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RESEARCH

Evaluation of water use and yield responses of drip-irrigated sugar beet with different irrigation techniques

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Effective water use should be investigated in terms of sustainable production strategy in arid and semi-arid regions. A 2 yr field study was conducted in order to investigate the effects of full root-zone wetting (FI) and partial root-zone drying (PRD) irrigation techniques with 4 (I1) and 8-d (I2) irrigation intervals and three different irrigation levels (W1, W2, W3) adjusted according to Class A pan evaporation on root, leaf, and sugar yields and irrigation water use efficiency (IWUE) of sugar beet (*Beta vulgaris* L.) Three different plant-pan coefficients (0.70, 0.60, and 0.50) were used for adjusting the three different irrigation levels. The irrigation techniques and levels affected yields significantly. Seasonal meanly irrigation quantities were 280.4 mm in FI treatments and 162.4 mm in PRD treatments. While mean root yield of 33.80 t ha^{-1} is obtained in FI treatments, it was 26.43 t ha^{-1} in PRD treatments. Similarly, mean white sugar yield (WSY) for FI treatments (5 t ha^{-1}) was higher than PRD treatments (3.81 t ha^{-1}). There were significant polynomial relationships between irrigation quantities and root yield or WSY in both FI and PRD treatment. PRD technique increased by 34.9% IWUE compared to FI. Although the highest root yield was determined in FI-I1W1 sub treatment as 37.57 t ha^{-1}, the highest IWUE was determined in PRD-I1W3 sub treatment as 173.9 kg ha^{-1} mm^{-1} since it has the lowest irrigation water amount as 140.6 mm. However, among PRD treatments for more root yield and for more white sugar yield, I1W1 and I1W2 sub treatments were the best.

Key words: *Beta vulgaris*, partial root-zone drying irrigation, sugar yield, water productivity, water-yield relationships.

INTRODUCTION

There are more than two billion people living in highly water scarce regions (Oki and Kanae, 2006). Rising food demand will result in an increase in competition for land and water resources in the near future according to future population projections (Lotze-Campen et al., 2008). This would result in a reduction of renewable water resources used in agriculture, limitations on land available for agricultural production due to constraining factors and changing production conditions related to the climatic changing (Lotze-Campen et al., 2008).

Agriculture is the largest user of the available water resources. About 70% worldwide fresh water used by humans is for irrigation (Gerbens-Leenes and Nonhebel, 2004; Sepaskhah and Ahmadi, 2010). In some regions, insufficient water resources have increasingly becoming a serious issue in recent years (Kang and Zhang, 2004). So, increasing water productivity is particularly important in the regions with scarce water resources (Molden et al., 2003). Conventional deficit irrigation (DI) and partial root-zone drying (PRD) are used to improve irrigation water productivity in agriculture (Sadras, 2009; Sepaskhah and Ahmadi, 2010).

The DI irrigation is a precious production strategy commonly used in water shortage areas. It maximizes the water productivity, but a certain yield reduction is observed compared to the full irrigation (Geerts and Raes, 2009). The PRD is a more recent irrigation technique developed from DI (Yazar et al., 2009). In this technique, irrigation water is applied alternately to the two sides of a plant root system. While roots in the wet soil provide water for plant growth, the roots in the drying soil produce chemical signals at the same time (Saeed et al., 2008). Chemical signals like abscisic acid (ABA) are transported to leaves and allow for plant adaptation to water stress through decreased leaf growth and water loss (Schachtman and Goodger, 2008). According to the practical results, crops yields under PRD techniques are better than under DI techniques for the same amount of water application (Sepaskhah and Ahmadi, 2010).

Sugar beet (*Beta vulgaris* L.) is a field crop well suited for deficit irrigation applications (Vamerali et al., 2009). However, many studies reported yield losses in water deficit conditions. The results of Mahmoodi et al. (2008) showed that irrigation regimes had a significant effect on sugar yield of sugar beet and its quality. Optimum soil water content for maximum root yield and quality was 70% of the field capacity. Yonts (2011) expressed that root and sugar yield of sugar beet was the highest for full irrigation and sugar content did not significantly change by reducing irrigation to 25%. Kiziloglu et al. (2006) indicated that the deficit in the irrigation practices significantly decreased

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root, leaf, and total sugar yield of sugar beet under semiarid and cool season climatic conditions. There was a linear relationship between evapotranspiration and root yield. Water use efficiency was the highest at non-irrigated conditions. Similarly, Topak et al. (2011) found that root and white sugar yields of sugar beet significantly decreased by the increasing water deficit in the semiarid region. The relationship between evapotranspiration and root yield was linear. Irrigation water use efficiency was the highest at the lowest irrigation conditions.

Drip irrigation is widely used for irrigation of numerous plants to provide high water productivity and crop yields in regions especially with scarce water resources. However, its use for the sugar beet irrigation is still limited (Tognetti et al., 2003). Drip irrigation may be an appropriate method for the effective management of water resources in irrigations of sugar beet. Albayrak et al. (2010) indicated that drip irrigation in sugar beet production was a method causing high productivity and profit allowing for saving in input use compared to the sprinkler and furrow irrigation.

Partial root-zone drying (PRD) techniques can improve the water productivity in the sugar beet production without a significant yield reduction in regions having limited water resources. The objective of this study was to examine the effects of the full root-zone wetting (FI) and the PRD irrigation techniques on yield, yield components, water-yield relations and irrigation water use efficiency of the drip-irrigated sugar beet crop under the semiarid climatic conditions.

MATERIALS AND METHODS

Field experiments were conducted during the two growing seasons from May to October 2010 and 2011 at the Agricultural Research Station of Ataturk University, Erzurum (39º56’ N, 41º14’ E; 1793 m a.s.l.), Turkey. The experimental region has a semi-arid climate with annual precipitation of 407.5 mm averaged over 1970-2011 (TSMS, 2012). The temperature, humidity, wind speed, and sunshine values were taken from Erzurum Meteorological Station (39°57’ N, 41°10’ E, 1757 m a.s.l., 5 km from experimental area) during the growing seasons in 2010 and 2011 (Table 1). Precipitation and evaporation data were measured with a standard pluviometer and a Class A pan, respectively, located in the experimental area.

The experimental area soils were classified as an Aridisol according to the US Soil Taxonomy (Soil Survey Staff, 1992). Some physical and chemical soil properties for layers of 0-30, 30-60, and 60-90 cm are given in Table 2. These properties were determined according to the methods used in Klute (1986) and Page et al. (1982). Available water holding capacity of the soil is 121.3 mm in the 0.90 m soil profile.

Plots in the experimental field were arranged as 8 m long and 2.25 m wide. A 1.5 m space was left between plots to prevent passage of water from each other. Monogerm cv. Arosa was used as plant experiment material. Crops were planted on 5 May 2010 and 11 May 2011. Each plot was planted in five rows with an inter row spacing of 45 cm and intra-row spacing of 8 cm. Before planting and during the soil preparation, N, P, and K fertilizers were applied over the whole area as a basal fertilizer at the rate of 120 kg N ha^{-1}, 150 kg P_2O_5 ha^{-1}, and 100 kg K_2O ha^{-1}

Table 2. Some physical and chemical properties of experimental field soil.

	Soil depth, cm		
Properties	0-30	30-60	60-90
Texture	Clay loam	Loam	Loam
Clay, %	30.1	26.2	22.1
Silt, %	34.4	33.1	32.5
Sand, %	35.5	40.7	45.4
Bulk density, g cm^{-3}	1.33	1.37	1.41
Field capacity, % by weight	30.9	27.8	25.1
Wilting point, % by weight	19.2	18.1	16.9
pH	7.61	7.39	7.47
Electrical conductivity, dS m^{-1}	1.46	1.59	1.32
$CaCO_3$, %	2.51	2.13	2.38
Organic C, g kg^{-1}	1.43	1.10	0.61

Table 1. Monthly mean climatic data of the experimental area in the growing periods in trial years.

		Climatic parameters					
Years	Months	Maximum temperature	Minimum temperature	Mean temperature	Relative humidity	Wind speed	Daily sunshine
			ºC		%	m s^{-1}	h
2010	May[1]	18.4	3.8	11.0	68.2	3.0	8.4
	June	24.5	7.2	15.9	60.1	2.8	9.1
	July	28.2	10.8	19.5	56.0	3.3	9.9
	August	29.1	10.4	20.3	44.8	3.7	10.1
	September	26.7	6.9	17.0	48.1	2.9	8.8
	October[2]	16.2	3.5	9.7	70.5	2.6	5.9
2011	May[3]	16.2	5.1	10.3	68.1	3.1	9.1
	June	22.3	6.1	14.6	63.4	2.7	10.9
	July	28.7	10.8	19.6	53.3	4.0	8.1
	August	28.6	10.2	19.4	48.2	3.8	6.4
	September	23.1	4.6	13.9	53.8	3.1	5.2
	October[4]	16.7	0.0	8.3	58.1	2.6	2.6

[1] Calculated from data 5-31 May.
[2] Calculated from data 1-26 October.
[3] Calculated from data 11-31 May.
[4] Calculated from data 1-21 October.

with a fertilizer spreader (Kiziloglu et al., 2006). When young sugar beet plants reached 2-4 leafy stage, plants were thinned. Plant density was adjusted to 9.6 plants m^{-2} after thinning (Çakmakçi et al., 2008). Hoeing was done by hand and repeated as necessary. No pesticides were applied.

Plots were irrigated with groundwater stored in a pool. Electrical conductivity, Na adsorption ratio, and pH of the irrigation water were 0.295 dS m^{-1}, 0.42, and 7.4, respectively. The first irrigations were realized on 2 July 2010 and 7 July 2011. Soil water content in 0-90 cm soil depth of all plots were increased up to field capacity in the first irrigations and subsequent irrigations were done periodically with 4 and 8-d intervals considering Class A pan evaporation values located in the experimental area. Irrigation water was applied via a drip irrigation system. The drip irrigation system consisted of a control unit (a pump, a screen filter, control valves, a pressure gauge, and a water flow meter) and distribution lines (main pipe, manifolds, and driplines). Polyethylene manifolds of 50 mm in diameter were placed along the edge of each plot. Polyethylene driplines of 16 mm in diameter had in-line type emitters. The distance between emitters along the dripline was 0.33 m. Round emitters had a double water inlet and four outlets that had a flow rate of 3.8 L h^{-1} under 0.1 MPa operation pressure. Driplines were placed between crop rows in the experimental plots. There were six driplines on each plot. The irrigation was controlled manually using the valve on each manifold. Plots were irrigated for the period of calculated time. Irrigation quantities for plots was recorded and used for the calculation of monthly and seasonal irrigation amounts.

The experimental field was a completely randomized design with two different irrigation techniques (full root-zone wetting [FI] and partial root-zone drying [PRD]), two different irrigation intervals (I1: 4-d and I2: 8-d), three different irrigation levels (W1, W2, and W3) adjusted according to the Class A pan evaporation using three different plant-pan coefficients (0.70, 0.60, and 0.50) and three replicates. Irrigation techniques (FI, PRD), irrigation intervals (I1, I2) and irrigation levels (W1, W2, and W3) were the main treatments. The combination of irrigation intervals and irrigation levels with irrigation techniques were the sub-treatments (FI-I1W1, FI-I1W2, FI-I1W3, FI-I2W1, FI-I2W2, FI-I2W3, PRD-I1W1, PRD-I1W2, PRD-I1W3, PRD-I2W1, PRD-I2W2, PRD-I2W3).

In the calculation of irrigation quantity applied to plots, the below pan evapotranspiration equation was used (Ertek and Kanber, 2003):

$$W = E_{pan} \times K_{cp} \times P$$

where W is irrigation quantity (mm), E_{pan} is the Class A pan evaporation amount for considering irrigation intervals (mm), K_{cp} is the plant-pan coefficient, and P is the wetting factor. Plant-pan coefficients of 0.70, 0.60, and 0.50 were selected considering the value of 0.50 suggested for sugar beet irrigated with surface method in this region by Sahin et al. (2007). The wetting factor during growing period was determined by dividing the plant row interval by the plant cover width (Ertek and Kanber, 2003). While the irrigation water was applied on the two sides of the plant rows in the FI plots, it was applied on only one side of the plant rows in the PRD plots due to the fact that three of six driplines alternately provide irrigation water to the sugar beet plants in PRD plots. Thus, half of the water applied to FI treatments was applied to the PRD treatments. Surface moisture observations after irrigations under PRD application showed that there was no water penetration into dry side of the root zone. Also, moisture measurement results which are made monthly in wet and dry root-zones under the PRD treatments, showed that the water transition to the dry root-zone remained limited. No runoff problems from the plots were observed during the irrigation period. Also, there was no capillary rise from water table in the plots because of the deep water table level. Soil water content at the effective rooting depth (0-90 cm) and below the effective rooting depth (90-120 cm) was measured using gravimetric method for only monthly periods because of the difficulty of soil sampling. The moisture measurements in soil were made also at the end of vegetation period. Soil water contents were between field capacity and wilting point according to the measurements made. Moisture below effective root depth was approximately constant during moisture measurement period. Additionally, deep percolation from precipitation has been ignored because the maximum daily precipitation value during irrigation periods in 2010 and 2011 did not exceed 10 mm.

Harvesting from the 6 m sections of three centre rows in each plot was done by hand on 26 and 21 October, in 2010 and 2011 respectively. Data were collected at harvest on root yield (t ha^{-1}) and leaf yield (t ha^{-1}). Beet sugar content (%), α-amino N, Na and K contents as mmol 100 g^{-1} were analyzed in the laboratories of the Sugar Factory of the Turkish Sugar Factories Corporation in Erzurum. White sugar content (WSC) and white sugar yield (WSY) were calculated according to Reinefeld et al. (1974):

$$\text{WSC (\%)} = \text{Sugar content} - [0.343\ (\text{Na} + \text{K}) + 0.094\ \alpha\text{-amino N} + 0.29]$$

$$\text{WSY (t ha}^{-1}) = (\text{WSC}/100) \times \text{Root yield}$$

The irrigation water use efficiency (IWUE) is commonly expressed by kg ha^{-1} mm^{-1} or kg m^{-3}, it was calculated by dividing yield (kg ha^{-1}) to the amount of seasonal irrigation water (mm) applied to the plots (Howell, 2001).

Regression technique was used to determine water-yield relationships. ANOVA was conducted to evaluate effects of the full root-zone wetting and partial root-zone drying irrigation techniques according to different irrigation intervals and irrigation levels on root yield, leaf yield, sugar content (SC), white sugar content (WSC), and white sugar yield (WSY). Duncan's multiple range test was used to compare and rank the treatment means.

RESULTS AND DISCUSSION

Evaporation, precipitation, and irrigation quantity

Monthly pan evaporation and precipitation values measured in experimental area during 2010 and 2011 growing periods (5 May-26 October 2010 and 11 May-21 October 2011) are shown in Figure 1. Evaporation values measured from a Class A pan increased to August and then decreased in both years. Seasonal evaporation value was 987.7 mm in the growing period of 2010 and 919.8 mm in the growing period of 2011. Total evaporation values in irrigation periods of 2010 and 2011 (2 July-12 September 2010 and 7 July-17 September 2011) were also 477 and 511 mm, respectively. Although evaporation values were high, precipitation values were low during growing and irrigation periods of trial years. Total precipitation throughout the growing period was 238.1 mm in 2010 and 198.3 mm in 2011 (Figure 1). Precipitation values throughout the irrigation periods of 2010 and 2011 were 71.8 and 36.0 mm, respectively.

Water requirement of sugar beet was high during irrigation periods due to high evaporation and low precipitation. In the first irrigation, soil water contents in 0-90 cm soil depth of all plots were increased up to field capacity applying 40 mm water in 2010 and 48 mm in 2011 and then scheduled irrigations with 4 and 8-d intervals were initiated. Table 3 shows monthly and seasonal irrigation quantities of the sub-treatments. Plots were irrigated for 19 times at irrigation interval of 4-d and 10 times at irrigation interval of 8-d throughout the irrigation periods during both years. Although there were high Class A pan evaporation values in irrigation period, irrigation water amounts applied to the sub-treatments were not high due to the fact that the selected plant-pan coefficients were less than 1 and only plant cover area in plots was irrigated. Mean applied water quantity was 250.9 mm for W1 treatments, 221.2 mm for W2 treatments, and 191.9 mm for W3 treatments. Treatments W2 and W3 were irrigated with 11.8% and 23.5% less water as compared with W1 treatments, respectively. Moreover, the amount of irrigation water applied to PRD treatments was lower than for FI treatments due to the alternating irrigation in the PRD technique. Mean irrigation quantities were 280.4 mm for FI treatments and 162.4 mm for PRD treatments. Thus, the irrigation quantity of PRD plots was 42.1% lower compared to the FI plots. Among sub-treatments, the PRD-I1W3 sub-treatment was irrigated with the lowest amount of water (133.6 mm in 2010 and 147.5 mm in 2011), while the FI-I2W1 sub-treatment was irrigated with the highest amount of water (312.3 mm in 2010 and 339.2 mm in 2011) (Table 3).

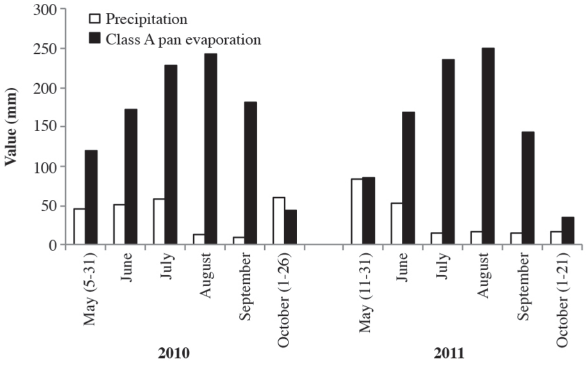


Figure 1. Monthly pan evaporation and precipitation values in 2010 and 2011 growing periods of sugar beet.

Yield and yield components

Root yield, leaf yield, SC, WSC, and WSY were significantly affected by irrigation techniques and levels (Table 4). However, irrigation intervals did not affect these parameters significantly. There was no significant difference between 2010 and 2011 root yield and WSY

Table 3. Monthly and seasonal irrigation quantities applied to sub-treatments in 2010 and 2011 irrigation periods of sugar beet.

	2010				2011			
Sub-treatments	July	August	September	Total	July	August	September	Total
	mm				mm			
FI-I1W1	98.0	139.8	63.7	301.5	114.5	120.4	91.0	325.9
FI-I1W2	89.6	119.9	54.6	264.1	104.8	103.1	78.0	285.9
FI-I1W3	81.5	100	45.5	227.0	95.5	86.1	65.0	246.6
Irrigation number	8	8	3	19	7	7	5	19
FI-I2W1	85.4	144.3	82.6	312.3	120.4	107.5	111.3	339.2
FI-I2W2	78.9	123.6	70.8	273.3	110.0	92.1	95.4	297.5
FI-I2W3	72.5	103.1	59.0	234.6	99.7	76.8	79.5	256.0
Irrigation number	4	4	2	10	4	3	3	10
Mean of FI	84.3	121.8	62.7	268.8	107.5	97.7	86.7	291.9
PRD-I1W1	68.9	69.9	32.0	170.8	81.2	60.2	45.6	187.0
PRD-I1W2	64.9	59.9	27.3	152.1	76.5	51.6	39.0	167.1
PRD-I1W3	60.7	50.0	22.9	133.6	71.8	43.1	32.6	147.5
Irrigation number	8	8	3	19	7	7	5	19
PRD-I2W1	62.8	72.2	41.5	176.5	84.4	53.8	55.8	194.0
PRD-I2W2	59.5	61.8	35.4	156.7	79.0	46.1	47.7	172.8
PRD-I2W3	56.3	51.7	29.7	137.7	74.0	38.5	39.9	152.4
Irrigation number	4	4	2	10	4	3	3	10
Mean of PRD	62.2	60.9	31.5	154.6	77.8	48.9	43.4	170.1

FI: Full root-zone wetting; PRD: partial root-zone drying; I1: irrigation interval (4-d); I2: irrigation interval (8-d); W1: irrigation level (70% Class A pan evaporation); W2: irrigation level (60% Class A pan evaporation); W3: irrigation level (50% Class A pan evaporation).

Table 4. Mean root and leaf yield, sugar content (SC), white sugar content (WSC), and white sugar yield (WSY) of main treatments (irrigation techniques, intervals, and levels) in trial years.

		2010					2011					2010-2011				
Main treatments		Root yield	Leaf yield	SC	WSC	WSY	Root yield	Leaf yield	SC	WSC	WSY	Root yield	Leaf yield	SC	WSC	WSY
		t ha^{-1}		%		t ha^{-1}	t ha^{-1}		%		t ha^{-1}	t ha^{-1}		%		t ha^{-1}
Irrigation techniques	FI	33.22	11.17	17.60	15.43	5.14	34.38	12.38	16.23	14.14	4.87	33.80	11.78	16.92	14.79	5.00
	PRD	25.99	8.99	16.49	14.44	3.76	26.87	10.36	16.51	14.40	3.86	26.43	9.67	16.50	14.42	3.81
P value[1]		0.000	0.000	0.000	0.000	0.000	0.000	0.003	0.242	0.271	0.000	0.000	0.000	0.020	0.033	0.000
Irrigation intervals	I1	29.85	10.23	17.06	14.93	4.48	31.64	11.89	16.47	14.35	4.55	30.74	11.06	16.77	14.64	4.52
	I2	29.36	9.93	17.03	14.94	4.41	29.61	10.84	16.27	14.19	4.19	29.49	10.39	16.65	14.57	4.30
P value		0.769	0.601	0.880	0.961	0.778	0.024	0.104	0.369	0.488	0.018	0.166	0.108	0.500	0.657	0.136
Irrigation levels	W1	32.57a	11.14a	17.25a	15.12a	4.95a	33.35a	11.81	16.25	14.09	4.70a	32.96a	11.48a	16.75ab	14.61ab	4.82a
	W2	29.84ab	10.05ab	17.48a	15.35a	4.59ab	30.96a	11.62	16.56	14.43	4.48a	30.40a	10.83ab	17.02a	14.89a	4.54a
	W3	26.40bc	9.05b	16.40b	14.33a	3.80b	27.56b	10.68	16.31	14.30	3.93b	26.98b	9.87b	16.35b	14.32b	3.86b
P value		0.015	0.016	0.000	0.000	0.002	0.000	0.307	0.516	0.487	0.000	0.000	0.009	0.011	0.028	0.000
P value (for years)												0.260	0.003	0.000	0.000	0.584

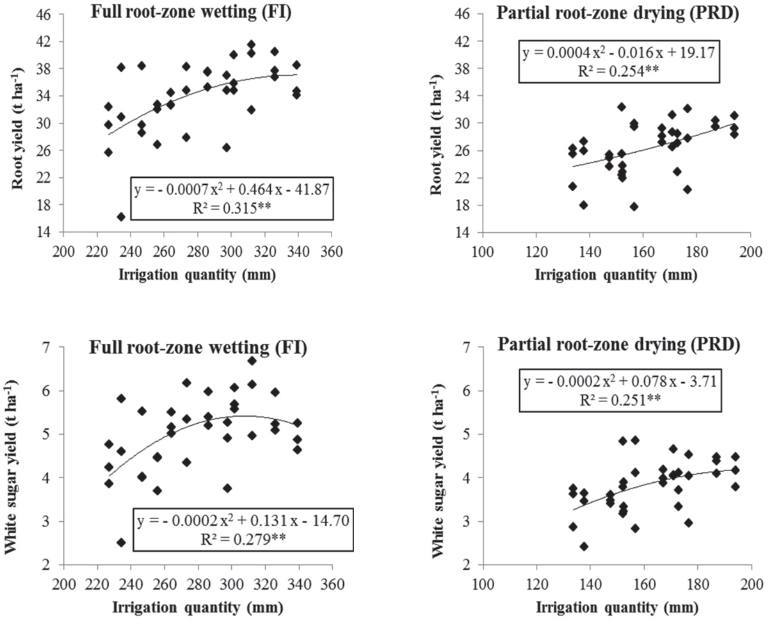
[1] Mean values are significantly different at the level of 0.01 or 0.05 from each other, respectively, if P value is smaller than 0.01 or 0.05.
Mean values marked with the same letter in columns do not differ significantly ($P < 0.01$ or $P < 0.05$) each other.
FI: Full root-zone wetting; PRD: Partial root-zone drying; I1: Irrigation interval (4-d); I2: Irrigation interval (8-d); W1: Irrigation level (70% Class A pan evaporation); W2: Irrigation level (60% Class A pan evaporation); W3: Irrigation level (50% Class A pan evaporation).

values when considering P values of 0.260 and 0.584 for root yield and WSY, respectively (Table 4). Yet, 2011 root yield values were higher than values for 2010. The primary reason for lower root yields in 2010 could probably be attributed to the higher air temperatures during the growing period in 2010 (Table 1) since the increasing air temperature has an adverse effect on the root yield (Kenter et al., 2006). Comparing the two irrigation techniques in terms of mean root yield and WSY, PRD treatments caused a 21.8% decrease in productivity according to FI treatments (33.80 t ha^{-1}) (Table 4). Similarly, the WSY value of PRD treatments was 23.8% lower than value of FI treatments (5.0 t ha^{-1}). In the irrigation with plant-pan coefficient of 0.7 (W1), the highest root yield and WSY values were obtained. While mean root yields for W1, W2, and W3 treatments were respectively 32.96, 30.40, and 26.98 t ha^{-1}, WSY for these treatments were respectively 4.82, 4.54, and 3.86 t ha^{-1} as an average of both years. There was a significant ($P < 0.01$) difference between W1 and W3 treatments. But the difference between W1 and W2 treatments for the root yield and for WSY was not significant (Table 4). Compared to W3 treatments, the W1 treatments provided 22.2% more root yield and 24.9% more WSY. It could be said that lower water caused lower root yield and WSY. Similarly, many researchers indicated that the water deficit caused less root and sugar yield for sugar beets (Kiziloglu et al., 2006, Mahmoodi et al., 2008; Esmaeili, 2011; Topak et al., 2011; Yonts, 2011; Ghamarnia et al., 2012).

Relationships between irrigation quantity and root yield or WSY values of both the FI and PRD treatments were polynomial and the relationship equations had significantly high determination coefficients (Figure 2). But, determination coefficients of relationships between irrigation quantity and root yield were higher than coefficients of relationships between irrigation quantity and WSY. As seen in Figure 2, the relationship between irrigation quantity and the root yield for both the FI and PRD treatments was nearly unique due to the different irrigation quantities applied. When we compared yields for a water level of 200 mm, it is observed that the PRD treatment displayed a slight increase compared to the FI treatment. It could be a consequence of the physiological effect of PRD and to the decrease in soil evaporation.

There is an extensive literature on the yield-water relations of sugar beet. According to the information transmitted from the literature by Uçan and Gençoğlan (2004) the relationship between yield and applied water is concave. Also this relation may be curvy and even sigmoidal. Shrestha et al. (2010) indicated that there was both a linear and polynomial relation between yield decline and water stress. Wright et al. (1997) compared linear and polynomial functions in sugar beet and concluded that the higher-order equations did not give significant advantages over linear relations. In addition, more significant linear relationships were obtained when sugar yield was considered instead of root yield. Also, many researchers determined that there was a linear relationship between water use and root yield of sugar beet (Uçan and Gençoğlan, 2004; Kiziloglu et al., 2006; Nourjou, 2008; Pejić et al., 2011; Topak et al., 2011). Therefore, we also examined linear relationships between irrigation quantity and root yield or WSY values. It was observed that determination coefficients of the linear relationship equations were significantly high although they were lower than the coefficients of polynomial relationship equations.

Among FI treatments, the highest root yield and WSY values were determined in the FI-I1W1 sub-treatment as 37.57 and 5.60 t ha^{-1}, respectively (Table 5). Similarly, among PRD treatments the PRD-I1W1 sub-treatment had the highest root yield (29.31 t ha^{-1}) and WSY (4.28 t ha^{-1}) values. So, the PRD-I1W1 sub-treatment obtained a lower root yield by 22% and a lower WSY by 23.6% compared to FI-I1W1 sub-treatment. However, the FI-I1W1 sub-treatment received higher irrigation water



**Equations in graphs are significant at $P < 0.01$.

Figure 2. Relationships between irrigation quantity and root yield or white sugar yield according to combined data of 2010 and 2011 (n = 36).

by 75.3% compared to the PRD-I1W1 sub-treatment (178.9 mm). Our results showed that the PRD technique provided higher yields compared to results of experiments conducted by different researchers for the same irrigation quantities. For example, Topak et al. (2011) applied irrigation water of 244.2 mm (water use 374.5 mm) and obtained root yield of 28.1 t ha^{-1} and WSY of 5.25 t ha^{-1} for the drip-irrigated sugar beet in semi-arid Konya, Turkey region. Uçan and Gençoğlan (2004) got the root yield of 10.4 t ha^{-1} and sugar yield of 1.94 t ha^{-1} in sugar beet irrigated by using a line-source sprinkler system obtained for the irrigation water of 363.5 mm (water use 541 mm) in semiarid Kahramanmaraş, Turkey region. Similar results were published by Sahin et al. (2007) for surface irrigated sugar beet in Erzurum conditions with semiarid climate.

Although there were not significant differences between 4 and 8-d irrigation intervals in terms of root yield and WSY, these values in irrigations with 8-d intervals were lower than values with 4-d irrigation

Table 5. Root and leaf yield, sugar content (SC), white sugar content (WSC) and white sugar yield (WSY) of sub-treatments in trial years.

	2010					2011					2010-2011				
Sub-treatments	Root yield	Leaf yield	SC	WSC	WSY	Root yield	Leaf yield	SC	WSC	WSY	Root yield	Leaf yield	SC	WSC	WSY
	—— t ha^{-1} ——		—— % ——		t ha^{-1}	—— t ha^{-1} ——		—— % ——		t ha^{-1}	—— t ha^{-1} ——		—— % ——		t ha^{-1}
FI-I1W1	36.88a	12.33	17.85a	15.68a	5.78a	38.26	14.00	16.47	14.16	5.42	37.57a	13.17	17.16ab	14.92	5.60a
FI-I1W2	33.23ab	10.73	17.93a	15.71a	5.22ab	36.79	12.87	17.09	15.01	5.52	35.01a	11.80	17.51a	15.36	5.37a
FI-I1W3	29.27b	10.20	16.79b	14.66b	4.29b	32.21	12.23	15.92	13.98	4.52	30.74b	11.22	16.36b	14.32	4.40b
P value[1]	0.031	0.421	0.027	0.030	0.005	0.153	0.670	0.120	0.188	0.170	0.006	0.318	0.044	0.083	0.001
FI-I2W1	37.85	12.90	17.83	15.65	5.93	35.76	11.87	15.86	13.76	4.92	36.81	12.38	16.85	14.71	5.42
FI-I2W2	33.66	11.50	17.82	15.69	5.29	32.73	11.90	16.22	14.19	4.64	33.20	11.70	17.02	14.94	4.97
FI-I2W3	28.42	9.37	17.36	15.22	4.31	30.53	11.43	15.85	13.77	4.20	29.47	10.40	16.61	14.49	4.26
P value	0.389	0.259	0.207	0.311	0.324	0.341	0.968	0.467	0.209	0.341	0.111	0.342	0.774	0.719	0.120
PRD-I1W1	28.82	10.37	16.88	14.76	4.25	29.79a	10.53	16.70	14.48	4.31a	29.31a	10.45	16.79	14.62	4.28a
PRD-I1W2	26.72	9.30	16.75	14.66	3.93	28.17a	11.90	16.52	14.27	4.02a	27.45a	10.60	16.64	14.47	3.98ab
PRD-I1W3	24.15	8.43	16.16	14.11	3.41	24.63b	9.83	16.15	14.23	3.50b	24.39b	9.13	16.16	14.17	3.46b
P value	0.358	0.120	0.259	0.247	0.294	0.001	0.279	0.627	0.909	0.002	0.011	0.186	0.144	0.410	0.008
PRD-I2W1	26.72	8.97	16.45ab	14.40ab	3.84	29.59a	10.83	15.96	13.96	4.14	28.16	9.90	16.21	14.18	3.99
PRD-I2W2	25.76	8.67	17.43a	15.35a	3.93	26.16ab	9.80	16.39	14.25	3.72	25.96	9.23	16.91	14.80	3.83
PRD-I2W3	23.77	8.20	15.29b	13.34b	3.17	22.88b	9.23	17.31	15.22	3.49	23.33	8.72	16.30	14.28	3.33
P value	0.834	0.858	0.042	0.043	0.522	0.016	0.561	0.145	0.166	0.172	0.161	0.505	0.431	0.507	0.176

[1] Mean values are significantly different at $P < 0.01$ or $P < 0.05$.

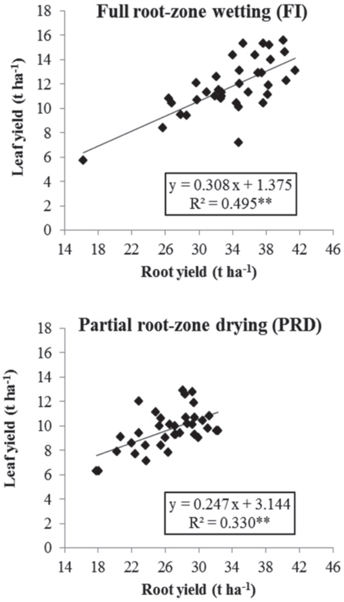
Mean values marked with the same letter in columns do not differ significantly ($P < 0.01$ or $P < 0.05$).

FI: Full root-zone wetting; PRD: partial root-zone drying; I1: irrigation interval (4-d); I2: irrigation interval (8-d); W1: irrigation level (70% Class A pan evaporation); W2: irrigation level (60% Class A pan evaporation); W3: irrigation level (50% Class A pan evaporation).

intervals (Table 4). Similarly, Nourjou (2008) determined that increasing the irrigation interval caused a decrease in root yield. According to the mean obtained from 2 yr data, root yield and WSY values were not significantly affected by irrigation levels in irrigations with 8-d interval (Table 5). On the contrary, irrigation levels affected these parameters significantly in irrigations with a 4-d interval. While W3 treatment values were significantly the lowest ($P < 0.01$), W1 and W2 treatment values were similar.

Mean total leaf yield was 11.37 t ha^{-1} in 2011 compared with 10.08 t ha^{-1} in 2010, i.e. a decrease of 11.3% (Table 4). While irrigation techniques and levels had a significant ($P < 0.01$) effect on the leaf yield, irrigation intervals did not affect leaf yield of sugar beet. Considering mean values of the 2 yr period, leaf yield in the PRD treatments was significantly ($P < 0.01$) lower than 17.9% the FI treatments (11.78 t ha^{-1}). Schachtman and Goodger (2008) indicated that leaf growth decreases due to the chemical signals produced by roots in the drying soil by the application of the PRD technique. The W1 treatment had significantly ($P < 0.01$) higher leaf yield by 16.3% compared to the W3 treatment (9.87 t ha^{-1}). Among all FI treatments, the mean leaf yield changed from 10.40 t ha^{-1} (FI-I2W3) to 13.17 t ha^{-1} (FI-I1W1). It changed from 8.72 t ha^{-1} (PRD-I2W3) to 10.60 t ha^{-1} (PRD-I1W2) among PRD treatments (Table 5). A decrease in irrigation levels reduced leaf yields in both irrigation intervals. Kiziloglu et al. (2006) and Mahmoodi et al. (2008) found that the lowest leaf yields for sugar beet were obtained in the lowest soil water content conditions. Also, Abayomi and Wright (2002) said that leaf growth of sugar beet was sensitive to changes in soil water deficit. However, Kenter et al. (2006) concluded that there was no significant influence on sugar beet leaf growth by soil water content.

Results of this study showed that treatments having low root yields had low leaf yields (Table 5). Similar results were also observed in some studies (Şahin et al., 2004; Kiziloglu et al., 2006; Mahmoodi et al., 2008). For this reason, root yields and leaf yields of the sub-treatments were regressed as linear, significant relationships determined between the root yield and the leaf yield of sugar beet for the combined values of 2010 and 2011 (Figure 3). This relationship for the FI treatments equated with a higher determination coefficient compared to the PRD treatments.



**Equations in graphs are significant at $P < 0.01$.

Figure 3. Relationships between root yield and leaf yield of sugar beet according to combined data of 2010 and 2011 (n = 36).

Sugar content and WSC values were also affected significantly ($P < 0.05$) with the irrigation techniques and levels (Table 4). The analysis of SC and WSC showed better performances for the FI treatments compared to the PRD treatments. According to the combined 2 yr values, the SC and WSC values of the FI treatments were 2.6% higher than values of the PRD treatments. Among the W1, W2, and W3 treatments, the lowest SC and WSC values obtained in the W3 treatment applied the lowest water; SC and WSC increased firstly with the decreasing applied water levels and then decreased. The W2 treatment had the highest SC and WSC values as 17.02% and 14.89%, respectively (Table 4). The W2 treatment values of SC and WSC were significantly ($P < 0.05$) different from the W3 treatment (Table 4). But, W1 and W3 treatments were statistically similar. All sub treatments are evaluated together; the FI-I1W2 treatment had the highest SC and WSC values as 17.51% and 15.36%, respectively (Table 5). But, the highest SC and WSC values among PRD treatments were determined in the PRD-I2W2 treatment as 16.91% and 14.80%, respectively. Uçan and Gençoğlan (2004), Topak et al. (2011), and Ghamarnia et al. (2012) found that SC of sugar beet increased with the increasing water deficit. In general, lower water stress caused the lower values. On the contrary, Sakellariou-Makrantonaki et al. (2002) indicated that SC values of drip-irrigated sugar beet were not significantly different at 100% and 80% of the irrigation depths. Yonts (2011) summarized that beet SC was not affected by reducing the irrigation to 25%.

The irrigation water use efficiency (IWUE)

Table 6 shows the main treatment's IWUE values calculated by dividing root yield by irrigation quantity. The IWUE values in 2010 were higher than the IWUE values in 2011 due to the lower irrigation quantities in spite of the lower root yields (Tables 3 and 4). However, there was no significant difference between trial years (Table 6). The highest IWUE with 168.9 and 158.2 kg ha^{-1} mm^{-1} was obtained under the PRD treatments for years 2010 and 2011, respectively. Partial root-zone drying treatments (163.5 kg ha^{-1} mm^{-1}) had higher IWUE as 34.9% compared to the FI treatments (121.2 kg ha^{-1} mm^{-1}) according to the 2 yr mean values. The increase of ABA produced by roots of plants under drying soil conditions causes partial stomata closure. This is the main physiological response to decrease transpiration in the plants under PRD treatment and so enhance the water productivity (Davies et al., 2002). Also, Sepaskhah and Ahmadi (2010) indicated that crop yields using the same water amount are higher for the PRD technique.

The 4-d irrigation interval had an 8.0% higher IWUE value compared to the 8-d irrigation interval. Although the lowest root yield was determined in the W3 treatment among irrigation levels, this treatment showed high IWUE due to the less water applied. The IWUE value for the W3 treatment was 6.6% higher than the value for the W1 treatment.

The PRD sub-treatments with irrigation intervals of 4-d had higher IWUE values (Table 7). On the basis of means over 2 yr, the IWUE value of the PRD-I1W3 sub-treatment was the highest at 173.9 kg ha^{-1} mm^{-1}. The lowest IWUE value was obtained in the FI-I2W1 sub-treatment at 113.3 kg ha^{-1} mm^{-1}. Among FI sub-treatments the highest IWUE value was obtained in the FI-I1W3 sub-treatment (129.8 kg ha^{-1} mm^{-1}). The PRD-I1W3 sub-treatment IWUE value was 34.0% higher than the FI-I1W3 sub-treatment IWUE value. Although less root yields obtained from treatments with lower water application they gave higher IWUE values. IWUE values were generally high under increasing water deficit conditions according to some research results (Nourjou, 2008; Esmaeili, 2011; Topak et al., 2011; Ghamarnia et al., 2012). But, El-Askari et al. (2003) and Uçan and Gençoğlan (2004) showed that the highest IWUE values were obtained at the highest irrigation conditions.

Table 6. Irrigation water use efficiency (IWUE) values of main treatments (irrigation techniques, intervals and levels) in trial years.

Main treatments		Years 2010	 2011	 2010-2011
		kg ha^{-1} mm^{-1}		
Irrigation techniques	FI	123.8	118.6	121.2
	PRD	168.9	158.2	163.5
P value[1]		0.000	0.000	0.000
Irrigation intervals	I1	150.4	145.3	147.8
	I2	142.3	131.5	136.9
P value		0.341	0.000	0.016
Irrigation levels	W1	140.9	133.7	137.3
	W2	147.3	139.7	143.5
	W3	150.9	141.7	146.3
P value		0.621	0.166	0.242
P value (for years)				0.075

[1]Mean values are significantly different at $P < 0.01$ or $P < 0.05$.
FI: Full root-zone wetting; PRD: partial root-zone drying; I1: irrigation interval (4-d); I2: irrigation interval (8-d); W1: irrigation level (70% Class A pan evaporation); W2: irrigation level (60% Class A pan evaporation); W3: irrigation level (50% Class A pan evaporation).

Table 7. Irrigation water use efficiency (IWUE) values of sub-treatments in trial years.

Sub-treatments	Years 2010	 2011	 2010-2011
	kg ha^{-1} mm^{-1}		
FI-I1W1	122.3	117.4	119.9
FI-I1W2	125.8	128.7	127.3
FI-I1W3	128.9	130.6	129.8
P value[1]	0.744	0.469	0.285
FI-I2W1	121.2	105.4	113.3
FI-I2W2	123.2	110.0	116.6
FI-I2W3	121.1	119.2	120.2
P value	0.996	0.499	0.871
PRD-I1W1	168.8	159.3	164.0
PRD-I1W2	175.7	168.6	172.2
PRD-I1W3	180.8	167.0	173.9
P value	0.838	0.143	0.570
PRD-I2W1	151.4	152.5	152.0
PRD-I2W2	164.4	151.4	157.9
PRD-I2W3	172.6	150.1	161.4
P value	0.800	0.967	0.827

[1]Mean values are significantly different at $P < 0.01$ or $P < 0.05$.
FI: Full root-zone wetting; PRD: Partial root-zone drying; I1: Irrigation interval (4-d); I2: Irrigation interval (8-d); W1: Irrigation level (70% Class A pan evaporation); W2: Irrigation level (60% Class A pan evaporation); W3: Irrigation level (50% Class A pan evaporation).

CONCLUSIONS

Two years of trials indicated that sugar beet root yield, leaf yield, sugar content, white sugar content, white sugar yield, and irrigation water use efficiency (IWUE) were affected significantly with irrigation techniques. In both full root-zone wetting (FI) and partial root-zone drying (PRD) techniques, the highest root and white sugar yields were obtained from the treatment of irrigation with a 4-d interval and irrigated at the highest irrigation level.

As a result of a 2 yr field study, PRD technique with higher IWUE for sugar beet production is a well suited irrigation technique compared to the FI irrigation technique. Therefore, irrigation with a 4-d interval and with irrigation quantities at the ratios of 0.7 and 0.6 of the Class A pan evaporation in the PRD technique could be the best irrigation treatment for drip-irrigated sugar beet in a semiarid region with limited water resources due to high IWUE and low yield reduction.

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