Effects of Tillage and Irrigation Management on Sugarbeet Production

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ABSTRACT

Increased water demands and drought have resulted in a need to determine the impact of tillage and deficit water management practices in irrigated sugarbeet (*Beta vulgaris* L.) production. This study was conducted over three growing season (2011–2015) at the USDA-Agricultural Research Service facility in Kimberly, ID, on a Portneuf silt loam soil. Treatments consisted of two tillage treatments (strip tillage [ST] and conventional tillage [CT]) and four water input treatments ranging from 100 to 25% of model calculated crop evapotranspiration [ETc]). Estimated recoverable sucrose (ERS) yield, root yield, and sucrose and brei nitrate concentrations were similar for ST and CT across all water treatments. Strip tillage reduced runoff compared to CT. Across all years, quantitative relationships between both actual crop evapotranspiration (ETa) and water input, and sugarbeet yield and quality variables were developed. Significant positive linear relationships were found between ETa and sugarbeet ERS and root yields (r^2 values of 0.84 and 0.91, respectively). Estimated recoverable sucrose and root yields increased at rates of 28.5 kg ha^{-1} mm^{-1} ETa and 0.194 Mg ha^{-1} mm^{-1} ETa, respectively. Equal yield potential for ST, tillage cost savings, and agronomic and environmental benefits associated with soil surface residue indicates ST can be implemented successfully in sugarbeet production systems. The developed quantitative relationships between both ETa and water input, and sugarbeet yield and quality variables can be used to help understand sugarbeet production under deficit irrigation conditions, which may arise due to water shortage scenarios.

Core Ideas

- Strip tillage and conventional tillage had the same sugar yields under all irrigation levels.
- Relationships between water input/use and sugarbeet yields were established.
- Sucrose yields were the same under strip tillage and conventional tillage.
- Strip tillage reduced runoff and increase water infiltration compared to conventional tillage.

INCREASED WATER DEMAND from agriculture and non-agricultural sectors, variable regional and seasonal precipitation, and increased irrigation costs have resulted in concerns about water supplies and availability for irrigation in the northwestern United States. Alternative management practices that conserve irrigation water need to be developed and evaluated for irrigated crops in this region. The introduction of reduced tillage practices in the region has raised questions about the effects of the reduced tillage on ET. Many reduced tillage practices disturb less soil and maintain more crop residue on the soil surface compared to CT practices. Reduced tillage practices have been shown to both reduce surface soil water evaporation and increase water infiltration (Klocke et al., 2009; van Donk et al., 2010). The use of the reduced tillage practice ST has increased in Northwest U.S. sugarbeet and corn (*Zea mays* L.) production systems. One sugarbeet growing area reported that ST use increased from 200 ha in 2008 to approximately 3000 ha in 2010 (Amalgamated Sugar Company, personal communication, 2010). In 2014, the Elwyhee District in southern Idaho had 31% of the district's 4500 ha of sugarbeet under ST which represented 60% of the growers (Crane, 2014). Sugarbeet and corn production in the Northwest (Idaho, Washington, and Oregon) occupies more than 72,000 and 250,000 ha, respectively. The sugarbeet and corn industries are interested in ST to reduce tillage costs and achieve other potential agronomic benefits.

Strip tillage and other conservation tillage practices are common in many areas of the Corn Belt region in the central Great Plains and Midwest in corn and soybean [*Glycine max* (L.) Merr.] production. Research comparing sugarbeet grown under ST and CT under optimum irrigation or natural rain-fed systems has been published (Tarkalson et al., 2012; Evans et al., 2009; Overstreet et al., 2007, 2008; Regitnig, 2007; Halvorson and Hartman, 1984). In general, ST produces comparable yields to CT, with ST increasing yield in a situation where the surface residue remaining in ST tillage protected young plants from damaging wind-blown soil (Evans et al., 2009). The use of ST became a viable option for sugarbeet growers in 2008 when genetically modified Genuity RoundUp Ready (Monsanto Company, St. Louis, MO) sugarbeet seed became available, resulting in more manageable weed control in a reduced tillage system. A major reason interest in ST developed

Abbreviations: CT, conventional tillage; ERS, estimated recoverable sucrose; ETa, actual crop evapotranspiration; ETc, calculated crop evapotranspiration; ST, strip tillage; TDR, time domain reflectometry.

was the potential time and money savings due to less tillage required to prepare the sugarbeet seed bed with ST (1 tillage pass) compared to CT (three to five tillage passes). Growers in one sugarbeet growing district estimated that ST saved them US$123 to $185 ha^{-1} compared to CT practices (Crane, 2014). Current ST equipment designs typically incorporate a series of coulters and shanks to create a residue free zone where the crop can be planted and fertilizers placed below the seed (Overstreet, 2009). The tilled area is approximately 15 to 20 cm wide with the remaining area of the field left undisturbed with residue from the previous crop remaining on the soil surface (Overstreet, 2009).

There is very little published research evaluating irrigation management in irrigated production systems of the Northwest under ST. The influence of tillage practices on sugarbeet irrigation management needs to be evaluated to improve irrigation management practices. In recent years numerous research studies have focused on crop production under deficit water inputs. This research has been conducted all over the world and has focused on a variety of crops. For example, several studies have focused on irrigated corn production in the United States (Payero et al., 2006, 2008; O'Neill et al., 2004). Several studies have evaluated the effect of deficit irrigation timing on sugarbeet under CT practices (Erie and French 1968; Carter et al.,1980; Hang and Miller, 1986; Hills et al., 1990; Yonts et al., 2003; Yonts, 2011). Tarkalson et al. (2014) evaluated the effects of deficit irrigation on different sugarbeet hybrids. They found genetic diversity for drought tolerance exists among hybrids.

Water stress negatively affects plant physiology and metabolism (Zhu, 2002). The severity of water stress on plant function can range from mild to severe depending on the degree and extent of the stress (Jaleel and Llorente, 2009). Water deficits can limit growth and influence a host of physiological functions in plants to a greater extent than any other environmental factor (Jaleel and Llorente, 2009; Cattivelli et al., 2008). Thus, considerable research effort has been undertaken to improve crop production under deficit conditions (Cattivelli et al., 2008; Wang et al., 2003).

The objective of this study was to compare sugarbeet yield and quality under ST and CT receiving water input rates ranging from full irrigation to various deficit irrigation levels.

MATERIALS AND METHODS
Site Description

The field study was conducted during 2012, 2013, and 2015 at the USDA-ARS Northwest Irrigation and Soils Research Laboratory in Kimberly, ID. The study was not conducted in 2014 due to the need to equilibrate soil water in the study area. The climate at Kimberly is arid, with average annual precipitation and alfalfa-reference ET of approximately 237 and 1443 mm, respectively. On average, about 36% of the annual precipitation occurs during the growing season, which extends from late April to mid-October (Bureau of Reclamation AgriMet System). The climatic data for each year of the study is located in Table 1. The soil at the experimental site is a Portneuf silt loam (coarse-silty mixed mesic Durixerollic Calciorthid). The

Table 1. Total alfalfa reference evapotranspiration (ETr), average daily minimum air temperature (T_{min}), average daily maximum air temperature (T_{max}), daily average air temperature (T_{avg}), total precipitation, and average daily solar radiation (Rs) during 2012, 2013, and 2015 in Kimberly, ID.

Date	ETr	T_{min}	T_{max}	T_{avg}	Total precipitation	Rs
	mm	°C	°C	°C	mm	MJ m^{-2} d^{-1}
Nov. 2011–Jan. 2012	96.0	–5.5	5.8	–0.3	90.4	7.7
Feb. –Apr. 2012	273.6	0.1	12.4	6.0	69.6	14.9
May 2012	207.5	5.5	20.7	13.2	14.7	26.5
June 2012	260.1	8.8	25.9	17.9	2.8	29.8
July 2012	257.8	15.1	31.8	23.2	10.9	25.4
Aug. 2012	237.5	12.7	31.6	22.1	7.9	22.6
Sept. 2012	172.5	7.7	26.9	17.2	0.0	19.0
Oct. 2012	101.6	2.1	17.5	9.7	17.0	13.1
Nov. 2012–Jan. 2013	80.0	–5.8	4.5	–0.8	83.6	6.6
Feb.–Apr. 2013	273.8	–1.6	10.8	4.2	60.7	14.5
May 2013	194.3	5.7	21.5	13.8	5.1	22.1
June 2013	239.8	9.8	27.3	19.1	4.8	25.0
July 2013	265.4	14.2	33.2	23.9	1.5	23.3
Aug. 2013	236.7	13.0	32.1	22.7	2.0	21.5
Sept. 2013	144.5	9.9	23.8	16.5	37.6	14.7
Oct. 2013	91.2	0.5	15.6	7.7	2.8	11.8
Nov. 2014–Jan. 2015	87.1	–3.8	5.9	0.9	94.5	6.1
Feb.–Apr. 2015	306.1	0.0	14.7	7.2	26.9	14.9
May 2015	159.0	6.9	21.0	13.6	66.5	19.8
June 2015	241.6	12.3	29.6	21.4	9.7	25.5
July 2015	231.6	12.8	29.3	21.0	2.0	22.4
Aug. 2015	208.5	12.1	29.9	20.9	5.3	19.8
Sept. 2015	150.4	7.7	25.8	16.6	7.1	17.1
Oct. 2015	96.5	5.8	20.7	12.8	13.2	11.3

soil profile was well drained with a saturated hydraulic conductivity of 3.2 cm h^{-1}. Available water holding capacity was 0.2 cm available water per centimeter soil depth (USDA, 2009). Plant available water was determined based on calculated water content at field capacity (approximately 0.32 m^3 m^{-3}) and water at permanent wilting point (approximately 0.14 m^3 m^{-3}).

Experimental Design

The field study utilized a strip plot randomized complete block design (Fig. 1) with two tillage practice treatments (ST and CT) and four irrigation treatments (W1-approximately 100%, W2-approximately 75%, W3-approximately 50%, and W4-approximately 25% of model calculated crop ET). Each treatment combination was replicated four times. Each replicated block was separated by at least a 33 m wide strip of barley (*Hordeum vulgare* L.), the center of which was used to change sprinkler nozzles and randomize the treatment locations. Each experimental plot was 6.7 m wide (12 rows) by 41.1 m long. The length of the plot represented the distance between the linear move irrigation system towers. The harvest area within each plot was the 3.7 m (2 rows) by 22.9 m centered in the plot. The centered harvest areas allowed for 9.1 m borders at each end plot, eliminating experimental error associated with reduced water application uniformity caused by towers on the linear-move irrigation system. Each year of the study was conducted in the same field, rotating the plots into the sprinkler nozzle change areas planted to barley in the previous year.

Cultural Practices

To determine crop nutrient needs, two soil cores (4.4 cm diam.) were taken in the spring of each year prior to planting across each replicated block to a depth of 60 cm. The cores were split into two sampling depths of 0 to 30 cm and 30 to 60 cm.

Fig. 1. Study design.

Soil samples were composited by depth increment. Soil samples were analyzed for nitrate N (NO$_3$–N) and ammonium N (NH$_4$–N) after extraction in 2 M KCl (Mulvaney, 1996) using a flow injection analyzer (Lachat Instruments, Loveland, CO). The 0 to 30 cm soil samples were tested for sodium bicarbonate extractable P and exchangeable K concentrations (Olson et al., 1954). The study site was fertilized uniformly based on University of Idaho recommendations (Moore et al., 2009). During each year of the study, N fertilizer was applied through the irrigation system when the sugarbeet crop reached the four leaf stage, prior to the start of significant crop N uptake (Amalgamated Sugar Company, 2010). Nitrogen application rates during the study were 168, 134, and 168 kg ha^{-1} in 2012, 2013, and 2015, respectively. All nutrients were applied based on science-based recommendations.

Each year of the study, tillage for the CT treatment consisted of four tillage passes; moldboard plow in the fall prior to the study year, tandem disk, roller harrow, and bedding in the spring prior to planting. For the ST treatment, ST was performed in one pass during the spring prior to planting. A Strip Cat tillage implement was used for ST (Twin Diamond Industries, LLC, Minden, NE) in the spring. Barley was grown
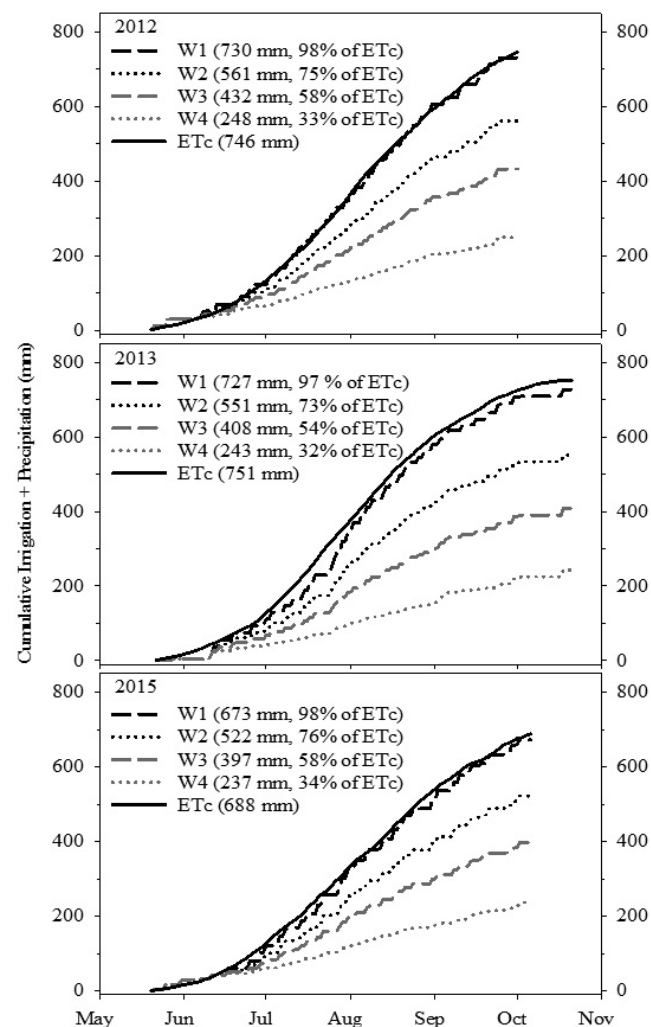

Fig. 2. Cumulative water (irrigation and precipitation) input depth over the growing season for water treatments and calculated crop evapotranspiration (ETc) based on the 1982 Kimberly–Penman Reference Evapotranspiration Model.

the year previous to the study years. The number of tillage passes within each tillage treatment was based on farmer practices for sugarbeet production to obtain suitable seedbed conditions.

The study was planted to sugarbeet on 1 May 2012; 2 May 2013; and 5 May 2015 at rate of 128,000 plant ha^{-1}. The seed variety planted all 3 yr of the study was BTS 27RR20 (Betaseed Inc., Kimberly, ID). The seeds for all years were treated with the insecticide Pancho Beta (60 g a.i. clothianidin [1-(2-Chloro-1,3-thiazol-5-ylmethyl)-3-methyl-2-nitroguanidine] and 8 g a.i. β-cyfluthrin {[(R)-cyano-[4-fluoro-3-(phenoxy)phenyl]methyl] (1R,3R)-3-(2,2-dichloroethenyl)-2,2-dimethylcyclopropane-1-carboxylate} per 100,000 seeds) and the fungicides Allegiance and Thiram (Bayer AG Crop Science Division, Monheim am Rhein, Germany). The crop was planted at 0.56 m row spacing at a seeding spacing of 76.2 mm.

Glyphosate [*N*-(phosphonomethyl)glycine] was applied each year to all plots at the labeled rate of 1.12 kg acid equivalent (in the form of its isopropylamine salt) ha^{-1} to control weeds.

Irrigation

Irrigation was applied using a linear-move irrigation system which traveled perpendicular to the tillage treatment strips (Fig. 1). The irrigation system operated at a pressure 193 kPa in the main line. Irrigation treatments were imposed by using a range of sprinkler nozzles with application rates of 24.71, 18.24, 12.71, and 6.58 L min^{-1} at a pressure of 138 kPa (for all irrigation treatments). The nozzles were all attached to 138 kPa pressure regulators to reduce the pressure from 193 to 138 kPa at the nozzles to maximize uniformity of water application. The 24.71 L min^{-1} nozzle was used to apply the W1 treatment, applying water (offset by in-season precipitation) to match model ETc. Model estimated crop evapotranspiration was based on the 1982 Kimberly–Penman Reference Evapotranspiration Model and daily crop coefficients (Wright, 1982) using data from an Agrimet weather station (U.S. Bureau of Reclamation, Boise, ID) located 4.5 km from the plots. Estimated crop ET rates were based on non-water stressed conditions. The Kimberly–Penman ET model (Wright, 1982) estimates ETc by modeling alfalfa-reference ET from measured data from a local Agrimet weather station (U.S. Bureau of Reclamation, Boise, ID) and multiplying the reference ET by a crop coefficient (K_c) that varies through the season depending on the growth stage of the sugarbeet crop.

The K_c values range from 0.22 at emergence, 1.0 at full cover, and 0.7 at harvest (www.usbr.gov/pn/agrimet/cropcurves/BEETcc.html). The remaining nozzles applied irrigation water at approximately 75, 50, and 25% of ETc based on the manufacturer published values listed above. For treatments W1, W2, W3, and W4, irrigation water and precipitation applied 98, 75, 58, and 33% of ETc in 2012; 97, 73, 54, and 32% of ETc in 2013; and 98, 76, 58, and 34% of ETc in 2015, respectively (Fig. 2). Irrigation depth was measured during each irrigation event using a transect of rain gages placed in plots within each replication in the center of each irrigation treatment.

Irrigation occurred twice a week early and late in the growing season and three times a week during the peak of the growing season. Figure 2 shows the cumulative irrigation and precipitation for each water treatment over time in relation to ETc. Actual seasonal crop ET was estimated based on soil water balances as (Evett et al., 2012):

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

where ΔS is the change in soil water storage in the soil profile (1.07 m in 2012 and 2.4 m in 2013 and 2015) between sugarbeet emergence and harvest, P is cumulative precipitation, I is cumulative irrigation, R is the difference between runoff and run on, DP is water percolating below the root depth. All units are in millimeters. Precipitation was measured at the research site in each replication. In 2013 and 2015, R was estimated for each irrigation and precipitation event in the W1 and W2 treatment plots by measuring runoff from an area of 1.4 m^2 using runoff collection frames. The runoff collection frames collected the runoff from the area and directed it to a collection buried bucket. Runoff was not measured in the W3 and W4 treatments and assumed to be zero based on field observation during irrigation and precipitation events. The DP was assumed to be zero based on soil water content being less than field capacity from emergence through harvest over the measured soil depth.

Soil Water

Soil water in the 0- to 30-cm depth was continuously measured in each plot in the crop row of two replicated blocks using time domain reflectometry (TDR) probes. Two TDR probes were installed in each plot. The TDR data was collected continuously in 15-min increments using a data logger. In 2012, volumetric soil water content was measured in the same plots at soil depths of 30

Table 2. Model probability values (*P* > *F*) of fixed effects for the measured factors related to actual crop evapotranspiration (ETa) and water input. Model analysis was across all years (random effect). Bolded values represent significance at the 0.05 probability level. Tillage × regression interactions were not significant for all measured factors. Therefore, the interactions were removed from the analysis and the model was reduced to include only the linear and quadratic continuous main effects.

Model effects	df	ERS†	Root yield	Sucrose concentration	Root nitrate	Root conductivity
ETa						
Tillage	1	0.880	0.732	0.212	0.584	0.356
Linear	3	**<0.001**	**<0.001**	0.219	**0.037**	**0.008**
Quadratic	3	**0.038**	**0.012**	0.052	0.437	0.593
Irrigation + Precipitation						
Tillage	1	0.978	0.827	0.342	0.726	0.560
Linear	3	**<0.001**	**<0.001**	**0.036**	**0.029**	**0.002**
Quadratic	3	0.070	0.108	**0.021**	0.441	0.150

† ERS, estimated recoverable sucrose.

to 45, 45 to 61, 61 to 76, 76 to 91, 91 to 107, and 107 to 122 cm. In 2013 and 2015, volumetric soil water content was measured at soil depths of 30 to 45, 45 to 61, 61 to 76, 76 to 91, 91 to 107, 107 to 122, 122 to 137, 137 to 152, 152 to 168, 168 to 183, 183 to 198, 198 to 213, 213 to 229, and 229 to 244 cm. The soil water content was measured using the neutron probe method (Evett and Steiner, 1995) on a weekly basis following plant emergence from three replications of each treatment. Volumetric soil water measurements were multiplied by soil depth to obtain soil water depth. For each neutron probe measurement date and time, soil water depths for each depth increment were summed over a depth of 244 cm (120 cm in 2012) to determine total profile water content. Plant available water was determined based on estimated water content at field capacity ($0.32 \ m^3 \ m^{-3}$) and water at permanent wilting point ($0.14 \ m^3 \ m^{-3}$). Soil water measurements were compared to field capacity, 55% of available water and permanent wilting point. A management allowable depletion (MAD) level of 55% was set as the depletion level above which the crop would be water stressed (Jensen et al., 1990).

Harvest

The roots in the center two rows of each plot were counted and harvested on 3 Oct. 2012, 22 Oct. 2013, and 6 Oct. 2015. Total root yield was determined from each plot using a load cell-scale mounted on the plot harvester. From each plot, four to eight-root samples were collected and sent to the Amalgamated Sugar Co. tare lab for analysis of percent sugar and impurities. Percent sugar 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 tonnes of roots was estimated by:

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

Recoverable sucrose yield per metric tonne of roots was multiplied by root yield to give estimated recoverable sucrose (ERS) yield (kg ha^{-1}) in this article.

Statistical Analyses

Data were analyzed using a PROC MIXED model in SAS (SAS Institute, 2013). Tillage, and linear and quadratic continuous effect relationships between measured production factors (ERS yield, root yield, sucrose concentration, root nitrate concentration, root conductivity) and ETa and irrigation + precipitation, and their interactions (linear × tillage and quadratic × tillage) were the fixed effects. Year and the year × tillage interaction were
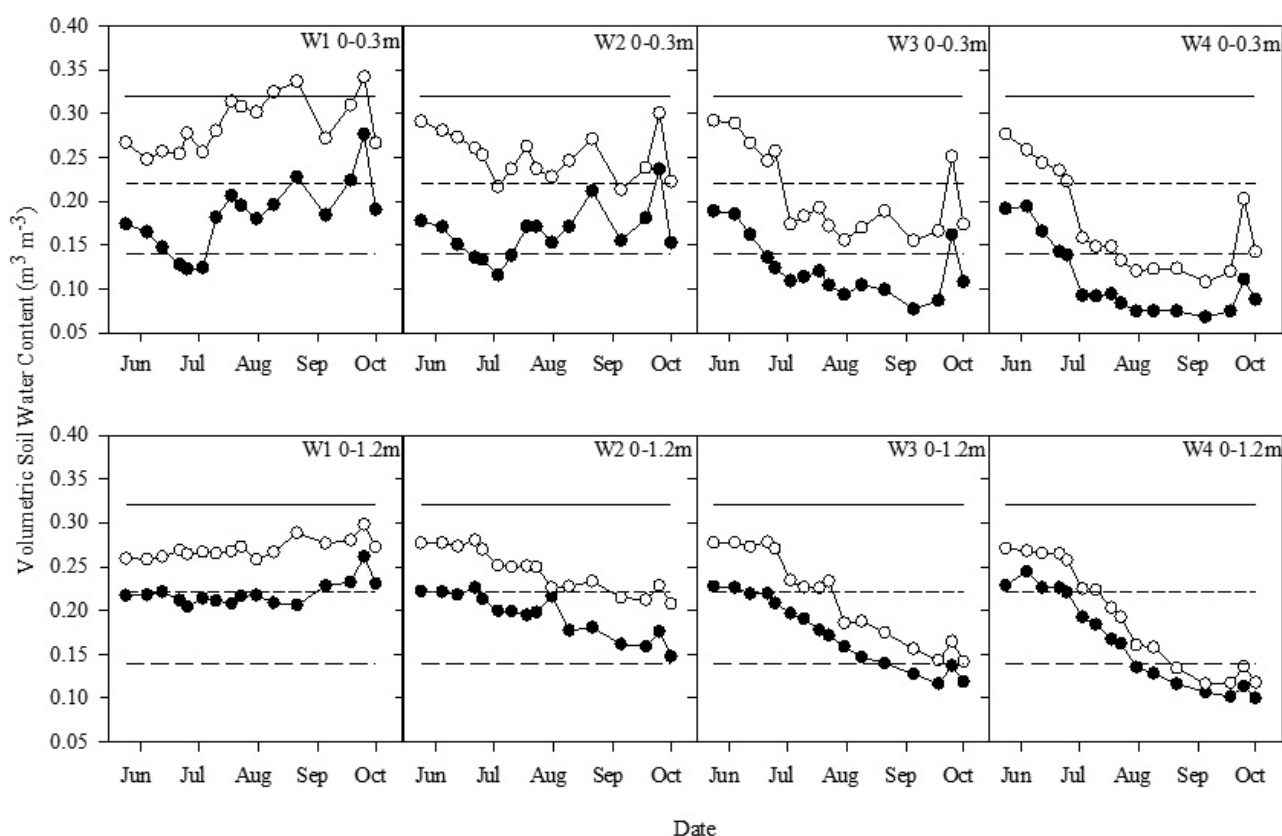

Fig. 3. 2012 Volumetric soil water content over time for conventional tillage (filled circles) and strip tillage (unfilled circles) for water treatments (W1–W4) at the 0- to 0.3-m and 0- to 1.2-m depth. Each value is the average of two replications. The solid line represents field capacity, the middle short dashed line represents 55% depletion of total available water, and the bottom wide dashed line represents permanent wilting point.

the random effects. Residual diagnostics were conducted to test for assumptions of ANOVA and to determine the need for data transformations. Transformations were not necessary. Regression equations were developed to describe the response of the dependent variables (ERS yield, root yield, sucrose concentration, root nitrate concentration, root conductivity) to independent variables (ETa and irrigation + precipitation) when the linear and quadratic main effects were significant at $p = 0.05$.

RESULTS AND DISCUSSION

Measured production factor means (averaged across replications) were used for linear and quadratic continuous effect relationships with water input because years provided a higher level of random effect used for error estimation. Tillage × regression interactions were not significant for all measured factors. Therefore, the interactions were removed from the analysis and the model was reduced to include only the linear and quadratic continuous main effects.

Across all years of the study there were no significant tillage main effects on ERS, root yields, sucrose concentrations, and root nitrate concentrations, and root conductivity (Table 2). Thus, results will be discussed averaging across ST and CT

at each water input treatment. These results were unexpected since it was hypothesized that under deficit water inputs, sugarbeet grown under ST would have had access to more soil water, increasing yields. The residue on the soil surface in the ST treatment did increase soil water especially in 2012 (Fig. 3), but this did not lead to increased yields over CT. It is possible that soil water below 1.2 m in 2012 resulted in buffering yield differences between tillage treatments.

Runoff data collected in 2013 and 2015 shows that ST had greater infiltration compared to CT. Runoff under CT for the W1 and W2 treatments were 97.9 and 14.4 mm in 2013, and 26.5 and 16.6 mm in 2015. Runoff under ST was insignificant, <1 mm, for the W1 and W2 treatments during both years (Table 3).

In 2012 soil water in the surface 0.3 m and from 0 to 1.2 m was higher for ST at all measurement dates (Fig. 3) and averaged over the entire growing season. In 2013 and 2015, the differences in soil water between tillage treatments were not as great as in 2012 (Fig. 4 and 5). Although, in the deficit water treatments in 2013 and 2015, ST generally had higher soil water content in the entire rooting depth averaged over the season (Fig. 6). However, in the soil surface (0–0.3 m) in 2013 and 2015, there are some cases when the CT had a trend for greater soil water content

Table 3. Growing season soil water change (emergence-harvest), precipitation, irrigation, runoff, measured crop evapotranspiration (ETa), and percent of W1 ETa for study irrigation treatments in 2012, 2013, and 2015. Depth of soil water decrease was 1.2 m in 2012, and 2.1 m in 2013 and 2015.

Year	Tillage	Treatment†	ΔS‡	P	I	R§	ETa	ETa/ETc¶
			———————————— mm ————————————						%
2012	CT	W1	−16.6	44.2	730.4	–	758	102
		W2	90.6	44.2	561.0	–	696	93
		W3	132.7	44.2	432.0	–	609	82
		W4	157.1	44.2	248.9	–	450	60
	ST	W1	−15.8	44.2	730.4	–	759	102
		W2	84.7	44.2	561.0	–	690	92
		W3	165.3	44.2	432.0	–	642	86
		W4	186.4	44.2	248.9	–	480	64
2013	CT	W1	99.8	51.1	676.0	97.9	729	97
		W2	170.9	51.1	500.1	14.4	708	94
		W3	186.0	51.1	356.6	–	594	79
		W4	163.7	51.1	191.8	–	407	54
	ST	W1	62.2	51.1	676.0	0.1	789	105
		W2	138.6	51.1	500.1	0.3	690	92
		W3	194.8	51.1	356.6	0	602	80
		W4	187.4	51.1	191.8	0	430	57
2015	CT	W1	101.5	68.1	604.5	26.5	747	109
		W2	160.6	68.1	454.2	16.6	666	97
		W3	222.7	68.1	329.6	–	620	90
		W4	282.8	68.1	168.9	–	520	76
	ST	W1	32.4	68.1	604.5	0.7	704	102
		W2	98.0	68.1	454.2	0	620	90
		W3	239.0	68.1	329.6	–	637	93
		W4	331.3	68.1	168.9	–	568	83

† W1, W2, W3, and W4, irrigation water and precipitation applied 98, 75, 58, and 33% of ETc in 2012; 97, 73, 54, and 32% of ETc in 2013; and 98, 76, 58, and 34% of ETc in 2015, respectively.

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

§ Runoff was not measured in 2012 and in the W3 and W4 treatments in 2014 and 2015. If not measured, runoff was assumed to be 0 in the ΔS calculation.

¶ ETa/ETc × 100. ETc = evapotranspiration calculated from the Kimberly–Penman evapotranspiration model (Wright, 1982) to supply 100% of crop water requirement.
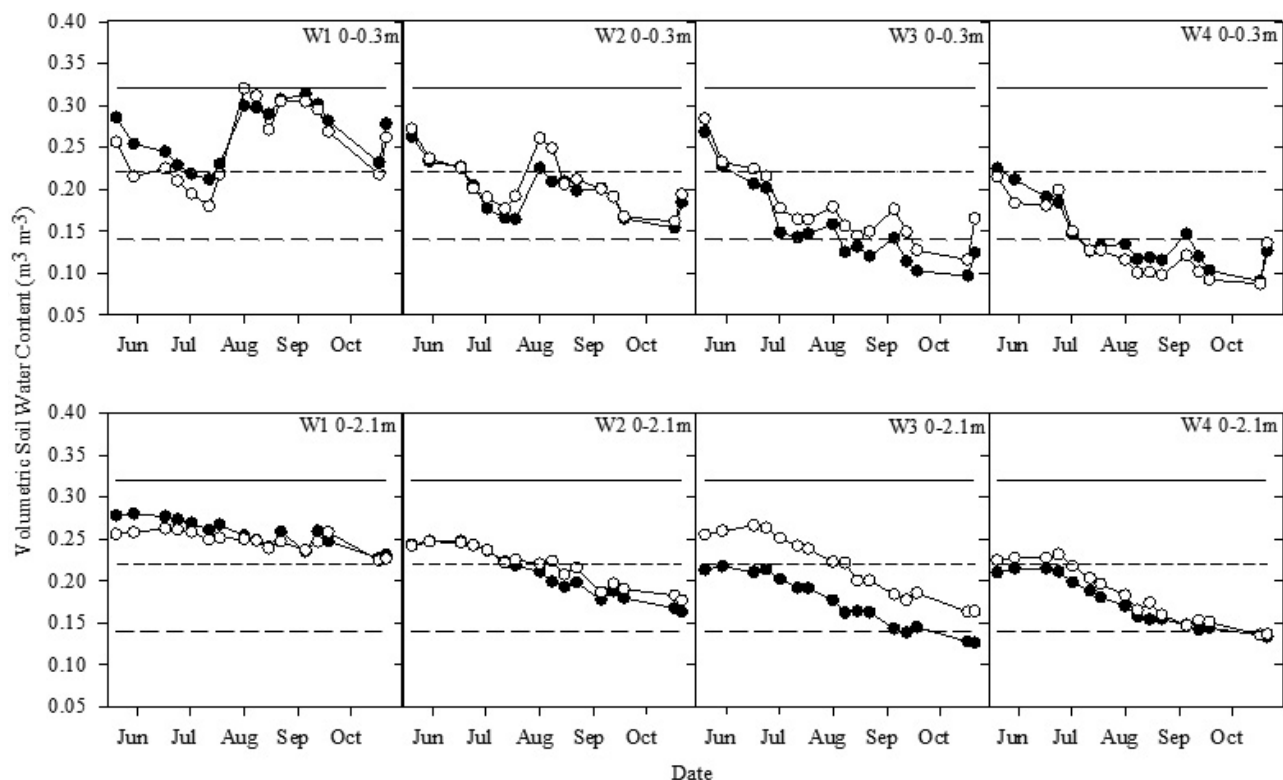
Fig. 4. 2013 Volumetric soil water content over time for conventional tillage (filled circles) and strip tillage (unfilled circles) for water treatments (W1–W4) at the 0- to 0.3-m and 0 to 2.1-m depth. Each value is the average of two replications. The solid line represents field capacity, the middle short dashed line represents 55% depletion of total available water, and the bottom wide dashed line represents permanent wilting point.
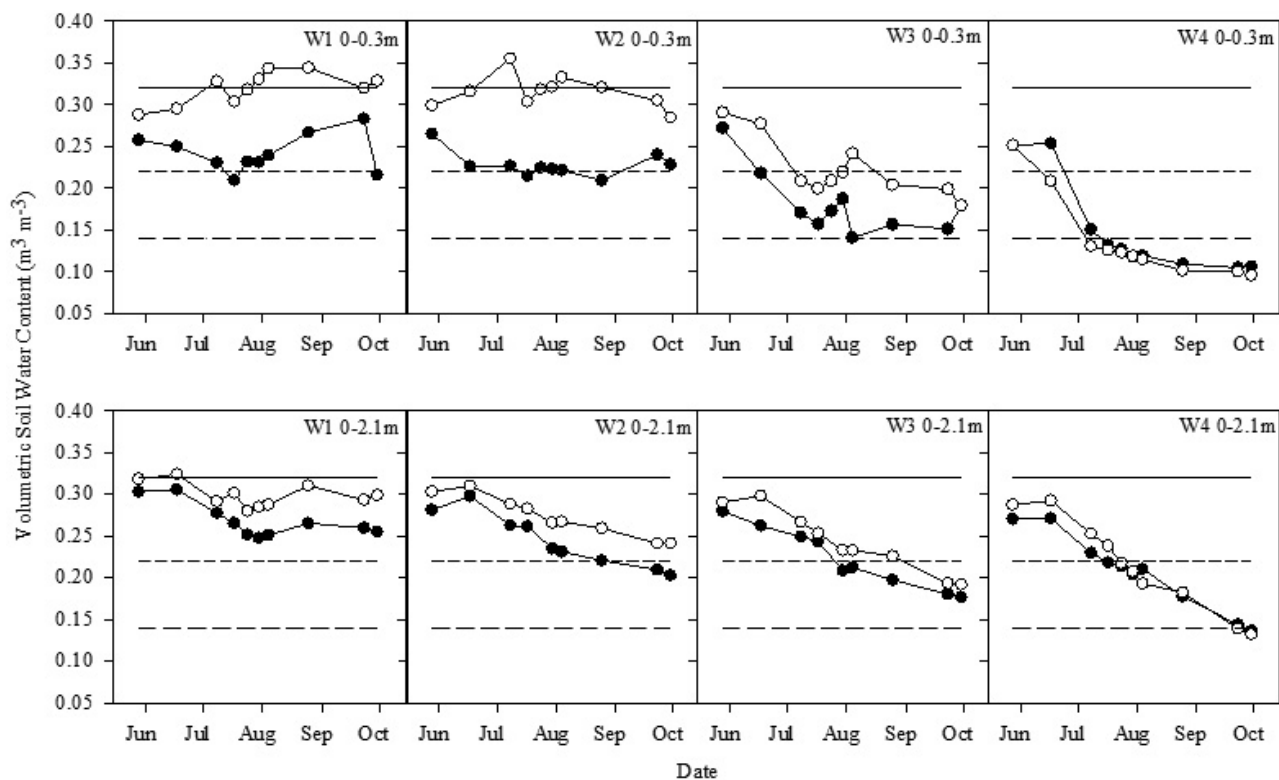

Fig. 5. 2015 Volumetric soil water content over time for conventional tillage (filled circles) and strip tillage (unfilled circles) for water treatments (W1–W4) at the 0- to 0.3-m and 0- to 2.1-m depth. Each value is the average of two replications. The solid line represents field capacity, the middle short dashed line represents 55% depletion of total available water, and the bottom wide dashed line represents permanent wilting point.
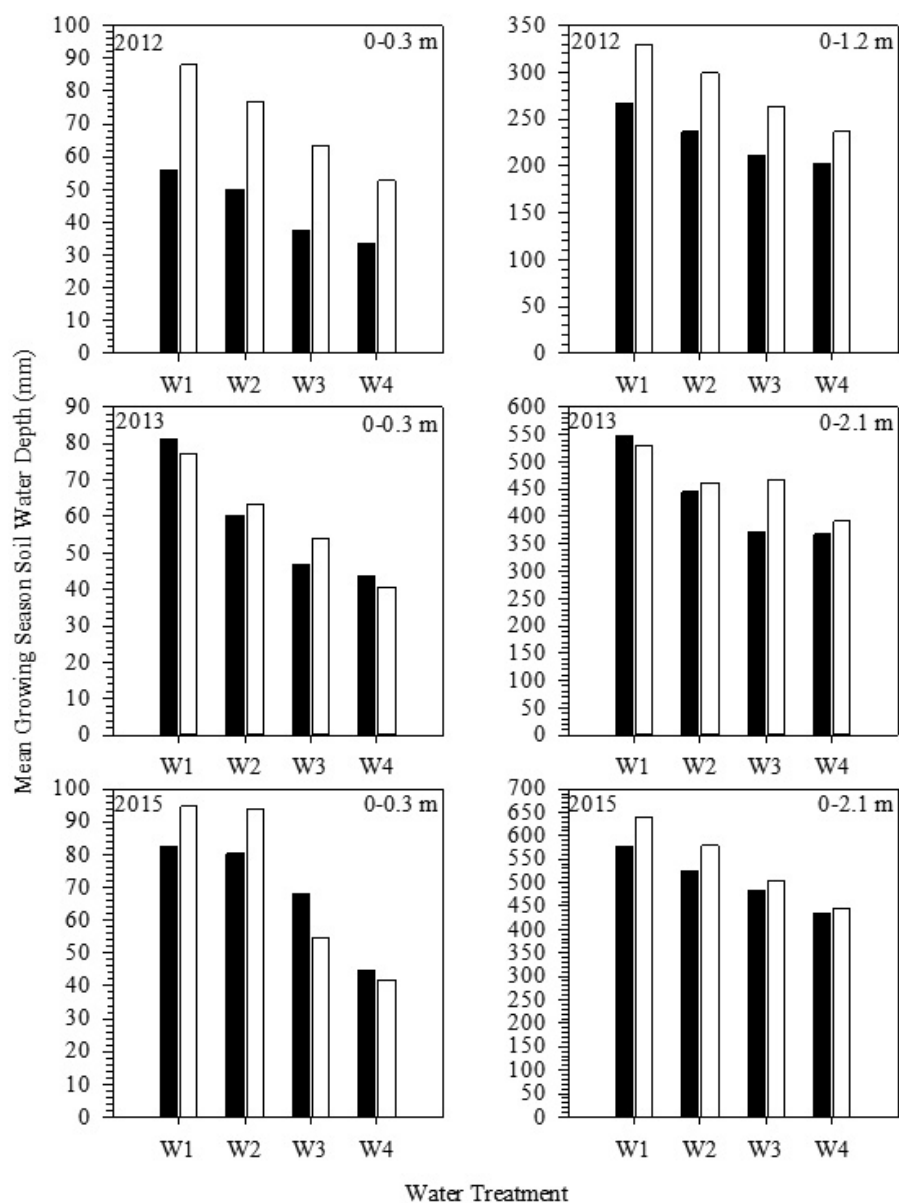
Fig. 6. Mean growing season soil water depths in 2012, 2013, and 2015 for conventional tillage (filled bars) and strip tillage (unfilled bars) for water treatments (W1–W4) at the 0- to 0.3-m and 0- to 1.2-m or 2.1-m depths. Each value is the averaged over the entire season for two replications.

(Fig. 6). The differences in growing season mean soil water content between tillage/water treatment combinations in 2012 ranged from 35 to 41% in the 0- to 0.3-m depth and 15 to 21% in the 0- to 1.2-m depth (Fig. 6). In 2013 and 2015 the differences were smaller ranging from 3 to 20% across all treatment combinations and soil depths. Due to the lack of yield differences and large differences in soil water content in 2012 between tillage treatments, in 2013 and 2015 the depth of soil water measurement was increased from 1.2 to 2.1 m. It was hypothesized that the sugarbeet crop was extracting water from a greater depth than measured in 2012 resulting in the nonsignificant differences. In 2013, runoff measurements were initiated to account for runoff differences between treatments. The greater soil water content in 2012 for ST and less differences in soil water content 2013 and 2015 was not well understood. Climatic differences over each year (Table 1) did not elucidate potential reasons. Similar air temperature, ETr, and precipitation ranges existed across each year. Data from this study supports conclusions from

other studies that ST and CT produce similar sugarbeet yields under similar management practices (e.g., water input, nutrient supply, etc.) (Tarkalson et al., 2012; Overstreet et al., 2007, 2008; Regitnig, 2007; Evans et al., 2009).

For most measured variables, there were significant linear relationships with ETa and irrigation + precipitation (Table 2). The quadratic relationships were significant for fewer measured variables. Actual ET and sucrose concentration were not related. The relationships between independent variables and dependent measured variables across all years of the study are shown in Fig. 7. In Fig. 7, linear regression lines were presented for significant linear relationships. The regression analysis results are presented in Table 4. The strongest relationships were between ETa, and ERS and roots yields. The linear correlation coefficients for ERS yield and root yield were 0.84 and 0.91, respectively (Table 4, Fig. 7). The quadratic correlation coefficients for ERS yield and root yield were 0.89 and 0.94. As ETa and irrigation + precipitation increased, ERS
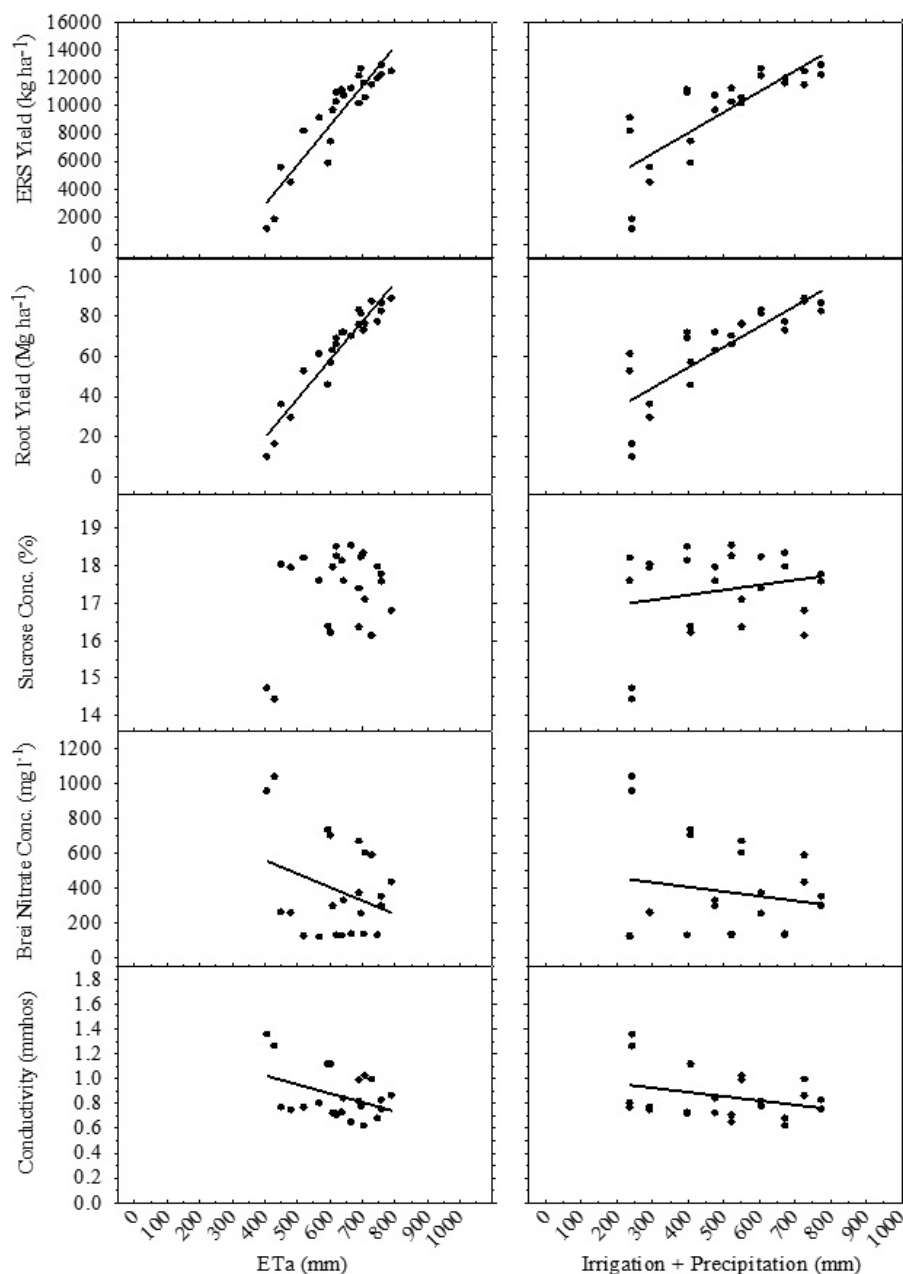
Fig. 7. Relationships among dependent and independent variables (Tables 2 and 4). ETa is the actual measured sugarbeet evapotranspiration and Irrigation + Precipitation was measured as an accumulation over the sugarbeet growing season. Linear regression lines were presented for relationships with significant linear relationships. Each value is the average of four treatment replications for a given year of the study.

and root yields increased. The relationships between ERS yield and independent variables during the 3 yr of the study were similar to many reported yield responses over a range of a yield limiting input factors (Dobermann et al., 2011). Sugarbeet ERS increased by 28.5 kg ha^{-1} mm^{-1} ETa, root yield increased by 0.194 Mg ha^{-1} mm^{-1} ETa. The relationships between irrigation + precipitation and ERS and root yields were not as strong (Fig. 7). Sugarbeet ERS increased by 14.9 kg ha^{-1} mm^{-1} irrigation + precipitation, root yield increased by 0.102 Mg ha^{-1} mm^{-1} irrigation + precipitation (Fig. 7). Other significant relationships between the independent variables, and brei nitrate concentration and conductivity were weaker. In general as ETa and irrigation + precipitation increased brei nitrate concentration and conductivity decreased (Table 4, Fig. 7).

Although water treatments were based on applying water at set amounts relative to ETc (approximately 100, 75, 50, and 25%), ETa for each treatment was higher than ETc due to crop soil water use, especially in the deficit water treatments (W2, W3, and W4; Table 3). The W1 treatment ETa rates ranged from 97 to 108% of ETc across years and tillage treatments. The W2 treatment had a range from 92 to 124%. For the W2 treatment in 2012 and 2013, even though the ETa was close to recommended full ETc, soil water data indicates that much of the water use occurred below the published maximum allowable soil water depletion level of 55% depletion of available soil water (Fig. 3 and 4) (Jensen et al., 1990; James, 1988). Whereas for the W1 treatment during all years of the study, most soil water used was between field capacity and the 55% depletion of available water threshold. The linear and quadratic relationships between

Table 4. Results of linear and quadratic regression analysis (Table 2 and Fig. 3).

		Linear† regression		
Independent variable	Dependent variable	$y0$	a	r^2
ETa‡	ERS Yield	−8540.97	28.51	0.84
Irrigation+Precipitation	ERS Yield	2079.76	14.90	0.63
ETa	Root Yield	−58.08	0.194	0.91
Irrigation+Precipitation	Root Yield	13.67	0.102	0.69
ETa	Sucrose concentration	−	−	−
Irrigation+Precipitation	Sucrose concentration	16.69	0.001	0.05
ETa	Root nitrate	867.74	−0.771	0.09
Irrigation+Precipitation	Root nitrate	511.56	−0.262	0.03
ETa	Root conductivity	1.31	−0.0007195	0.16
Irrigation+Precipitation	Root conductivity	1.03	−0.0003416	0.10

		Quadratic regression§			
Independent variable	Dependent variable	$y0$	a	b	r^2
ETa	ERS Yield	−29030.34	99.50	−0.059	0.89
Irrigation+Precipitation	ERS Yield	−	−	−	−
ETa	Root yield	−166.99	0.57	−0.0003157	0.94
Irrigation+Precipitation	Root yield	−	−	−	−
ETa	Sucrose concentration	−	−	−	−
Irrigation+Precipitation	Sucrose concentration	14.35	0.012	−0.00001099	0.12
ETa	Root nitrate	−	−	−	−
Irrigation+Precipitation	Root nitrate	−	−	−	−
ETa	Root conductivity	−	−	−	−
Irrigation+Precipitation	Root conductivity	−	−	−	−

† $y = y0 + ax$, where $y0 = y$ intercept, a = slope.

‡ ETa = actual measured crop evapotranspiration; ERS, estimated recoverable sucrose.

§ $y = y0 + ax + bx^2$, where $y0$ = constant, a = linear coefficient, b = quadratic coefficient.

ETa and yields show that yields continue to increase across the irrigation range used in the study. This data supports the need to monitor both soil water status and ETa during the season to understand sugarbeet water stress levels, and to assist in irrigation scheduling. Past research shows that the maximum allowable soil water depletion for sugarbeet can vary between 55 and 65% (Jensen et al., 1990; James, 1988). The ability of sugarbeet to efficiently use water at higher depletion levels likely explains why yields similar for ST and CT across all water input treatments. These results were based on sugarbeet growth in a deep silt loam soil. Results could be different in sand-based soils and shallow soils. It is possible that ST could increase sugarbeet yields in sandier and shallow soils compared to CT as a result of increased soil water storage. An area of future research would be to assess similar objectives from this study in sandy and shallow soils.

The growing region's 10-yr (2005–2014) mean ERS yield, root yield, sucrose concentration, and brie nitrate concentration were 10,700 kg ha^{-1}, 76.9 Mg ha^{-1}, 16.0%, and 294 mg kg^{-1}, respectively (Amalgamated Sugar Company, personal communication, 2015). The mean ERS yield, root yield, sucrose concentration, and brie nitrate concentration over the 3 yr of this study were 9400 kg ha^{-1}, 63.9 Mg ha^{-1}, 17.3%, and 382 mg kg^{-1}, respectively. The ranges of mean ERS yield, root yield, sucrose concentration, and brie nitrate concentration over the range of water input treatments were 1130 to 12,950 kg ha^{-1}, 9.8 to 90.0 Mg ha^{-1}, and 14.4 to 18.5%, and 120 to 1036 mg kg^{-1}, respectively. The higher mean brie nitrate concentration compared to 10-yr average and the Amagamated Sugar Companies 200 mg kg^{-1} threshold indicating that excess available soil N was likely present late in the growing season.

CONCLUSIONS

Sugarbeet ERS and root yields were similar for ST and CT across all water input rates, although differences in available soil water existed between the tillage treatments across all water input rates. Data from this study supports the use of strip tillage in sugarbeet production at various water input rates ranging from deficit irrigation to full irrigation. This support is based on equal yield potential with CT, tillage cost savings compared to CT, and agronomic and environmental benefits associated with increased soil surface residue (e.g., reduced runoff/increased infiltration). In general, sugarbeet ERS and root yields increased with increasing water input and water use. Quantitative relationships between ETa and water input, and sugarbeet yield and quality variables were developed. These relationships can be used to help understand sugarbeet production under deficit irrigation conditions, which may arise due to water shortage scenarios. An area of future research would be to assess similar objectives from this study in sandy and shallow soils, where increased soil water storage from ST could increase yields.

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