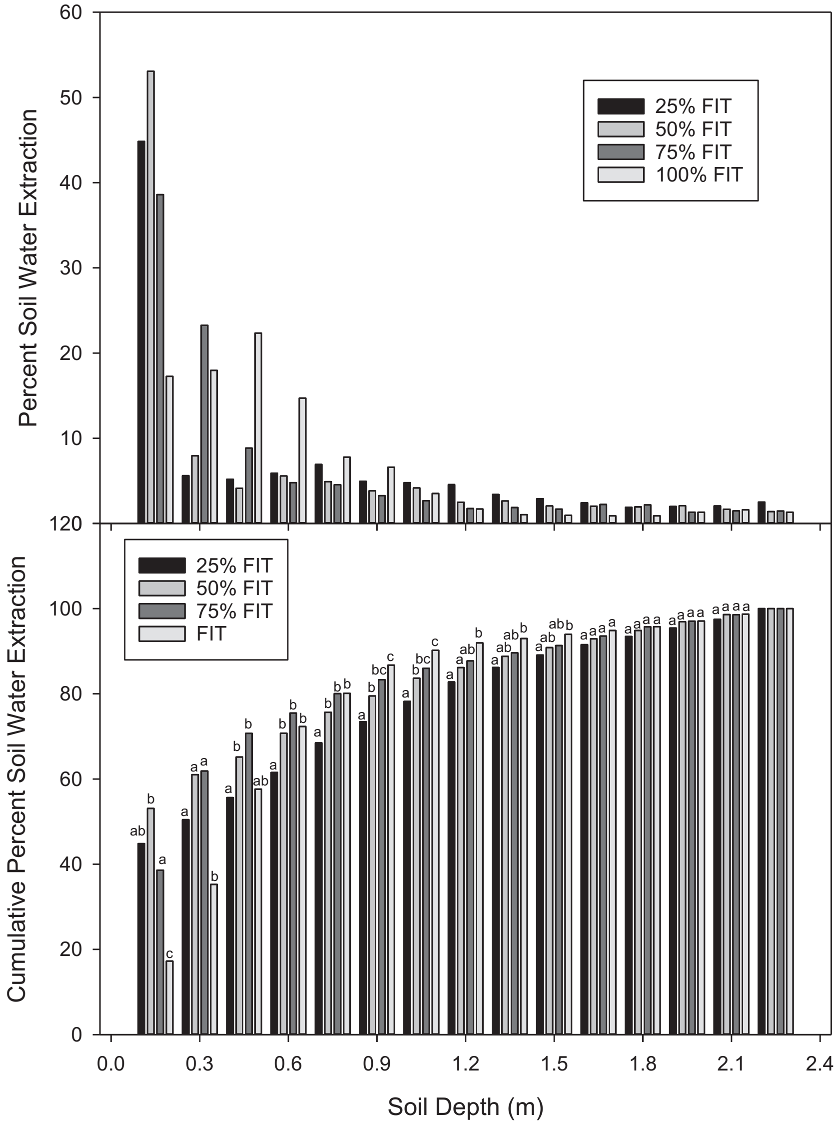
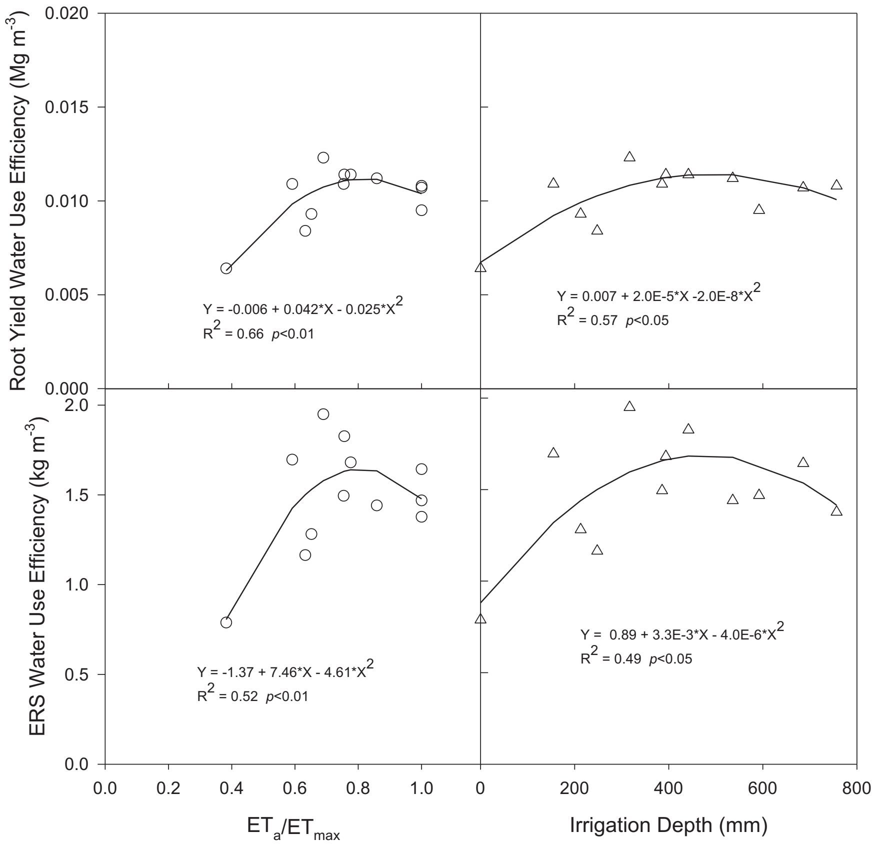


Figure 7. Root yield and estimated recoverable sucrose (ERS) water use efficiency as related to the ratio of measured crop ET_a to measured crop ET_a for the fully irrigated treatment and seasonal irrigation application in each study year.



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