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Root Length Density of Rainfed Fig Trees under Different Times, Amounts, and Positions of Supplemental Irrigation

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ABSTRACT

The changes in Root Length Density (RLD) of rainfed fig trees due to supplemental irrigation were studied during two growing seasons in Estahban, southern Iran, with objective of finding out the optimum position, time, and amount of supplemental irrigation. Irrigation position treatments were: (1) In a micro-catchment close to tree trunks; (2) Inside the tree canopies (1-1.1 m from tree trunks); and (3) Outside the tree canopies (2.1-2.2 m from tree trunks). Irrigation time treatments included: (a) In early spring and (b) In mid-summer; and the treatments of irrigation amount were: (i) No supplemental irrigation (control), (ii) 1,000, and (iii) 2,000 L per tree. Results showed that the highest RLD in different irrigation amounts occurred at 15-45 cm depth during late winter and late spring. However, during summers, the high RLD occurred 15 cm lower at 30-60 cm depth. Irrigation water treatments of 1,000 and 2,000 L per tree increased RLD values by 11.3 and 19.3%, respectively, in late spring and 10.5% and 14.7%, respectively, in late summer, compared with the rainfed treatment. Whereas this increase generally occurred in the wetted area; supplemental irrigation out of tree canopy could develop the root horizontal extension to a greater distance. Lower temporal variation in RLD profile was obtained for depths deeper than 75 cm, which was in agreement with soil water content variations. Supplemental irrigation applied out of tree canopy with 2,000 L per tree (200 m^3 ha^{-1}) during early spring is recommended to improve root development of fig trees in drought prone rainfed areas.

Keywords: Drought, *Ficus carica* L., Scheduling supplemental irrigation, Soil water content.

INTRODUCTION

Iran is the fifth largest producer of figs in the world with an average production of 70,730 tons and 54,200 ha of harvested area in 2017 (FAO, 2019). About 90% of the total dried figs produced in Iran come from the dryland orchards of Estahban Region (Javanmard and Mahmoudi, 2008; Javanmard, 2010; Jafari *et al*., 2012).

In recent years, repeated severe droughts have caused tree mortality and serious losses in production in this area (Hoseini *et al*., 2016). Although soil water content has an important effect on tree root growth and distribution (Ahmadi *et al*., 2011), the influence of drought conditions on root growth remains obscure (Malik *et al*., 1979). Root growth, in general, and the depth of rooting, in particular, are important determinants of the plant ability to withstand water stress in the dry soils. Root Length Density (RLD) also plays a critical role in determining the plants ability to tolerate drought (Smucker and Aiken, 1992), with higher RLD values known to improve the water and nutrient absorption by the plants (Wasaya *et al*., 2018).

Very limited data are available on the horizontal and vertical distribution of fig roots. Most of the authors have found that the fig trees have a fibrous root system devoid of the taproot, which spreads to considerable distances laterally (Condit, 1947; Flaishman *et al*., 2007).

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The limited published data about the depth of root in fig tree is more contradictory than its lateral spread. It is reported that despite typically shallow nature of fig tree root (Rigitano, 1955; Maiorano *et al*., 1997), it can extend to a surprisingly great depth in some soils (Condit, 1941; Faghih and Sabet-Sarvestani, 2001).

The extensive and wide-ranging root system of rainfed fig trees increases water and mineral absorption from the root zone soil (Himelrick, 1999; Leonel and Damatto Junior, 2007; Adriano *et al*., 2017). This makes fig tree a suitable fruit species for the water-stressed dry areas (Stover *et al*., 2007; Hallaç-Türk and Aksoy, 2011; Gholami *et al*., 2012; Karimi *et al*., 2012). Nonetheless, intense drought conditions can have a debilitating effect on growth and development of fig trees (Melgarejo, 1996).

Repeated drought impacts on the rainfed fig orchards of Estahban Region in the last few years are increasingly compelling the local fig growers to provide supplemental irrigation for minimizing the yield losses (Sharifzadeh *et al*., 2012; Kamyab, 2015). In semi-arid, drought-prone areas, supplemental irrigation in years of below-average rainfall would have a vital role in providing water for transpiration and reasonable yield (Abdel Razik and El Darier, 1991; Whitmore, 2000). Nevertheless, it must be mentioned that fig trees are very sensitive to root rot and, therefore, excess irrigation must be avoided (Dominguez, 1990). Although there are some reports about the effect of supplemental irrigation on fig trees (Al-Desouki *et al*., 2009; Kamgar-Haghighi and Sepaskhah, 2015; Abdolahipour *et al*., 2019a; Abdolahipour *et al*., 2018), little attention has been paid to the fig root system performance under the new soil water regime created by supplemental irrigation. In order to achieve an environmentally sustainable water management, more knowledge is needed on the root growth (Palese *et al*., 2000). It is assumed that supplemental irrigation at an appropriate time and in proper amount in a place with high RLD around the trees can enhance their ability for water uptake, helping the trees endure the rigours of severe drought.

Therefore, the aim of the current research was to investigate the changes observed throughout the growing seasons of two years in the rooting density of rainfed fig trees under different amounts and times of supplemental irrigation at different distances from the tree trunk.

MATERIALS AND METHODS

Experimental Site

Root distribution system of rainfed fig trees was studied in an orchard located in Estahban County, Fars Province, Iran (29° 07′ N, 54° 04′ E, 1749 m asl) in 2013 and 2014. The soil at the experimental site was gravelly loam with 30% sand, 48% silt, and 22% clay on fine soil particle basis (less than 2 mm) and also 30% (v/v) gravel at 1.5 m depth. The studied soil had a pH of 7.54, soil saturation extract Electrical Conductivity (EC_e) of 1.34 dS m^{-1}, Permanent Wilting Point (PWP) of 14 % (v/v) and Field Capacity (FC) of 31% (v/v).

The climate of the region is typically Mediterranean, with rainy winters and dry summers. Annual average rainfall is about 354 mm with the minimum and maximum values of 92 and 739 mm, respectively (Bagheri and Sepaskhah, 2014). The total annual rainfall in 2013 and 2014 was 266 and 258.5 mm, respectively, which were lower than the long-term average. Most of the rainfall occurs during late fall and winter. Extreme temperatures in the region are in the range of -7 to 41°C (Jafari *et al*., 2012). The average relative humidity is 45%, which decreases during the fruit maturing and harvest period of fig trees in summer. Meteorological data for the experimental period are presented in Figure 1.

The experiment was done on 72 uniform, 45-year-old rainfed fig trees (Ficus carica L. cv. Sabz) planted 10 m apart. Different rain-fed fig cultivars are grown in the Estahban Region, and among them, Sabz cultivar (Smyrna type) is the dominant one (Bagheri and Sepaskhah, 2014). The Sabz fig tree is a cultivar with suitable vegetative and reproductive features, dense foliage, round canopy, vertical growth, and usually 3-4 trunks (Faghih and Sabet-Sarvestani, 2001). In Estahban area, fig shoot growth takes place from mid-April to mid-May and the leaves usually become fully expanded in May. Flowering and fruiting occurs from April to July. Fruit maturation starts in August and may last until temperature drop in October. At the end of

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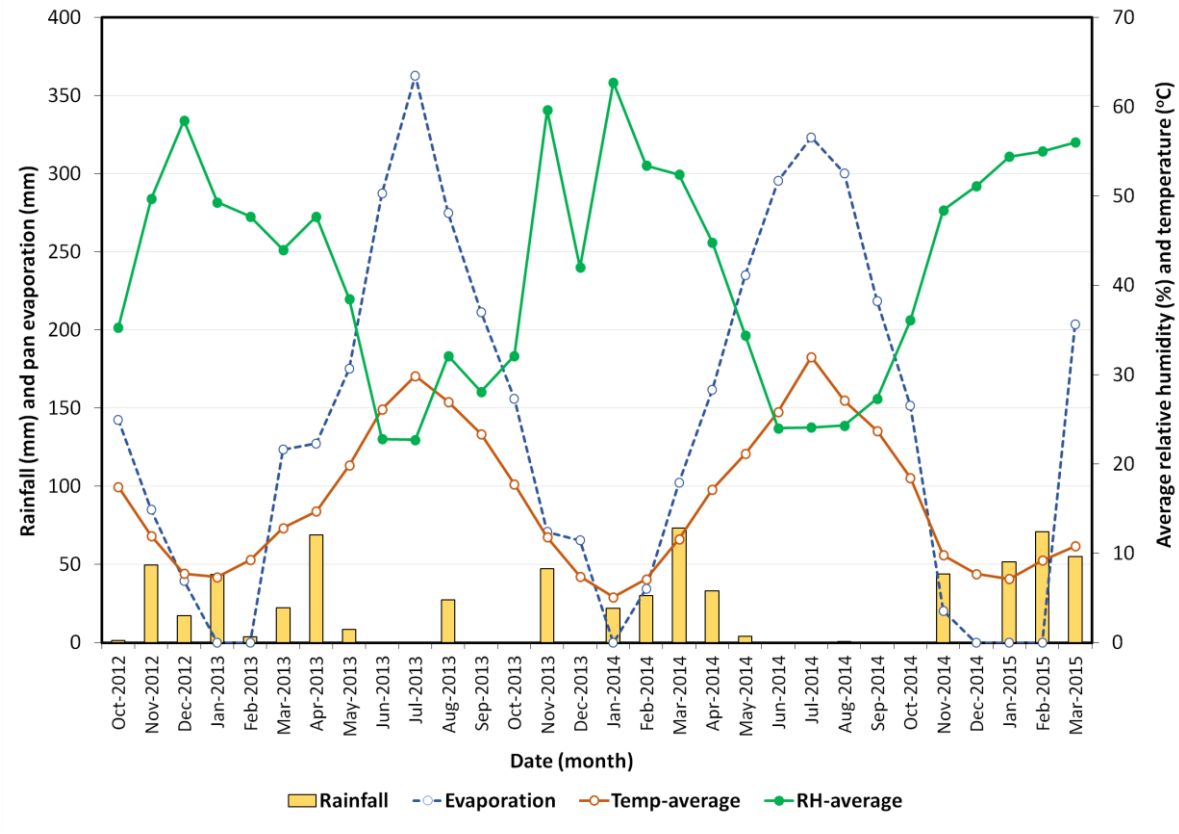

Figure 1. Mean daily agrometeorological data for the study area (Estahban, Iran).

the growth period, the leaves fall and the trees enter the rest period. Environmental factors such as temperature, photoperiod, and humidity affect the development and yield of the fig trees (Flaishman *et al*., 2007).

In the experiment, the cultural practices and caprifig used (Pouz Donbali cultivar) were similar for all trees. Mean tree canopy diameter was 3.2 m. Different treatments of supplementary irrigation were applied in a split-split plot design with four replications and 18 fig trees at each block. However, because of gravelly texture of experimental soils, root sampling (up to 90 cm of soil depth) and installing of access tubes (up to 150 cm of soil depth) were extremely difficult. Accordingly, soil water content and root measurements were only recorded from the first block (18 trees) and the experiment included one replication.

Treatments of supplemental irrigation included three different application distances (positions from the trunk (main plots), three irrigation water amounts (subplots), and two irrigation times (sub-subplots). Each sub-subplot consisted of one experimental tree. Block orientation was randomized. Irrigation positions, amounts, and times were randomized within blocks.

In the conventional method of supplemental irrigation in the area, the fig growers apply irrigation water in the micro-catchments built around the tree trunks using a tractor water tanker. Accordingly, in this study, the irrigation water was applied by a basin irrigation method in the positions determined in different distances from tree trunks. Irrigation treatments based on the applied irrigation position were: (1) Irrigation in a micro-catchment around tree trunks (NT); (2) Irrigation water applied in three holes placed 1-1.1 m from tree trunks Under Tree canopies (UT); and (3) Irrigation applied in four holes Outside of Tree canopies placed 2.1-2.2 m from tree trunks (OT) (Figure 2).

Treatments based on time of irrigation were: (a) In early spring and (b) In mid-summer and treatments based on the quantity of applied irrigation water were: no supplemental irrigation

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(control), and either 1,000 or 2,000 L irrigation water per tree (equal to 100 and 200 m^3 ha^{-1}, respectively). The volume of irrigation water for each tree was measured by using a flow meter installed at the inlet of the irrigation pipe.

Results of Soil Water Content (SWC) measured by using the neutron scattering method (CPN® 503 ELITE Hydroprobe™) at 30 cm intervals up to 90 cm soil depth were used in the study (Abdolahipour *et al*., 2018). Access tubes were installed for trees in the first block at three different distances from the trunk in the closest possible place to the irrigated area (Figure 2). The times of SWC measurements were April 17, August 12, October 2 and December 20 in 2013, and February 16, May 18, July 22, October 17 in 2014.

Root Sampling and Measurements

Before soil sampling, a trench was excavated to find the root depth and horizontal expansion around a typical tree. Then, by using a hand-driven auger (0.06-m-diameter and 1.0-m-long), soil samples were taken from trees under different irrigation treatments in the first block. Soil cores were collected at the beginning of spring (before the first irrigation), the end of spring (the maximum water absorption by trees) and the end of summer. Measurement dates were April 5, June 21, and September 16, 2013 and March 25, June 18, and September 20, 2014.

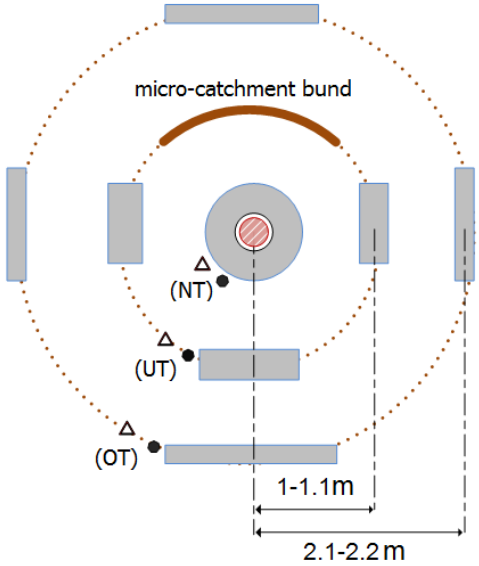

Figure 2. Different irrigation application positions from tree trunk in the experiment for tree with a canopy cover diameter about 3.2 m. (Gray area: Irrigation positions, Hatch area: Tree trunk, Black points: Access tube for measuring soil moisture, Triangle points: Root sampling positions, NT: Around the Tree trunk, UT: Under the Tree canopy and OT: Out of Tree canopy).

Soil samples were taken from a place near neutron tubes in NT, UT and OT positions (Figure 2) at six depth intervals, up to 0.9 m depth (*i.e.*, 0-0.15, 0.15-0.3, 0.3-0.45, 0.45-0.6, 0.6-0.75, and 0.75-0.9 m) in the area near the irrigated point. Therefore, considering one sample for each depth in each distance from tree trunks, 18 samples were collected for each tree. As a result, a total of 324 samples were collected from all 18 trees in the investigated block. After sampling at each position, the samples were placed in plastic bags and stored at -6°C for analysis.

In the next step, the samples were first submerged in a 5-L pot for 24 hours, and then, the roots were separated from the soil particles by gently stirring the mixture. The floating roots were collected in a 250-µm mesh-size sieve (Ahmadi *et al*., 2017). Additional water was again added, and the previous procedure was repeated until no more roots were observed floating in the suspension (Oliveira *et al*., 2000). After removing the soil particles, the mixture was transferred into a tray and fresh roots were separated from the organic debris and dead roots recognized by dark colour and elasticity (Izzi *et al*., 2008). The collected fresh root samples were placed in a small bottle, with acetic acid (10%) being added to preserve the roots (Oliveira *et al*., 2000). After storage of samples at -6°C, root length (cm) was determined by the method given in Newman (1966) and then converted to RLD (cm cm^{-3}), based on the sampled soil volume (424.12 cm^3). The horizontal and vertical distributions of RLD over time were determined for different treatments.

RESULTS

The Root Length Density (RLD) profiles for each treatment for different times of the growing season are shown in Figure 3. To examine the primitive root distribution in the soil profile, the

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root sampling of all trees was done on April 5, 2013; one week before the first early spring irrigation event in the first year. There was no sensible difference between RLD profile under different treatments and RLD distribution showed a similar pattern for all treatments at this time. While higher RLD was obtained for the top layers compared to deeper ones, the maximum RLD was found in 30-60 cm depth of soil profile. The variation in RLD in profiles deeper than 75 cm was very low.

In the second measurement time that occurred 70 days after first irrigation (on June 21, 2013), the differences between irrigation treatments were mainly observed in the top layers. The rainfed treatment and 2000 L treatment showed the lowest (0.19 cm cm^{-3} at 75 cm depth) and the highest (0.48 cm cm^{-3} at 45 cm depth) RLD values, respectively. The maximum difference between rainfed and 2000 L treatments was observed at 0-15 cm and 30-45 cm depths (35.8 and 26.1%, respectively). Among the irrigation timing treatments, trees with spring irrigation showed higher RLD, particularly in the first 45 cm top soils.

The third measurement results of September 16, 2013, showed about 14.2% higher RLD for irrigated trees in all depths compared to the rainfed treatment. The difference between 1,000 and 2,000 L irrigation treatments (100 and 200 m^3 ha^{-1}, respectively) was negligible, except in the top 30 cm. The RLD was similar for both irrigation time treatments in the surface layers. The RLD values for UT and OT treatments in 0-15 and 15-30 cm were about 6.3 and 11.7% higher than NT treatment. However, in deeper layers, the difference between RLD for trees under different irrigation positions was negligible.

The RLD values in the next measurement at the end of winter (on March 25, 2014), 10 days before the spring irrigation treatment, were quite similar in different irrigation treatments. It showed an increase of 7% in RLD of rainfed trees compared with prior measurement (late summer) and 5.5% compared with the measurement in the corresponding time during the first year (April 5, 2013). For both 1,000 and 2,000 L irrigation treatments, the difference between the observed RLD in late winter of the second year and previous late summer was negligible ($P< 5\%$).

In the second, i.e. late spring, root measurement, higher RLD values were obtained by using 2,000 L of water in the intervals between 0-15 cm and 15-30 cm depth compared with other irrigation amount treatments. The effect of spring irrigation on RLD profiles is clearly shown for all layers in Figure 3. The maximum difference between rainfed and irrigated trees occurred in 45 cm depth (9.1%) and the maximum difference between 1,000 and 2,000 L occurred in the first layer (17.6%).

This trend continued in the following

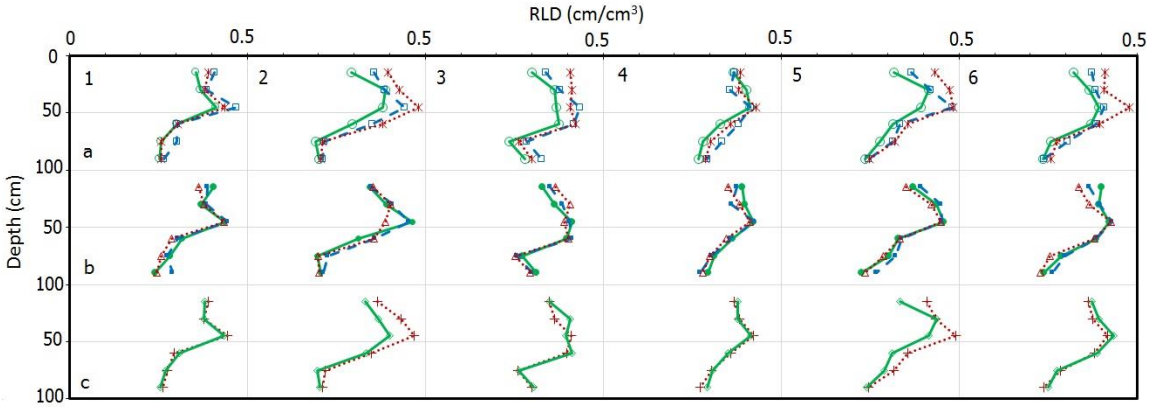

Figure 3. Comparison of root length density (RLD) profiles for different irrigation treatments during two experimental years. (○: Rainfed, □: 1000 L, X: 2000 L, ●: Around Tree trunk (NT), ■: Under the Tree canopy (UT), Δ: Out of Tree canopy (OT), +: Early spring irrigation, ◊: Mid-summer irrigation; Rows (Treatments): (a) Irrigation water amount treatments, (b) Irrigation position treatments, (c) Irrigation timing treatments; Columns (Times): (1) April 5, 2013, (2) June 21, 2013, (3) September 16, 2013, (4) March 25, 2014, (5) June 18, 2014, (6) September 20, 2014).

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measurement at the end of summer, and higher RLD was obtained for irrigation with 2000 L in surface layers. The difference between RLD values of 1,000 and 2,000 L treatments in 45 cm depth increased to 17.1% compared with previous measurement time. However, there was a small difference between different irrigation amount treatments at deeper soil depth.

The root distribution profiles at different distances from the tree trunk in different irrigation treatments are shown in Figure 4. Results showed that the RLD was mainly higher in distances far from tree trunk during the two years for both rainfed and irrigated trees. This difference was more evident at deeper depths. For the two years, the mean variation of RLD (the difference between maximum and minimum values) versus the minimum RLD over depth in the RLD profile for close to the Tree trunk (position NT), Under Tree canopy (position UT) and Out of canopy (position OT) in the rainfed treatment were 81.6, 71.9, and 67.8%, respectively. It reached 82, 77.6, and 70.9% for 1,000 L treatment and 100.1, 80.2, and 78.4% for three positions in 2,000 L irrigation water treatment, respectively.

The highest and the lowest RLD values among different depths of 2000 L treatment were 0.48 and 0.21 cm cm^{-3}; for 1,000 L they were 0.48 and 0.21 cm cm^{-3}, and for rainfed conditions 0.41 and 0.19 cm cm^{-3}, respectively. After each irrigation event, the RLD values were constantly higher in distances far from the tree trunk. Supplemental irrigation water increased the RLD in the irrigated parts. This increase was, however, more noticeable in the superficial layers (Figure 4). The average of observations made after the irrigation events showed that the differences between NT and OT positions and also UT and OT positions were about 7.6 and 9% for irrigation around tree trunk, it reached 9.7 and 5% for irrigation in 1-1.1 m distance from tree trunks and 13.6 and 13.3% for irrigation out of canopy, respectively.

During the two years, there was not a big difference between RLD values of the two irrigation timing treatments at the end of winter. However, the RLD for early spring and mid-summer irrigation treatments was higher in the late spring and late summer root observations, respectively. The SWC measurements showed higher SWC for trees under irrigation treatments

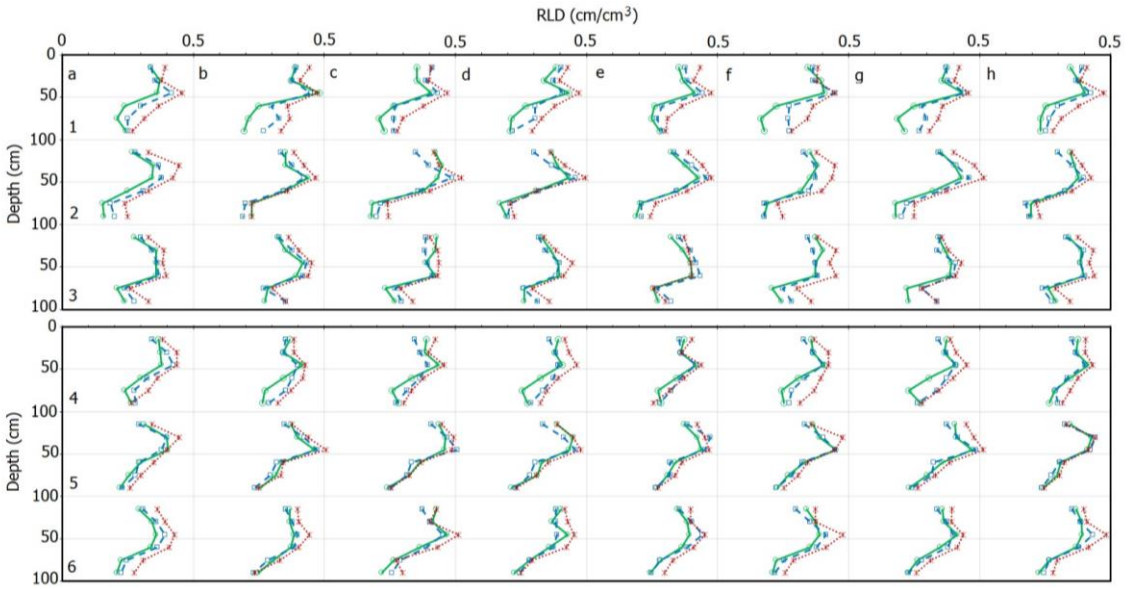

Figure 4. The root length density (RLD) profiles in different positions for irrigation treatments during two experimental years. [○: Root sampling NT position (around Tree trunk), □: Root sampling UT position (Under the Tree canopy), ×: Root sampling OT position (Out of Tree canopy); Columns (Treatments): (a) Rainfed, (b) 1000 L, (c) 2000 L, (d) Around tree trunk, (e) Under the tree canopy, (f) Out of tree canopy, (g) Early spring irrigation, (h) Mid-summer irrigation; Rows (Times): (1) April 5, 2013, (2) June 21, 2013, (3) September 16, 2013, (4) March 25, 2014, (5) June 18, 2014, (6) September 20, 2014].

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during spring, summer, and early autumn in comparison with the rainfed treatment (Figure 5). Also, irrigation with 2,000 L water showed higher SWC in comparison with 1,000 L treatment. However, the SWC of 1,000 L treatment was not markedly different from its corresponding values in rainfed treatment, particularly in deeper soil layers.

The SWC profile in late autumn and winter changed mainly with rainfall distribution. The highest and lowest SWC for trees under rainfed conditions were obtained near tree trunk and far from trees, respectively, in spring, summer and early autumn (except spring of the second year). During the months after irrigation events, higher SWC values were observed in the irrigated area. There was a small correlation coefficient between RLD and SWC for different dates of RLD measurements. However, significant correlation coefficient was found between the mean annual evapotranspiration (ET) and RLD for different depths. In this experiment, the evapotranspiration was determined for different treatments by soil water balance method. Details are available in Abdolahipour *et al.* (2018). Figure 6 shows the relationships between the evapotranspiration (ET) and RLD of all irrigation treatments in 0-30, 30-60 and 60-90 cm depths of soil profile. Higher significant R^2 values were obtained for the top soil profile (up to 60 cm) compared to lower depth.

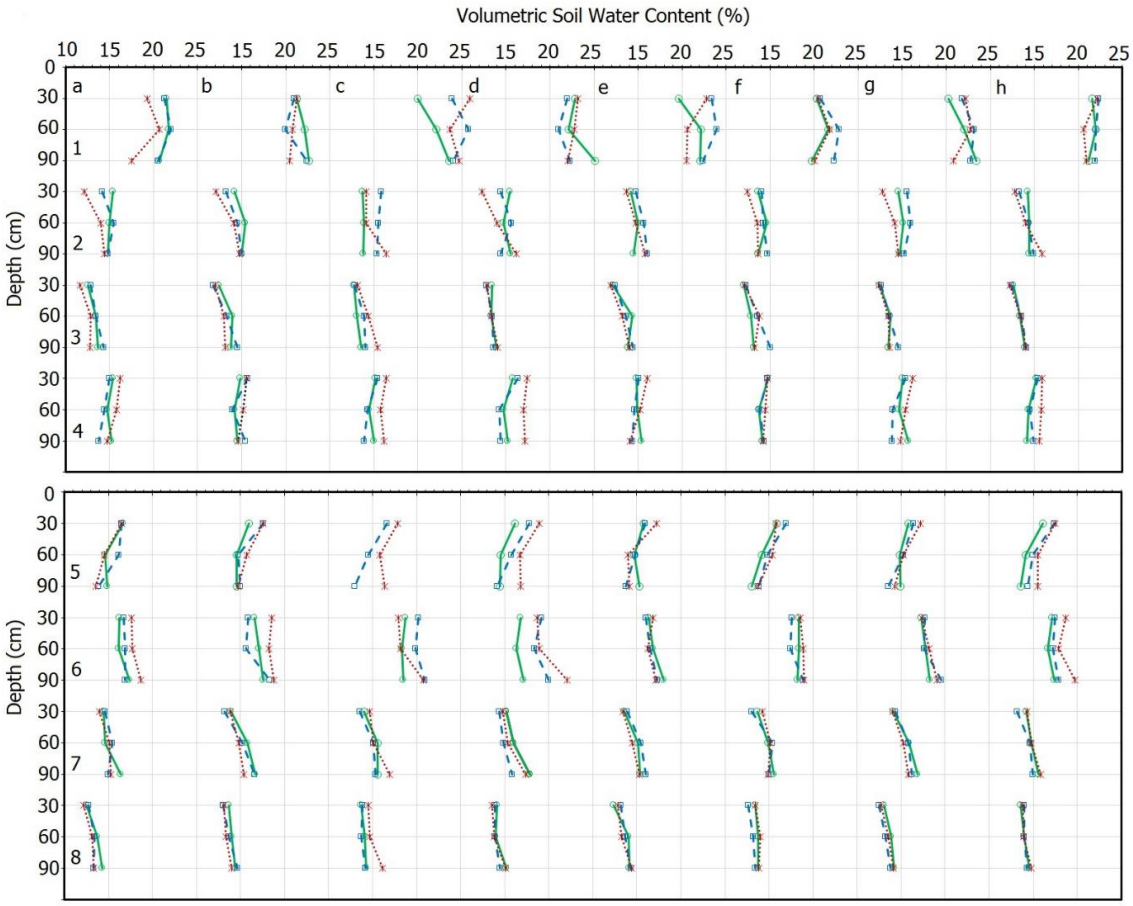

Figure 5. The Soil Water Content (SWC) profiles for irrigation treatments during two experimental years. [○: Position NT (around Tree trunk), □: Position UT (Under the Tree canopy), X: Position OT (Out of Tree canopy); Columns (Treatments): (a) Rainfed, (b) 1000 L, (c) 2000 L, (d) Near the tree trunk, (e) Under the tree canopy, (f) Out of tree canopy, (g) Early spring irrigation, (h) Mid-summer irrigation; Rows (Times): (1) April 17, 2013, (2) August 12, 2013, (3) October 2, 2013, (4) December 20, 2013, (5) February 16, 2014, (6) May 18, 2014, (7) July 22, 2014, (8). October 17, 2014].

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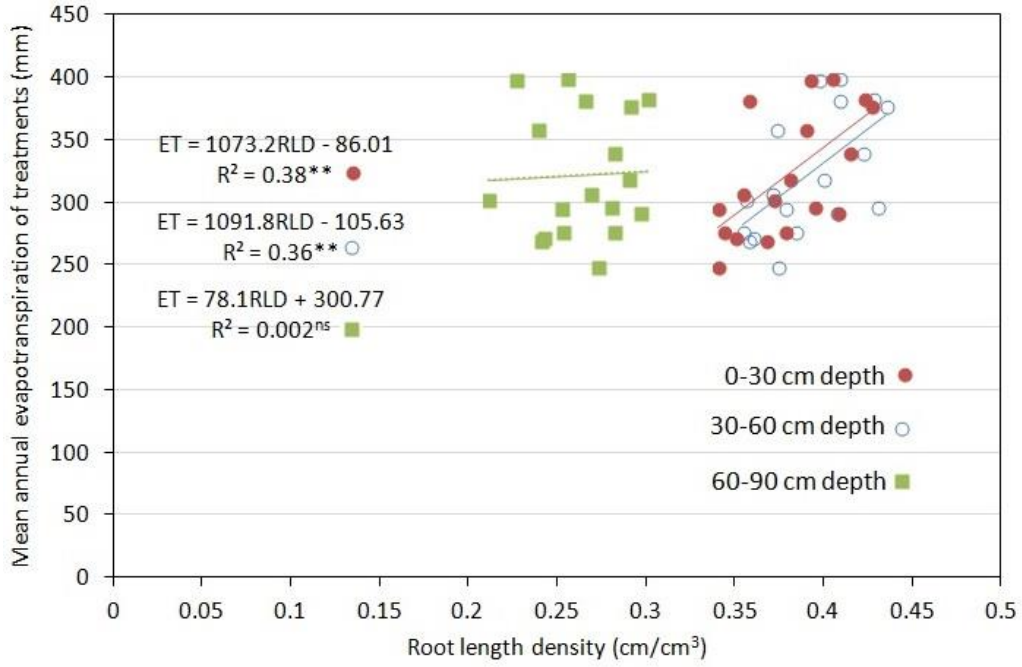

Figure 6. Relationships between mean annual Evapotranspiration (ET) and Root Length Density (RLD) of all irrigation treatments in 0-30, 30-60 and 60-90 cm depths of soil profile, data (n= 18) are from the average of 6 times of RLD measurements and 24 times of soil water content measurements during 2013 and 2014. (ns, * and **: Non-significant, significant at P< 0.05 and P< 0.01, respectively).

DISCUSSION

Horizontal Extension of Fig Tree Roots

The similar pattern of Root Length Density (RLD) for irrigation treatments at the end of winter indicated that RLD in all treatments before irrigation events tended to be similar to the rainfed conditions.

Higher RLD in superficial layers, particularly in 30-45 cm depth, and away from the tree trunk indicated the superficial spread of roots in rainfed fig trees. Superficial and horizontal extension of fig tree roots has previously been reported. Faghih and Sabet-Sarvestani (2001) found that fig tree roots in Estahban area spread 5-11 m horizontally. It is reported that fig tree roots can easily spread by two (Keleg *et al.*, 1981) to three times higher than canopy diameter (Himelrick, 1999). Traub and Stansel (1930) found that a five-year-old Brunswick (Magnolia) fig tree in Texas had a root spread of 15.24 m, a single lateral reaching 10.67 m from the main trunk (Condit, 1941). In areas like Estahban, under strong wind (e.g. the maximum 13.46 m s^{-1} wind speed at 2 m height for March and April of 2013), trees with shallow structural roots commonly develop the lateral roots to long distances to keep the trees against the wind. Rainfed nature of fig trees could be another reason for higher RLD in distances far from the tree trunk. Fig roots explore a big mass of soil far from tree trunk to find soil water. Under rainfed conditions, the roots are in contact with a greater volume of soil to absorb more water.

RLD for Different Irrigation Amount Treatments

The mean RLD values over depth profile for rainfed, 1000 and 2000 L treatments during 2013 and 2014 were 0.32, 0.35 and 0.36 cm cm^{-3}, respectively. Although the range of temporal variation in RLD of fig trees was negligible, its values were similar to the values reported for deciduous fruit trees. Chiraz (2013) found a range of absolute values between 0.001and 0.670

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cm cm^{-3} for young irrigated olive trees (*Olea europaea* L.). The mean RLD of trickle irrigated almond trees (*Amygdalus communis* L. cv. Atocha) ranged from 0.1 to 2 cm cm^{-3} (Franco and Abrisqueta, 1997). Values of RLD of irrigated olive trees averaged over the entire rooting zone were estimated to range from 0.19 to 0.48 cm cm^{-3} in three commercial orchards (north-west Argentina) (Searles *et al*., 2009). Average fibrous root length density to 0.9 m depth for the irrigated mature 'Hamlin' orange trees Carrizo citrange and Swingle citrumelo was 0.36 and 0.41 cm cm^{-3}, respectively (Morgan *et al*., 2007). The RLD values ranged from 0.15 to 0.66 cm cm^{-3} for 12-year old *Vitis vinifera* Riesling grapevine (Linsenmeier *et al*., 2011). Lower values of RLD for rainfed fig trees in this experiment compared with other fruit trees might be due to rainfed conditions during the previous years. Comparison of root length density for rainfed and irrigated twenty-year-old olive tree by Fernández *et al.* (1992) showed lower values for RLD over depth in rainfed treatments (up to 0.1 cm cm^{-3}) compared to drip- irrigated (up to 0.22 cm cm^{-3}) and flood-irrigated (up to 0.3 cm cm^{-3}) trees.

Lower RLD variation of rainfed treatment over time in depths deeper than 75 cm was due to uniform condition of root development and lower RLD in that depth of soil profile for this treatment. Also, for irrigated trees, the temporal variation over depth was more significant in shallow depths compared with deep layers. There was higher spatial variation over the distance from tree trunk in RLD profile (in NT, UT and OT positions) for irrigation with 2,000 L compared with other irrigation amount treatments. These results may be explained by the difference in SWC conditions, which showed a uniform distribution in deep layers (Figure 5). Also, soil texture can play an important role in root growth in rainfed conditions (Masmoudi *et al*., 2007). While the root development is often superficial in clay textured heavy soils, vertical penetration is more significant in light sandy soils (Ben Rouina *et al*., 1997).

While in superficial layers irrigation with higher volumes of water (2,000 L per tree) resulted in higher RLD than lower irrigation water, their difference in layers below a depth of 60 cm was negligible in all root measurement times. This difference may be attributed to high soil temperature in months of root sampling. Jafari *et al.* (2012) found increasing and decreasing trends in soil temperature during Mar to Aug and Aug to Feb, respectively, at 15 cm depth in conditions of Estahban. Higher soil temperature possibly has an inhibitory effect on root development in the surface layers. Also, the higher air temperature in spring and summer times resulted in higher soil evaporation and reduction in SWC of soil surface that can be another reason for the difference in the RLD profile (Figure 5). The total evaporation values were 1855 and 1843 mm in 2013 and 2014, respectively (88% more than mean annual rainfall of the two study years). The evaporation was higher than the rainfall amount in the area for most months, particularly during summer season (Figure 1). However, fig trees have adapted to the rainfed conditions through suitable physiological responses to water stress and decreasing the transpiration rate (Abdolahipour *et al*., 2018; Abdolahipour *et al*., 2019b).

Effect of Rainfall and Evapotranspiration on RLD

In the second year, the increase in RLD of rainfed trees in the late winter measurement compared with the earlier one can be attributed to winter rainfall. Also, this RDL value (0.34 cm cm^{-3}) showed an increase in comparison with the RLD measurement during the corresponding time of the first year. It might be due to higher rainfall amount (41%) in winter of the second year compared with that of the first year (78.2 mm), the adaptation of fig trees to supplemental irrigation, and also effects of the water stored in the soil profile in the first year. The amount of annual rainfall was also similar in the two study years. However, during winter, rainfall can have a predominant effect on root distribution of fig trees due to no irrigation event. Bagheri and Sepaskhah (2014) showed that rainfall in winter is the most effective factor for stable fig yield in the rainfed regions. As shown in Figure 3, in rainfed treatment (non-irrigated trees) the RLD was higher in the late winter and early spring seasons. It might be due to higher rainfall and higher SWC as depicted in Figure 5.

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The measurements of SWC and RLD were not in the same date, thereby considering the dynamic change in SWC, no significant correlation was found between RLD and SWC in different dates of RLD measurements. However, there were significantly moderate correlation coefficients between the mean evapotranspiration and RLD of all irrigation treatments in 0-30 and 30-60 cm depths of soil profile (Figure 6). Higher R^2 values in the top soil profile (up to 60 cm) compared to the lower depth (60-90 cm) indicated that higher RLD in top soils would provide fig water requirement more conveniently. Relationship between the mean ET and RLD for the 0-90 cm soil profile was obtained by linear regression analysis as follows:

$$ET=1037.3RLD-36.2 \quad (1)$$

$R^2= 0.25$, n= 18, SE= 44, $P< 0.05$

Where, ET is the Evapotranspiration (mm) and RLD is the Root Length Density (cm cm^{-3}). Talebnejad and Sepaskhah (2014) reported a relatively high correlation coefficient ($R^2= 0.6$) between seasonal ET and RLD for rice through the experiments conducted in the lysimeters. Their higher R^2 between ET and RLD compared to that in the current study is probably due to lower rooting depth of rice, seasonal based calculation of ET, and controlled conditions of crop in lysimeters compared to that in rainfed fig orchards.

RLD for Different Irrigation Timing Treatments

Comparison of irrigation timing treatments indicated the more effectiveness of early spring irrigation on RLD compared with the results after mid-summer irrigation. It is mainly due to higher SWC during early spring when the roots have higher growth in the vegetative period. Also, a long period of time between early spring irrigation and late spring RLD measurement allows considerable time for developing roots. This is almost twice the time that elapsed between mid-summer irrigation and late-summer RLD measurement. The results indicated that irrigation following stress period led to slow recovery, which might be attributed to the root damage occurring during water deficit conditions.

RLD for Different Irrigation Position Treatments

Results of irrigation position treatments showed an RDL increase in the zone affected by applied irrigation water as the highest RLD difference between NT and OT positions and also UT and OT positions were obtained for OT treatment (irrigation out of canopy). Differences in RLD between the position treatments were related to the changes in soil water content (Figure 5) for the two years of study. For the rainfed treatment, the high RLD in OT position (Figure 4) could be attributed to a larger volume of soil explored by the roots. The difference between RLD values of different positions under supplemental irrigation are attributed to the large differences in the soil water profiles as shown in Figure 4 (NT, UT and OT positions).

RLD Changes Over Soil Depth

The highest and lowest RLD values among different depths were higher for irrigated trees compared with the rainfed treatment. The highest values were obtained in 15-30 and 30-45 cm depths and the lowest values in 60-75 and 75-90 cm depths. Again, the lower values for 0-15 cm depth compared to 15-60 cm might be due to high evaporation and lower SWC in the late spring (Figure 5). Another reason might be explained by high content of small sized gravels on the soil surface (Karami *et al*., 2006), which has adverse effects on root development and restricts root length extension and penetration in the shallow layers (Grewal *et al*., 1984; Lal and Shukla, 2004). The literature suggests as much as a 40 to 75% decline in root growth in gravelly soils (Babalola and Lal, 1977).

The reduction in RLD values of lower soil layers (60-90 cm) was more noticeable in the irrigated trees. This reduction in RLD might decrease soil water absorption in lower layers; as soil profile up to 90 cm showed higher SWC in 60-90 cm depth for irrigated trees and in 30-60 cm depth for non-irrigated trees. Lower RLD is expected in layers below a depth of 90 cm with declining trend of RLD at lower depths. This is in agreement with the results reported by Abdolahipour *et al.* (2018) indicating higher SWC values for depths deeper than 90 cm in the

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current experimental site possibly due to lower RLD and lower water absorption by fine roots. The amounts of water that can be stored in the soil profile depends on the amount and distribution of annual precipitation, the depth and capacity of the soil profile, and the extent of the plant root system (Oweis and Hachum, 2012).

A vertical extension of fig roots in the hardpan lands near Fresno, California was reported as 6 m or more (Condit, 1941). The deepest vertical penetration of roots is reported 3-7 m for the fig trees in rainfed Estahban area (Faghih and Sabet-Sarvestani, 2001). Application of modern irrigation systems (drip irrigation) in some orchards of the investigated area decreased the wind stability of trees, though higher fruit yields were obtained. In surface drip irrigation systems, the roots accumulate in the vicinity of emitters and decrease with soil depth (Zribi *et al*., 2017). Thus, for the fig trees, especially the older ones with horizontal superficial roots, it is necessary to consider the suitable irrigation system like traditional surface irrigation methods, in order to increase the root extension to deeper layers. A large root system keeps relatively high transpiration efficiency during drought and may increase a plant ability to continue growth under water stress conditions (Puangbut *et al*., 2009).

CONCLUSIONS

Based on the results of the current study, the highest root concentration was observed in 30-45 cm depth for all treatments. The highest mean RLD for rainfed, 1,000 and 2,000 L of irrigation water per tree occurred in depth of 15-45 cm during late winter and late spring. However, the depth of high RLD during summer occurred 15 cm lower at 30-60 cm depth for irrigated and non-irrigated trees.

Irrigation with 1,000 and 2,000 L increased RLD by, respectively, 11.3 and 19.3% in late spring and 10.5 and 14.7% in late summer measurements compared to rainfed treatment. Whereas this increase occurred mainly in the irrigated area, supplemental irrigation in distances far from tree trunk improved the root horizontal spread. The difference between 1,000 and 2,000 L treatments was negligible in the layers below 60 cm. It is concluded that high rainfall in winter and soil water stored from irrigation in the previous year would have an important role in increasing the root length density. Lower temporal variation in RLD profile was obtained for depths deeper than 75 cm, in agreement with SWC variations. Higher correlation coefficient between RLD and evaportranspiration for top soil layers compared to lower depth showed that higher RLD in top soils would have an important role in evapotranspiration. Whereas fig growers apply irrigation water to micro-catchment near tree trunk, based on our results, it is recommended to apply irrigation water outside of the tree canopies (2.1-2.2 m from tree trunks). To improve the root system of fig trees in drought prone rainfed areas, application of limited irrigation water of 2,000 L per tree (equal to 200 m^3 ha^{-1}) during early spring is suggested. Results can be useful for farmers to improve water irrigation management in the dryland areas with limited water resources.

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تراکم طولی ریشه درختان انجیر دیم تحت تأثیر زمان، مقدار و محل آبیاری تکمیلی

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چکیده

به منظور بررسی زمان، مقدار و محل مناسب آبیاری تکمیلی باغات انجیر دیم استهبان، در جنوب ایران، تغییرات تراکم طولی ریشه طی دو فصل رشد تحت شرایط آبیاری تکمیلی مورد مطالعه قرار گرفت. تیمارهای آبیاری بر اساس فاصله آبیاری از درخت شامل آبیاری در آبگیر مجاور تنه درخت، در ناحیه سایه انداز (۱ تا ۱/۱ متر از تنه درخت) و خارج از سایه انداز (۲/۱ تا ۲/۲ متر از تنه درخت) بود. تیمارهای زمان آبیاری شامل آبیاری در ابتدای بهار و وسط تابستان بود و تیمارهای مقدار آب آبیاری شامل تیمار بدون آبیاری (شاهد)، ۱۰۰۰ و ۲۰۰۰ لیتر آب به ازای هر درخت بود. نتایج نشان داد بیشترین تراکم طولی ریشه برای تیمارهای مقدار آب آبیاری، در انتهای زمستان و انتهای بهار در عمق ۱۵ تا ۴۵ سانتی‌متر اتفاق می‌افتد. با این حال، در تابستان، عمق حداکثر تراکم طولی ریشه به ۱۵ سانتی‌متر پایین‌تر یعنی ۳۰ تا ۶۰ سانتی متری از سطح خاک رسید. در مقایسه با تیمار دیم، تیمارهای ۱۰۰۰ و ۲۰۰۰ لیتر آب به ازای هر درخت مقدار تراکم طولی ریشه را به ترتیب ۱۱/۳ و ۱۹/۳ درصد در آخر بهار و به ترتیب ۱۰/۵ و ۱۴/۷ درصد در آخر تابستان افزایش دادند. درحالیکه این افزایش عمدتاً در ناحیه آبیاری‌شده مشاهده شد، آبیاری تکمیلی خارج از سایه انداز، توانست توسعه افقی ریشه را تا فاصله ای دورتر گسترش دهد. نیمرخ تراکم طولی ریشه در اعماق بیش از ۷۵ سانتی متر، مطابق با تغییرات رطوبتی خاک، تغییرات کمتری طی زمان نشان داد. آبیاری تکمیلی در اوایل بهار، خارج از سایه انداز با ۲۰۰۰ لیتر آب (۲۰۰ متر مکعب در هکتار) به ازای هر درخت می‌تواند برای توسعه ریشه درختان انجیر دیم در مناطق خشک توصیه شود.

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