Effect of Deficit Irrigation on Root Growth, Soil Water Depletion, and Water Use Efficiency of Cucumber

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Abstract. Water scarcity is increasing in the world, which is limiting crop production, especially in water-limited areas such as Southern High Plains of the United States. There is a need to adopt the irrigation management practices that can help to conserve water and sustain crop production in such water-limited areas. A 2-year field study was conducted during the summers of 2019 and 2020 to evaluate the effect of deficit irrigation levels and cultivars on root distribution pattern, soil water depletion, and water use efficiency (WUE) of cucumber (*Cucumis sativus*). The experiment was conducted in a split-plot design with four irrigation levels [100%, 80%, 60%, and 40% crop evapotranspiration (ET_c)] as main plot factor and two cultivars (Poinsett 76 and Marketmore 76) as subplot factor with three replications. Results showed that root length density (RLD) was unaffected by the irrigation levels in 2019. In 2020, the RLD was comparable between 100% and 80% ET_c , and it was significantly higher in 100% ET_c than both 60% and 40% ET_c . Root surface area density (RSAD) was not significantly different between 100% and 80% ET_c , and it was significantly lower in both 60% and 40% ET_c than 100% ET_c in both years. Soil water depletion was the highest in 40% ET_c followed by 60% and 80% ET_c , and it was least in 100% ET_c in both years. Evapotranspiration (ET) was the highest in 100% ET_c followed by 80%, 60%, and 40% ET_c . The WUE was not statistically different among the irrigation treatments. However, numerically, WUE was observed in the following order: 80% ET_c > 100% ET_c > 60% ET_c > 40% ET_c . The RLD, RSAD, soil water depletion, and ET were not significantly different between ‘Poinsett 76’ and ‘Marketmore 76’. However, fruit yield was significantly higher in ‘Poinsett 76’ than ‘Marketmore 76’, which resulted in higher WUE in Poinsett 76. It can be concluded that 80% ET_c and Poinsett 76 cultivar can be adopted for higher crop water productivity and successful cucumber production in SHP.

Water scarcity is one of the major constraints that limits crop production, especially in arid and semiarid regions of the world such as the Southern High Plains (SHP) of the United States. In the SHP, a tremendous decline in the water table has been observed in past few decades. In particular, Ogallala Aquifer, which is a primary source of supplemental irrigation in SHP, has been depleted by more than 50% of its maximum water storage

capacity from 1935 to 2012 (Haacker et al., 2016). In SHP, an average annual ET (1500 to 1750 mm) is considerably higher than an average annual precipitation (350 to 550 mm) (Bhattarai et al., 2020b; Parkash et al., 2021). This huge gap between the ET and precipitation necessitates the withdrawal of water from Ogallala aquifer for supplemental irrigation to meet the crop water requirements in the SHP. As a consequence of this higher water withdrawal rate there is a decline in the water table in SHP. This declining water availability from aquifer is creating a challenge to sustain the crop production in the region, and it has obliged the adoption of water-conserving irrigation management practices.

An efficient and effective utilization of scarcely available water for crop production depends on improved irrigation management practices, which can help conserve water and sustain crop production in water-limited areas (El-Mageed and Semida, 2015; Howell, 2001).

Deficit irrigation (DI) is one of those potential water conserving irrigation management practices. In DI, crop is irrigated with a lower amount of irrigation water than its full water requirement (crop ET) either at specific crop growth stages or throughout the growing season (Costa et al., 2007; Parkash and Singh, 2020b; Parkash et al., 2021). With DI, a crop is exposed to water deficit to some extent. Crops can be subjected to water deficit up to a certain limit (threshold limit) without causing a significant decline in plant growth and yield (Parkash and Singh, 2020b; Parkash et al., 2021). In a review, Singh et al. (2019) reported that in 52% of 134 studies on DI in vegetable crops, there was a severe decline in yield under all DI levels, whereas in 44% of the studies, yield was statistically similar between minor to moderate DI levels and full irrigation. However, response and adaption of plant to DI varies among the crop species or cultivars, plant growth stages, environmental conditions, and duration and severity of water deficit (Cattivelli et al., 2008; Parkash and Singh, 2020b). Water-stress-tolerant crops can adapt to increased water deficit conditions, and under water-deficit conditions, these crops can produce yields comparable to full irrigation (Singh et al., 2019). Water-stress-tolerant crop species can prevent the yield losses due to water stress through physiological and morphological adaptations. Moreover, by implementing DI, WUE of the crop can be increased because decreasing the amount of irrigation water up to certain extent does not cause a significant decrease in economical yield of the crop while considerable amount of water can be saved. As a consequence, WUE increases with DI specifically in crops or cultivars that are water stress tolerant (Kirda, 2002; Singh et al., 2019).

Root growth adjustments are crucial for efficient utilization of the available soil water and to get better yield under DI conditions (Xue et al., 2003). Root traits such as root thickness, rooting depth, and root penetrating capacity through highly compacted soil layers are related to morphological adaptations of a crop species to water stress. Crops with deep root system are more capable of extracting water from deeper soil layers to meet the transpiration requirements; thus, these crops are able to maintain plant growth and yield under water-deficit conditions (Sharma et al., 2018). An increase in root biomass under water-deficit conditions enhances production of aboveground biomass, which subsequently increases the yield (Qi et al., 2012). Melons increased their root growth to adapt to DI conditions (Sharma et al., 2014), whereas potatoes had similar root growth under both DI and full irrigation treatments (Ahmadi et al., 2008). Thus, crop species can vary in root growth adjustments under water-deficit conditions. However, root growth adjustments are also dependent on the soil properties and environmental conditions (Sharma et al., 2017).

Root water uptake mainly depends on the rooting depth, root length at a particular soil depth, and water extraction capability of

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roots at a particular level of soil moisture (Kondo et al., 2000). However, available soil water content also influences the depth and density of roots (Man et al., 2016). So, root water uptake depends on root distribution as well as on available soil moisture content. Under DI, soil water content is affected, which further affects the root distribution as well as root water uptake patterns (Li et al., 2010). Root distribution and root water uptake patterns are critical for determining the ability of a plant to efficiently use the resources (such as water and nutrients) from the soil profile (Robinson et al., 1991). Root water uptake pattern can help determine the ability of a crop to extract stored soil moisture, which is necessary under DI conditions. Thus, it is important to determine the effect of deficit irrigation on the root distribution and root water uptake patterns especially in vegetable crops which are more susceptible to water stress. This research can further help to develop efficient crop production and breeding strategies to improve crop water productivity of vegetable crops (Sharma et al., 2014).

Cucumber (*Cucumis sativus*) is a high value vegetable crop and is among the most commonly produced vegetable crops in the world. Cucumbers are cultivated around the world, and area under their cultivation is ≈ 2 million hectares with total production nearly 75 million tonnes in 2018 (Food and Agriculture Organization, 2018). In Texas, cucumbers are cultivated on ≈ 6000 acres (US Department of Agriculture, 2017), and 50% of these acres are planted in West Texas (Tower, 2017). Effect of DI on plant growth and yield of cucumber has been evaluated in a number of studies (Al-Omran and Louki, 2011; Alomran et al., 2013; Amer et al., 2009; Kirnak and Demirtas, 2006). However, studies on effect of DI on the root distribution and root water uptake patterns of cucumber are lacking. Therefore, the objective of this study was to examine the effect of different levels of DI on the root distribution, soil water depletion pattern, and WUE of two cucumber cultivars.

Materials and Methods

Experimental site. A 2-year field study was conducted from 30 May to 29 Aug. 2019 and

from 8 June to 7 Sept. in 2020 at the Quaker Research Farm of Texas Tech University, Lubbock, TX. The climatic conditions of the experimental site are characterized as semiarid with an average annual rainfall of 469 mm and average annual minimum and maximum temperatures of 7.83 and 23.33 °C, respectively (Texas A&M University, 2020). The soil of the experimental site was comprised of Amarillo sandy clay loam (fine-loamy, mixed, superactive, thermic Aridic Paleustoll) and Olton clay loam (fine, mixed, superactive, thermic Aridic Paleustolls) (National Resources Conservation Service, 2021). The soil texture of experimental site was sandy loam and particle size distribution was 73.21% sand, 10.07% silt, and 16.72% clay in 0- to 10-cm soil depth.

Experimental design and cultivation practices. The experiment was conducted as a blocked split-plot design and each experimental unit was replicated three times. Irrigation levels (100%, 80%, 60%, and 40% ET_c) were the main plot factor, and cultivars (Poinsett 76 and Marketmore 76) were the subplot factor. Seeds of Poinsett 76 and Marketmore 76 cultivars were purchased from Willhite Seed Inc. (Poolville, TX).

Seed beds were prepared using conventional tillage practices. The field was irrigated with a subsurface drip irrigation system, and specifications of drip irrigation system were as follows: drip tape was 30 cm deep, diameter of drip tape was 2.2 cm, emitters on drip tape were spaced 61 cm apart, and discharge rate from each emitter was 1.2 L/h. The field consisted of four irrigation zones, and each zone had its individual control for irrigation applications, which helped to assign one irrigation level to one irrigation zone. All irrigation zones were 55 m in length and 8 m wide. In each irrigation zone, six plots (three replications of each cultivar as a subplot) were made, and each plot was 6 m long and 8 m wide. Alleys 1.5 m wide were made to separate two consecutive experimental units in an irrigation zone. Seeds were directly planted using a four-row planter on 30 May 2019 and 8 June 2020. Row-to-row spacing was 1 m, and plant-to-plant distance was maintained manually at 0.3 m by uprooting the closely spaced plants. Hand weeding was done to

remove weeds. On the basis of soil test and recommendations, an equal amount of fertilizers was applied to all the experimental units in both years. Fertilizers were applied only once at 4 weeks after planting through drip irrigation system in both years. The URAN 32 (32-0-0, Nitrogen Fertilizer Solution, Nutrien Ag Solution, Loveland, CO) was used to apply 55 kg of nitrogen per hectare.

Crop was irrigated based on the daily ET_c requirements, which was calculated by multiplying the reference ET (ET_0) and crop coefficient (K_c). The ET_0 was calculated from weather data using the Penman-Monteith equation (Allen et al., 1998). Weather data were obtained from a weather station installed at the experimental site. Stage-specific crop coefficients for cucumber crop were as; $K_{c \text{ initial}} = 0.45$ [0–20 d after planting (DAP)], $K_{c \text{ development}} = 0.70$ (31 to 50 DAP), $K_{c \text{ midseason}} = 0.90$ (51 to 90 DAP) and $K_{c \text{ late-season}} = 0.75$ (91 to 105 DAP) (Brouwer and Heibloem, 1986). Supplement irrigation requirements were calculated by subtracting the rainfall from crop water requirements (ET_c). Irrigation was applied once a week to replace the amount of water used for ET_c in the previous week. In 2019, a total of 166 mm of water (irrigation + rain) was applied for good crop emergence and establishment (0 to 33 DAP), and in 2020, a total of 129 mm water was applied for crop establishment (0 to 30 DAP). In the 2019 crop establishment period, most of the crop water requirement was met from rainfall (104 mm), so there was less need for supplemental irrigation (62 mm), whereas in 2020, rainfall (19 mm) was much less, and most of the crop water requirement was met from the supplemental irrigation (110 mm) during the crop establishment period (Table 1). In 2019, heavy rainfall events lead to overirrigation of crop in the initial days of growing season. After the start of differential irrigation treatment, 100% ET_c , 80% ET_c , 60% ET_c , and 40% ET_c irrigation treatments received a total of 362, 285, 231, and 156 mm of water (irrigation + rain), respectively, in 2019. The respective values of water received by these irrigation treatments in 2020 were 416, 333, 250, and 167 mm, respectively. In 2019, during the whole growing season, a total

Table 1. Rainfall and irrigation applied during the whole growing season in 2019 and 2020 in Lubbock, TX.

Treatments	Initial			Differential			Whole growing season		
	Rain (mm)	Irrigation (mm)	Total (mm)	Rain (mm)	Irrigation (mm)	Total (mm)	Rain (mm)	Irrigation (mm)	Total (mm)
2019	0–33 DAP			33–91 DAP			0–91 DAP		
Irrigation level, ET_c									
100%	104	62	166	27	335	362	131	397	528
80%	104	62	166	27	258	285	131	320	451
60%	104	62	166	27	204	231	131	266	397
40%	104	62	166	27	129	156	131	191	322
2020	0–30 DAP			31–91 DAP			0–91 DAP		
Irrigation level, ET_c									
100%	19	110	129	37	379	416	56	489	545
80%	19	110	129	37	296	333	56	406	462
60%	19	110	129	37	213	250	56	323	379
40%	19	110	129	37	130	167	56	240	296

DAP = days after planting; ET_c = crop evapotranspiration.

of 528, 451, 397, and 322 mm of irrigation water (irrigation + rain) amounts were applied to 100%, 80%, 60%, and 40% ET_c, respectively; in 2020, the irrigation amounts for corresponding irrigation treatments were 545, 462, 379, and 296 mm.

Soil water content measurements. Volumetric water content (VWC, m³·m⁻³) was measured at 9, 20, 50 and 91 DAP using a capacitance probe (Model: PR2/6 Profile Probe, Delta-T Devices Ltd., Cambridge, UK). Time period of 9 to 20 DAP represents initial stage, 20 to 50 DAP represents development stage, and 50 to 91 DAP represents reproductive stage. Access tubes (100 cm long) for the PR2 probe were installed manually into soil using the augering kit supplied by the access tube manufacturer. Access tubes were installed in the center of each plot between two plants in a row and 5 cm away from drip tape. Access tubes were installed at 9 DAP in both years when there was a good crop emergence. The PR2 probe measures the VWC at 0.1, 0.2, 0.3, 0.4, 0.6, and 1 m depths of the soil profile. Soil water content (millimeters) at each depth was determined as the product of VWC at each depth and depth increment (millimeters) (Bhattarai et al., 2020b). Soil water content for complete 1-m soil profile was calculated as sum of soil water content at each depth. To calculate soil water depletion (millimeters) in a given period, soil water content at the end of a given period was subtracted from soil water content at starting of that period. To determine seasonal change in soil water storage (ΔS), soil water content at harvest was subtracted from initial soil water content.

ET and WUE. ET was calculated by using the water balance equation: $ET = P + I \pm \Delta S - D - R$, where P is precipitation (millimeters), I is irrigation (millimeters), ΔS is the change in soil water storage in the 100-cm soil profile (millimeters), D is the downward drainage below the root zone (millimeters), and R is surface runoff (millimeters) (Singh et al., 2016; Wang et al., 2012). Because subsurface drip irrigation system was used to apply supplemental irrigation and experimental field was leveled, and also no heavy rainfall was received during the whole crop growing season, therefore, surface runoff and drainage were considered negligible (Bhattarai et al., 2020b; Hao et al., 2015; Singh et al., 2016). The WUE (kg·ha⁻¹·mm⁻¹) was calculated by the using the formula: $WUE = \text{fruit yield (kg·ha}^{-1}\text{)}/\text{total seasonal crop ET (mm)}$ (Bhattarai et al., 2020a; Hao et al., 2015). The irrigation water use efficiency (IWUE, kg·ha⁻¹·mm⁻¹) was calculated by the using the formula: $IWUE = \text{fruit yield (kg·ha}^{-1}\text{)}/\text{total seasonal irrigation applied (irrigation + rain, mm)}$ (Zotarelli et al., 2009). Fruits were harvested at a weekly interval from the marked area (6.19 m² per plot) for data recording. Fruit harvesting was started at 54 and 55 DAP in 2019 and 2020, respectively.

Root core sampling and root growth parameters analysis. To collect root samples, soil core samples were collected at the end of each crop growing season using a split-core

sampler (60 cm length and 5 cm diameter). Root samples were taken up to 60-cm soil depth. Sliding hammer was used to push the core in the soil profile and a Hi-Lift Jack was used to take out the soil-core sampler without disturbing the soil. Drip tape was located in the center of bed and beneath the plant rows; therefore, soil core samples were taken at a location 5 cm away from the drip tape and parallel to a plant. Soil core samples in the split-core sampler were cut into 10-cm-deep increments to obtain six soil samples to represent 0 to 10, 10 to 20, 20 to 30, 30 to 40, 40 to 50, and 50 to 60 cm of soil depths. Each soil core sample was placed in individual Ziploc bag and stored at 4 °C until roots were washed out of them (Parkash and Singh, 2020a; Sharma et al., 2014). Roots were washed out of the soil core samples by placing the soil core samples on the fine mesh sieve strainer and another fine mesh sieve strainer was kept vertically below the strainer containing soil core sample so as to collect the roots escaping from the upper strainer while washing. Water with little pressure was sprinkled over the upper strainer to drain out the soil from the strainers. After draining out the soil from both strainers, roots were taken out from the strainers using a forceps and stored in 50 ml falcon tubes containing 20% ethanol solution (cm³·cm⁻³) at 4 °C for later root morphology analysis (Parkash and Singh, 2020a; Sharma et al., 2014). Images of the washed root samples were acquired using a flatbed scanner (Model: STD 4800, EPSON V800 Photo Dual Lens System, Reagent Instruments Inc., Quebec, Canada) at 600 dpi resolution. The acquired images were analyzed to determine RLD [root length per unit volume of soil (cm·cm⁻³)], RSAD (root surface area per unit volume of soil (cm²·cm⁻³)), and root fineness classification (percentage of total root length in a given diameter class) using WinRHIZO Pro version 2016a software (Regent Instruments Inc.). Total root length was distributed into three diameter classes—0 to 0.5, 0.5 to 1.0, and >1 mm—and percent of total root length lying in a given diameter class was calculated (root length in a given diameter class/total root length × 100).

Statistical analysis. Data collected for each parameter was analyzed using analysis

of variance (ANOVA) with a split plot design in R version 3.5.2 using Agricolae package version 1.2-8. Root data were analyzed using ANOVA with a split-split plot design with irrigation levels as main plot factor, cultivars as subplot factor, and soil depth as sub-subplot factor (Sharma et al., 2014). Soil water depletion data were analyzed individually for each soil depth using ANOVA with a split plot design (Bhattarai et al., 2020b). Data for each year was analyzed separately. Treatment means were compared using least significant difference test at 5% significance level. Figures were made using SigmaPlot software version 14 (Systat Software, San Jose, CA).

Results and Discussion

Weather conditions. The daily minimum, maximum, and average temperatures, and daily rainfall during the growing seasons of 2019 and 2020 are shown in Fig. 1. Total rainfall received during the growing seasons of 2019 and 2020 was 131 and 56 mm, respectively. Average air temperatures during the growing seasons of 2019 and 2020 were 26.94 and 28.47 °C, respectively. The overall highest and lowest temperatures observed during the growing seasons were 42.30 and 12.54 °C, respectively, in 2019 and 44.06 and 9.83 °C, respectively, in 2020. Total ET₀ for whole growing season was higher in 2020 (751 mm) than in 2019 (686 mm). All these weather parameters suggest that weather conditions were more stressful in 2020 than in 2019.

Root growth. The RLD and RSAD decreased with decrease in irrigation amounts in both years (Table 2). However, RLD was significantly different among the irrigation treatments only in 2020, whereas RSAD was significantly different among the irrigation treatments in both years (Table 2). In 2019, RLD decreased by 2%, 24%, and 30%; in 2020, it decreased by 5%, 43%, and 48% in 80%, 60%, and 40% ET_c, respectively, compared with 100% ET_c. The RSAD decreased by 0%, 33%, and 40% in 2019 and by 8%, 31%, and 39% in 2020 in 80%, 60%, and 40% ET_c, respectively, when compared with 100% ET_c. The RLD and RSAD were not significantly different between the two cultivars. The RLD and RSAD were significantly

Fig. 1. Daily rainfall events and minimum, maximum and average temperature during growing season of 2019 (A) and 2020 (B) at Lubbock, TX.

Table 2. Effect of deficit irrigation levels and cultivars on root length density (RLD), root surface area density (RSAD), and root classification (percent of total root length per diameter class) of cucumber in 60-cm deep soil profile in 2019 and 2020 in Lubbock, TX.

Treatments	RLD (cm/cm ³)	RSAD (cm ² /cm ³)	Root classification (% total root length per diam class)		
			0.0–0.5 mm	0.5–1.0 mm	>1.0 mm
2019					
Irrigation level (I), ET _c					
100%	1.52 a	0.15 a	92.17 a	6.54 a	1.28 a
80%	1.49 a	0.15 ab	91.70 a	6.82 a	1.48 a
60%	1.15 a	0.10 bc	89.88 a	8.39 a	1.73 a
40%	1.07 a	0.09 c	89.27 a	8.65 a	2.08 a
Cultivar (C)					
Marketmore 76	1.27 a	0.13 a	90.25 a	7.97 a	1.78 a
Poinsett 76	1.34 a	0.12 a	91.26 a	7.24 a	1.50 a
Depth (D), cm					
10	3.33 a	0.40 a	88.10 b	7.21 a	4.69 a
20	1.62 b	0.12 b	90.05 ab	8.35 a	1.59 b
30	0.94 bc	0.07 bc	92.45 a	5.85 a	1.70 b
40	0.80 c	0.09 bc	89.30 ab	9.38 a	1.32 b
50	0.62 c	0.04 c	91.72 ab	8.03 a	0.25 b
60	0.52 c	0.04 c	92.89 a	6.8 a	0.31 b
I × C	NS	NS	NS	NS	NS
I × D	NS	S	NS	NS	NS
C × D	NS	NS	NS	NS	NS
I × C × D	NS	NS	NS	NS	NS
2020					
Irrigation level (I), ET _c					
100%	1.32 a	0.13 a	80.25 ab	15.04 a	0.16 a
80%	1.26 a	0.12 a	82.16 a	12.19 a	0.08 a
60%	0.75 b	0.09 b	73.13 b	16.84 a	0.16 a
40%	0.69 b	0.08 b	76.46 ab	13.02 a	0.13 a
Cultivar (C)					
Marketmore 76	1.02 a	0.11 a	79.29 a	13.10 a	0.11 a
Poinsett 76	0.99 a	0.11 a	76.60 a	15.50 a	0.15 a
Depth (D), cm					
10	1.98 a	0.19 a	87.62 a	8.00 c	0.03 b
20	1.09 b	0.11 b	84.76 ab	10.00 bc	0.06 b
30	1.02 bc	0.10 bc	80.07 ab	12.50 bc	0.09 b
40	0.78 cd	0.09 bcd	76.90 bc	15.24 ab	0.14 ab
50	0.64 de	0.08 cd	70.29 cd	19.58 a	0.23 a
60	0.52 e	0.07 d	68.35 d	20.32 a	0.24 a
I × C	NS	NS	NS	NS	NS
I × D	S	S	NS	NS	NS
C × D	NS	NS	NS	NS	NS
I × C × D	NS	NS	NS	NS	NS

Mean values followed by the same letter in each column are not significantly different according to least significant difference test at $P \leq 0.05$. I × C, I × D, C × D, and I × C × D indicate irrigation level into cultivar, irrigation level into depth, cultivar into depth, and irrigation level into cultivar into depth interactions, respectively. NS = nonsignificant and S = significant at $P \leq 0.05$. ET_c = crop evapotranspiration.

different among the different soil profile depths (Table 2). The RLD and RSAD decreased significantly with increase in soil depth in both years. Irrigation level into cultivar interactions for RLD and RSAD were not significant in both years. Irrigation into depth interactions for RLD and RSAD were significant in both years except for RLD in 2019. Cultivar into depth interactions for RLD and RSAD were nonsignificant in both years. Irrigation level into cultivar into depth interaction for RLD and RSAD were nonsignificant in both years.

The RLD and RSAD were not significantly different among the irrigation treatments at each soil depth in 2019 except for RSAD in 0- to 10-cm soil depth (Figs. 2 and 3). Although there were no statistically significant differences in RLD and RSAD among the irrigation treatments, numerically RLD and RSAD were the highest in 100% ET_c followed by 80% and 60% ET_c, and these parameters were least in 40% ET_c at

the most of the soil depths in 2019. In 2020, RLD was significantly different among the irrigation treatments at soil depths of 0 to 10, 10 to 20, and 30 to 40 cm, whereas it was not significantly different at soil depths of 20 to 30, 40 to 50, and 50 to 60 cm (Fig. 2). In 2020, the RSAD was significantly different among the irrigation treatments at soil depths of 0 to 10, 10 to 20, 20 to 30, and 30 to 40 cm, whereas it was not significantly different among the irrigation treatments at soil depths of 40 to 50 and 50 to 60 cm (Fig. 3). In 2020 also, RLD and RSAD were the highest in 100% ET_c, followed by 80%, 60%, and 40% ET_c at most of the soil depths. The RLD and RSAD were not significantly different between 'Marketmore 76' and 'Poinsett 76' at each soil depth in both years except for RSAD in 40- to 50-cm soil depth in 2020.

The results suggest that root growth was affected by the irrigation amounts. Under water-deficit conditions, the root is the first to be affected, followed by a series of

changes in plants at cellular, physiological, and morphological levels. Maintenance of root growth is crucial for adaptation of the plant to declining soil moisture (Xu et al., 2013). Under water-stress conditions, plants undergo morphological adjustments in root traits such as root fineness, rooting depth, and penetrating capacity of root to penetrate through highly compacted soil layers (Sharma et al., 2018). In our study, we found that overall RLD and RSAD decreased with decrease in amount of irrigation water. The results of our study indicated that cucumber had not maintained its root growth under declining water availability so as to adapt to water stress and maintain plant growth, particularly in 2020. However, root growth was comparable between 80% ET_c and 100% ET_c, whereas it was significantly lower in 60% and 40% ET_c compared with 100% ET_c, which suggested that severe water stress is detrimental to root growth in cucumber. Similarly, Kirnak and Demirtas (2006) observed that dry root weight of cucumber was significantly lower in water-stressed irrigation treatment than the well-watered treatment in clay loam soil. On the other hand, in a study on watermelon in sandy soil, Miller et al. (2013) found that RLD was unaffected by irrigation quantity during all the growth stages of the plant. Additionally, Sharma et al. (2014) found that RLD and RSAD of melon in clay soil were not significantly different between 100% and 50% ET_c in 2011, whereas they were significantly higher in 50% than 100% ET_c in 2012. In present study, RLD and RSAD were not significantly different between the Marketmore 76 and Poinsett 76 cultivars. On the basis of these results, it can be interpreted that extreme reduction in irrigation had a severe negative impact on the root growth of cucumber, and both the cultivars showed a similar response to DI.

The RLD and RSAD decreased significantly with increase in soil depths. Approximately 68% to 75% of total RLD (in 0 to 60 cm) was present in 0- to 30-cm soil depth, and 25% to 32% of total RLD was present in 30- to 60-cm soil depth (Table 2, Fig. 2). This implies that most of the roots of the cucumber are present in shallow soils depths (0 to 30 cm). Similarly, Zotarelli et al. (2009) found that in tomato, more proportion of total RLD was present in 0- to 15-cm soil depth (51% to 78%) than in 15- to 90-cm soil depth (32% to 49%) at 66 DAP. Miller et al. (2013) found that in water melon more fraction of total root length was present in 0–30 cm soil depth (61% to 85%) than in 30–75 cm soil depth (15% to 39%) at 83 DAP. Sharma et al. (2014) found that in melons, higher RLD was present in 0- to 30-cm soil depth (74% to 78%) than in 30- to 70-cm soil depth (22% to 26%) at the end of growing seasons. Overall, it can be interpreted that the most proportion of roots are present in shallow soil depths (0 to 30 cm) in most of the vegetable crops, which supports the results for root growth in our study.

Fig. 2. Effect of deficit irrigation levels (A and B) and cultivars (C and D) on the root length density (RLD) along the 60-cm soil profile in 2019 (A and C) and 2020 (B and D) in Lubbock, TX. Bars indicate least significant difference (LSD) at $P \leq 0.05$ among treatments at a given soil depth. Symbol * on the LSD bar indicates significant differences among the treatments at a given depth at $P \leq 0.05$.

In our study, RLD and RSAD were not significantly different among the irrigation treatments at each soil depth except for RSAD in 0- to 10-cm soil depth in 2019. In 2020, RLD and RSAD were significantly different among the irrigation treatments only up to 40 cm of soil depth except for RLD in 20- to 30-cm soil depth. Beyond 40 cm, there were no significant differences in RLD and RSAD

among the irrigation treatments in 2020. Machado and Maria do Rosário (2005) also reported that RLD of tomato was unaffected by the irrigation levels at each soil depth. Overall, in our study, water deficit had no significant effect on the root distribution pattern in 2019, whereas in 2020, root distribution was affected by irrigation amounts only up to 40 cm of soil depth. Weather conditions were

more stressful in 2020 than in 2019, and these stressful weather conditions might have more negatively affected the root growth in 60% and 40% ET_c than in 100% ET_c in 2020. Root growth was similar between two cultivars. Overall, it can be interpreted that DI in cucumber did not cause the plants to allocate more resources to roots to promote root growth and deeper penetration of roots in the soil to extract more water from deeper soil layers to meet the transpiration demands of crop in 2020. Although there were comparatively favorable weather conditions in 2019, root growth was not significantly negatively affected by the decrease in irrigation amounts. In DI treatments, cucumber maintained RLD and RSAD comparable to full irrigation in 2019.

Root length distribution (percent of total root length in a given diameter class) among diameter classes was not significantly affected by the irrigation treatments in either year except for the percent of total root length allocated to 0- to 0.5-mm diameter class in 2020 (Table 2). Sharma et al. (2014) also reported that distribution of total root length among the diameter classes was unaffected by the amount of irrigation water. Overall, in our study, the greatest part of the total root length (89.27% to 92.17% in 2019 and 73.13% to 82.16% in 2020) was allocated to 0 to 0.5 mm diameter class and the least part of the total root length (1.28% to 2.08% in 2019 and 0.08% to 0.16% in 2020) was allocated to >1-mm diameter class. This implies that cucumber has more percentage of fine roots (0 to 0.5 mm diameter).

Distribution of total root length among the diameter classes was not significantly different between the cultivars in either year (Table 2). Root length distribution among the diameter class varied significantly at different soil depths. In 2019, the percent of the total root length in 0 to 0.5 mm did not follow any trend with soil depth increment, whereas in 2020, the percent of the total root length in this diameter class decreased in deeper soil depths. The percent of the total root length in 0.5- to 1.0-mm diameter class was not significantly different among different soil depths in 2019, whereas in 2020, percent of total root length in this diameter class was higher in deeper layers. The percent of total root length in >1-mm diameter class was higher in upper soil depths in 2019, whereas in 2020, it was higher in deeper soil depths. In a study by Sharma et al. (2014) on melon, it was reported that in 2011, percent of the total root length in 0 to 0.5 mm decreased with increase soil depth while in 2012, it did not follow any trend with increase in soil depth. In our study, irrigation level into cultivar, irrigation level into depth, cultivar into depth, and irrigation level into cultivar into depth interactions for root length distribution were nonsignificant in both years.

Soil water depletion. During the 9 to 20 DAP, soil water depletion was comparable among all the irrigation treatments in both years since all the treatments received equal amount of water in this period (Fig. 4). However, in 2019, due to heavy rainfall events

Fig. 3. Effect of deficit irrigation levels (A and B) and cultivars (C and D) on the root surface area density (RSAD) along the 60-cm soil profile in 2019 (A and C) and 2020 (B and D) in Lubbock, TX. Bars indicate least significant difference (LSD) at $P \leq 0.05$ among treatments at a given soil depth. Symbol * on the LSD bar indicates significant differences among the treatments at a given depth at $P \leq 0.05$.

Fig. 4. Effect of deficit irrigation levels on the soil water depletion along the 100-cm soil profile during initial stage [9 to 20 d after planting (DAP)], development stage (20 to 50 DAP), fruiting stage (50 to 91 DAP), and whole growing season (9 to 91 DAP) of cucumber in 2019 and 2020 in Lubbock, TX. Bars indicate least significant difference (LSD) at $P \leq 0.05$ among the irrigation treatments at a given soil depth. Symbol * on the LSD bar indicates significant differences among the treatments at a given depth at $P \leq 0.05$.

during 9 to 20 DAP, crop was overirrigated, which led to an increase in the amount of stored soil water in the 100-cm soil profile. In 2019, when averaged across all the treatments, soil water storage increased by 22 mm in the complete 100-cm soil profile (Fig. 4A). In 2020, when averaged for all the irrigation treatments, soil water depleted by 3 mm in the complete 100-cm soil profile (Fig. 4E).

During the 20 to 50 DAP period, soil water depletion was different among the irrigation treatments at each soil depth. Soil water depletion was the highest in 40% ET_c followed by 60% ET_c , 80% ET_c , and it was the least in 100% ET_c at most of the soil depths in 100-cm soil profile in both years (Fig. 4B and F). During 20 to 50 DAP, total soil water depletion along the complete 100-

cm soil profile was 1, 3, 5, and 11 mm in 100%, 80%, 60%, and 40% ET_c , respectively, in 2019, whereas respective values for soil water depletion in 2020 were 25, 26, 37, and 43 mm. In 2019, soil water depleted by 1 mm in 100% ET_c , which indicates that applied irrigation was able to meet the crop water requirements in 100% ET_c in 2019. In 2020, during an irrigation event in 20 to 50 DAP period, all the irrigation treatments received 24 mm less water than the calculated amounts due to irrigation system failure. Because of this, there was a considerable soil water depletion even in 100% ET_c in 2020.

During the 50–91 DAP period, soil water depletion was not significantly different among the irrigation treatments at each depth in 100 cm soil profile except for 60 cm soil

depth in 2019 and 30 cm and 100 cm in 2020. In both years, soil water depletion was the highest in 40% ET_c followed by 60% ET_c , 80% ET_c , and it was the least in 100% ET_c at most of the soil depths in 100 cm soil profile (Fig. 4C and G). During 50–91 DAP, total soil water depletion along the complete 100 cm soil profile was –54, –54, –45, and –28 mm in 100%, 80%, 60%, and 40% ET_c , respectively in 2019, while respective values for soil water depletion for irrigation treatments in 2020 were –27, –17, 5, and 19 mm. In 2019, there was an increase in amount of stored soil water in all irrigation treatments but still soil water depletion was higher in irrigation treatments which received lower amount of water (increase in soil water storage was less in irrigation treatments which received lower amount of irrigation water). In 2020, an irrigation event was started at 83 DAP and completed at 86 DAP to apply 50, 40, 31, and 21 mm of irrigation water to 100%, 80%, 60%, and 40% ET_c , respectively. So, it is possible that crop was not able to use this applied amount of water during 86–91 DAP resulting in overall increase in stored soil water in all treatments. It is also possible that during 50–91 DAP, crop might not have extracted the stored soil water in all irrigation treatments which resulted in increase in amount of stored soil water due to the last irrigation event even in 60% and 40% ET_c . In 2020, there was an increase in amount of stored soil water only in 100% and 80% ET_c while there was decrease in amount of stored soil water in 60% and 40% ET_c during 50–91 DAP. This indicates that crop in 60% and 40% ET_c had extracted stored soil water to meet crop water requirements to some extent during 50–91 DAP.

During the entire growing season (9 to 91 DAP), soil water depletion was significantly different among the irrigation treatments at each soil depth in 100-cm soil profile in both years except for 10-cm soil depth in 2019 (Fig. 4D and H). Soil water depletion was the highest in 40% ET_c followed by 60% and 80% ET_c , and it was the least in 100% ET_c at most of the soil depths in both years. During 9 to 91 DAP, total soil water depletion along the complete 100-cm soil profile was –77, –77, –59, and –38 mm in 100%, 80%, 60%, and 40% ET_c , respectively, in 2019, whereas respective values for soil water depletion for irrigation treatments in 2020 were 1, 12, 42, and 65 mm. Although there was an increase in amount of stored soil water at harvest compared with the initial amount of stored soil water in 2019 and there was a decrease in amount of stored soil water at harvest compared with the initial amount of stored soil water in 2020, soil water depletion was still significantly different among the irrigation treatments in both years. There was more soil water depletion in 80%, 60%, and 40% ET_c compared with 100% ET_c . This indicates that applied irrigation water was not sufficient to meet the crop water requirement in 80%, 60%, and 40% ET_c , so in these irrigation treatments, plants used stored soil water to compensate for the water stress to some

Fig. 5. Effect of cultivars on the soil water depletion along the 100-cm soil profile during initial stage [9 to 20 d after planting (DAP)], development stage (20 to 50 DAP), fruiting stage (50 to 91 DAP), and whole growing season (9 to 91 DAP) of cucumber in 2019 and 2020 in Lubbock, TX. Bars indicate least significant difference (LSD) at $P \leq 0.05$ between two cultivars at a given soil depth. Symbol * on the LSD bar indicates significant differences among the treatments at a given depth at $P \leq 0.05$.

extent. In 2020, weather conditions were more stressful, which resulted in higher crop water requirements; therefore, there was greater soil water depletion in 2020 than in 2019 in all irrigation treatments. In a study on tomato, Prieto et al. (2000) observed that the decrease in soil water content was greater in DI treatment indicating that there was more soil water depletion in DI treatment than in full irrigation treatment. Similarly, in a study on forage sorghum, pearl millet, and corn, Bhattarai et al. (2020b) observed that soil water depletion was higher in irrigation treatments, which received less irrigation water. Similarly, soil water extraction was higher in dryland treatment than full irrigation in spring canola (Katuwal et al., 2020). These studies support our findings that soil water depletion increases with decrease in amount of irrigation water. Under DI conditions, crops stored soil water to meet transpiration requirements to some extent.

From the amounts of irrigation water applied and soil water depletion results for irrigation treatments, it can be inferred that root water uptake (irrigation water + soil water extraction) was higher in irrigation treatments which received higher amount of irrigation water. Although soil water depletion was the highest in 40% ET_c, this amount could not compensate for the reduced amount of irrigation water. As a consequence, root water uptake was the lowest in 40% ET_c. Overall, amount of irrigation water, soil water depletion, and RLD results for irrigation treatments suggest that root water uptake was in correspondence to root density, that is, root water uptake was higher in treatments with higher RLD. Root water uptake mainly depends on root length at a particular depth and water extraction capability of roots at a particular level of soil moisture (Kondo et al., 2000). However, available soil water content also influences the depth and density of roots (Man et al., 2016). Thus, root water uptake depends on root distribution and on available soil moisture content. Overall, these results suggested that root water uptake decreased with decrease in irrigation amount.

In our study, soil water depletion was not significantly different between the two cultivars at each depth during all the growth stages in both years (Fig. 5). This implies that root water uptake capacity and capacity to extract stored soil water were similar in both cultivars. There were no significant differences in root growth parameters between two cultivars, which suggest that root water uptake capacity of both cultivars was comparable.

ET, fruit yield, and WUE. ET was significantly different among the irrigation treatments in both years (Table 3). It was the highest in 100% ET_c followed by 80% and 60% ET_c, and it was the least in 40% ET_c in both years. Irrigation treatments received different amounts of irrigation water (100% ET_c received the highest amount of irrigation water and 40% ET_c received the least amount), and ΔS was also different among the irrigation treatments (trend for ΔS was reverse, it was the highest in 40% ET_c and it

was the least in 100% ET_c). Even though, soil water depletion was the highest in 40% ET_c still it had lowest ET because difference in irrigation amount was higher than difference in soil water depletion among the irrigation treatments. Therefore, differences in irrigation amounts contributed more to inducing the differences in ET among the irrigation treatments. Bhattarai et al. (2020b) also reported that ET was higher in irrigation treatments that received greater amounts of irrigation water in forage sorghum, pearl millet, and corn. ET was comparable between 'Marketmore 76' and 'Poinsett 76' in both years (Table 3). Overall, ET was higher in 2020 than in 2019 because both the amount of applied irrigation water and soil water depletion were higher in 2020 than in 2019.

Fresh fruit yield was significantly affected by the irrigation treatments (Table 3). Fruit yield declined by 7%, 26%, and 37% in 2019 and by 13%, 39% and 56% in 2020 in 80%, 60%, and 40% ET_c, respectively, compared with 100% ET_c. This implies that decrease in amount of irrigation water resulted in decrease in fruit yield of cucumber. However, fruit yield was statistically similar between 100% and 80% ET_c. However, in 60% and 40% ET_c, applied irrigation amount and extraction of stored soil water were not sufficient to produce biomass comparable to 100% ET_c. The results showing that yield decreased with decrease in irrigation are supported by the results of other studies on DI (Abd El-Mageed et al., 2018; Kirnak and Demirtas, 2006; Sharma et al., 2014). Moreover, RLD and RSAD decreased with decrease in irrigation amount. A decrease in RLD and RSAD reduces the net absorption area for water and nutrient uptake. Thus, a decrease in root growth negatively affects plant growth and yield. Results of RLD and RSAD also support the results of lower yield in lower irrigation

amount treatments. An increase in root biomass enhances the production of aboveground biomass, which subsequently increases yield (Qi et al., 2012). Because weather conditions in 2020 were stressful, fruit yield declined in each treatment in 2020 compared with 2019. Abd El-Mageed et al. (2018) also observed that fruit yield of cucumber was lower in the summer than the fall season due to more stressful weather conditions in the summer season. In our study, fruit yield was significantly higher in 'Poinsett 76' than 'Marketmore 76' in both years. Fruit yield was lower in 2020 than 2019 in both cultivars. However, decline in fruit yield was higher in 'Poinsett 76' (20%) than 'Marketmore 76' (11%) which suggests that 'Poinsett 76' was more negatively affected by the stressful weather conditions than 'Marketmore 76' in 2020.

Effect of irrigation levels and cultivars on WUE and IWUE of cucumber are provided in Table 3. The WUE was not statistically different among the irrigation treatments in either year. However, numerically, WUE was the highest in 80% ET_c followed by 100%, 60% and 40% ET_c in both years. This means that among the irrigation treatments, plants in 80% ET_c had produced the highest fruit yield for each unit of water used. The 100% and 80% ET_c irrigation had comparable yields, but 80% ET_c received considerably less irrigation water than 100% ET_c, which resulted in higher WUE in 80% irrigation level. In 60% and 40% ET_c, plants faced severe water stress, which resulted in severe decline in fruit yield. As a consequence, plants in these treatments had produced less fruit yield for each unit of water used. In a study by Abd El-Mageed et al. (2018) on cucumber, it was found that WUE was the highest in 60% ET_c followed by 80% and 100% ET_c. In melons, WUE was unaffected by irrigation levels

Table 3. Effect of deficit irrigation levels and cultivars on soil water depletion, evapotranspiration (ET), yield, water use efficiency (WUE), and irrigation water use efficiency (IWUE) of cucumber in 2019 and 2020 in Lubbock, TX.

Treatments	ET (mm)	Yield (kg/ha)	WUE (kg·ha ⁻¹ ·mm ⁻¹)	IWUE (kg·ha ⁻¹ ·mm ⁻¹)
2019				
Irrigation level (I), ET _c				
100%	450 a	32,705 a	73 a	62 a
80%	374 b	30,289 a	82 a	67 a
60%	338 c	24,071 b	71 a	61 a
40%	284 d	20,510 b	73 a	64 a
Cultivar (C)				
Marketmore 76	359 a	21,701 b	61 b	51 b
Poinsett 76	364 a	32,087 a	89 a	76 a
(I × C)	NS	NS	NS	NS
2020				
Irrigation level (I), ET _c				
100%	547 a	30,781 a	56 a	56 a
80%	474 b	26,693 ab	56 a	58 a
60%	421 c	18,787 bc	45 a	50 a
40%	360 d	13,587 c	38 a	46 a
Cultivar (C)				
Marketmore 76	450 a	19,370 b	41 b	44 b
Poinsett 76	451 a	25,554 a	56 a	61 a
(I × C)	NS	NS	S	NS

"I × C" indicates irrigation level into cultivar interaction. NS = nonsignificant and s = significant at $P \leq 0.05$. Mean values followed by the same letter in each column are not significantly different according to least significant difference test at $P \leq 0.0$. ET_c = crop evapotranspiration.

(Sharma et al., 2014). In our study, the IWUE was not statistically different among the irrigation treatments. However, numerically, the trend observed for IWUE in 2019 was $80\% > 100\% > 40\% > 60\%$ ET_c and that observed in 2020 was $80\% > 100\% > 60\% > 40\%$ ET_c. These results suggest that among the irrigation treatments, 80% ET_c had produced the highest fruit yield for each unit of irrigation water applied. In 2019, IWUE was less than WUE because ET was less than irrigation applied in each irrigation treatment. The ET was lower due to increase in amount of stored soil water at harvest compared with amount of initially stored soil water. In 2020, IWUE was higher than WUE because ET was higher than applied irrigation in each irrigation treatment. Comparatively unfavorable weather conditions in 2020 negatively affected the fruit yield even though water applied was higher in 2020 than in 2019. As a result, WUE in 2020 was lower than in 2019. In a study on cucumber, it was found that WUE was higher in the fall than the summer season because in the fall season, weather was favorable for plant growth and fruit yield (Abd El-Mageed et al., 2018). WUE and IWUE were significantly higher in 'Poinsett 76' than 'Marketmore 76' in both years. The ET and irrigation amount at each irrigation level were same for both cultivars, and therefore the difference in WUE and IWUE was due to difference in yield between them. The WUE and IWUE were lower in 2020 than in 2019 in both cultivars. However, decline in WUE was higher in 'Poinsett 76' (37%) than 'Marketmore 76' (33%). This was due to more decline in yield of 'Poinsett 76' (20%) than 'Marketmore 76' (11%).

Conclusions

The results of this study indicate that root distribution was unaffected by the irrigation levels in 2019, whereas it was affected only up to 40-cm soil depth in 2020. The RLD and RSAD decreased with decrease in irrigation water, which suggests that DI in cucumber did not cause the plants to allocate more resources to root to promote root growth to extract more water from deeper soil layers. Root growth was comparable in both cultivars in all irrigation treatments. Soil water depletion increased with decrease in amount of irrigation water. It was the highest in 40% ET_c and the lowest in 100% ET_c. The ET and fruit yield were significantly different among the irrigation treatments. Overall, 80% and 100% ET_c had comparable fruit yield, but WUE was higher in 80% ET_c. Moreover, 80% ET_c irrigation had used less water ($\approx 15\%$, 80 mm) than 100% ET_c. Therefore, 80% ET_c irrigation level can be recommended for successful cucumber production. At an 80% ET_c irrigation level, cucumber will have the highest crop water productivity, and this irrigation level can help save a considerable amount of water (≈ 80 mm) to sustain crop production in water-limited areas. 'Poinsett 76' had higher fruit yield and WUE than 'Marketmore 76'. Therefore, 'Poinsett

76' can be recommended for cucumber production in West Texas.

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