Drip Irrigation Affects the Morphology and Distribution of Olive Roots

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Abstract. Under field conditions, this study investigated the influence of the irrigation amount on olive root morphology and spatial distribution. Soil samples were taken with an auger at distances of 30, 60, and 90 cm from the tree trunks in four directions. The roots were analyzed using an Epson Twain Pro root scanning system. The results indicated that under different irrigation treatments, the indicators of root morphology of different varieties showed different responses to the irrigation amount. The root length density (RLD), root surface area (RSA), and root volume (RV) of Arbosana first increased with increasing irrigation amount but then decreased; however, those of Arbequina monotonically increased with increasing irrigation amount. The root average diameter of the two varieties was inversely proportional to the irrigation amount. In the vertical dimension, the RLD and RSA of each treatment decreased with increasing soil depth and were mainly distributed in the surface soil (0–20 cm in depth). The RLD and RSA in the vertical direction (VD) of the drip irrigation belt were higher than those of the belt in the parallel direction (PD), and the range was 12% to 86%. Compared with the roots of the 0- to 20-cm soil layer, the roots of the 20- to 40-cm and 40- to 60-cm soil layers were more influenced by the irrigation amount. Horizontally, the RLD and RSA decreased with increasing radial distance. The 30-cm radial area contained most roots, the proportion of roots in this region increased with increasing irrigation capacity. The influence of irrigation quantity in the PD of the drip irrigation belt was greater than that in the VD. The results suggest that irrigation does not change the root spatial distribution pattern but does promote root growth. The two varieties had different responses to irrigation. In terms of soil moisture levels after irrigation, 75% of field capacity is appropriate for ‘Arbosana’, whereas 100% is advisable for ‘Arbequina’. To improve water use efficiency, moisture should be irrigated within the 30-cm radial distance from the trunk, and irrigation depth is not easy to more than 20 cm. This study provides a scientific basis for the efficient water management of olive trees.

Olive (*Olea europea* L.) trees are aiphyl- lium and subordinate members of *Olea* of the Oleaceae family. Originating in the Mediter- ranean, the olive tree is regarded throughout the world as an important type of oleiferous tree. Because olive oil contains various nat- ural nutrients, such as unsaturated fatty acids, phenols, and vitamins, among others, it has been considered “liquid gold” (Vossen, 2007). During recent decades, olive has been widely introduced to America, Australia, Argentina, and other countries for its great economic value and edibility. In the 1960s, the olive was first brought to China from Albania and was successfully grown (Breton et al., 2006). Since then, however, China has paid much more attention to intro- duction experiments, confirming and dividing

potential distributions rather than studying the technology of cultivation and manage- ment (Jiang et al., 2006; Ning et al., 2010). Thus, olives in suitable distributions are planted at a low density; consequently, they bear little fruit and produce little economic benefit, which severely hinders their devel- opment and promotion.

Irrigation is an important measurement for crops. Some foreign studies have re- ported that irrigation can improve olive fruit production (Moriana et al., 2003), enhance the density of olives, and expand the planting area (Connor, 2005). An im- portant use of irrigation is to improve the olive fruit yield. Irrigation can markedly influence the physical properties of olives (Bacelar et al., 2007; Fernandes-Silva et al., 2010; Gómez del Campo, 2007; Moriana et al., 2002), the growth and production of fruits (d’Andria et al., 2004; Grattan et al., 2006; Gucci et al., 2007), the oil content of the fruits, and the oil quality (Dag et al., 2008; Fernandes-Silva et al., 2013; Lavee et al., 2007; Ramos and Santos, 2010). Fernandes-Silva et al. (2016) found olive trees have a near-isohydric behavior with

a tendency to maintain a constant root-to- leaf water gradient. However, irrigation alters the water and nutrient status of the soil. Roots are the primary organ of plants that absorbs water and nutrients in the soil, and roots act as the dynamic interface between the plants and soil (Gordon and Jackson, 2000). The root morphology and distribution in the soil directly affect the growth of the aboveground parts and the efficiency of the absorption of water and nutrients (Ma et al., 2012). Root function is closely related to their morphology (Tang et al., 2010), and soil moisture directly and indirectly influences the growth and dis- tribution of roots (Feng, 1996). The degree of availability of plants to absorb water and nutrients depends on the root mor- phology and competitive ability (Schenk and Jackson, 2002). Quantitative studies of root morphology and distribution char- acteristics have played a vital role in estab- lishing models of root absorption and transportation of water, improving water management in woodlands and the devel- opment of water-saving forestry (Xi et al., 2011).

In recent years, many studies concern- ing the effect of irrigation on roots have been reported both domestically and abroad. Levin et al. (1979) studied the soil moisture and root system distribution cov- ered a wider area when irrigated twice a week with 81/h tricklers rather than by irrigating every day or once a week with 41/h tricklers. Zhao et al. (2012) reported that surface drip irrigation caused the roots of *Elaeagnus angustifolia* to be distributed in the topsoil and that the root biomass and the number of thick roots increased with the irrigation amount. Zhang et al. (2013) reported that subsurface drip irrigation did not change the vertical distribution pattern of the fine roots of *Populus tomentosa*; however, it did enlarge the biomass and volume of those roots, and the irrigation caused the RLD and organization density of each soil layer to be consistent. Never- theless, studies on how irrigation affects the morphology and distribution of the olive root system have less been conduct- ed. Therefore, a study about how irrigation affects the root morphology and distribu- tion will help not only to determine the spatial distribution characteristics of olive roots and provide information about how different varieties respond to irrigation but will also guide efficient water manage- ment, which, consequently, involves opti- mal water control and efficient use in olives.

The objectives of this study were to 1) clarify whether irrigation influences the spatial distribution pattern of olive roots and 2) uncover the morphology and distribution characteristics of olive roots of different varieties relative to irrigation. The above information can provide a theoretical foun- dation to formulate a scientifically rational and efficient water management regime for olives.

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Table 1. Physical and chemical properties of soil at the experimental site.

Depth (cm)	Bulk density (g·cm ⁻³)	Saturated water content (%)	Total N (g·kg ⁻¹)	Available P (mg·kg ⁻¹)	Available K (mg·kg ⁻¹)	Sand (%)	Silt (%)	Clay (%)	Soil texture
0–20	1.37	33.8	0.61	4.99	188.31	70.66	28.80	0.54	Sandy loam
20–40	1.33	35.1	0.52	4.82	193.22	66.07	33.36	0.57	Sandy loam
40–60	1.31	37.4	0.47	5.02	195.14	62.51	36.89	0.60	Sandy loam

Fig. 1. Relationship between soil water potential and soil moisture content.

Materials and Methods

Study site. The study site was located at the Dabao olive base (33°4'N, 104°92'E; 900 m elevation) in Wudu district, Longnan city, Gansu province. The district is of the northern subtropical semihumid climate, with an average annual rainfall of 474 mm that is generally concentrated in June through September. The average annual temperature is 14.9 °C (maximum 40 °C, minimum -11 °C). The annual sunshine duration is 1912 h, with a frost-free period of more than 270 d. The soil texture is sandy loam; its physicochemical properties are shown in Table 1 and Fig. 1.

Experimental design. Two olive varieties were sampled, 'Arbosana' and 'Arbequina', both of which were introduced from Spain as 1-year-old cuttings in 2011. The average diameter of 'Arbosana' trees was 4.3 cm, and the average height was 1.93 m, whereas 'Arbequina' trees were 5.2 cm thick and 2.36 m tall. The trees were evenly planted at a density of 3.0 × 3.0 m. Two water-dripping lines were placed on the south and north sides along the trees, 30 cm away from trees. The drip lines ran east west, with a pipe diameter of 14 mm and emitter spacing of 30 cm. The drip rate was 2 L·h⁻¹.

The experiment adopted a randomized block design with four irrigation levels: T1 (soil moisture content maintained at 35% of field capacity after irrigation), T2 (55%), T3 (75%), and T4 (100%). There were four treatments and three replications in total,

and all blocks were random. A tensiometer was installed just below the emitter of T4. When the soil water potential was less than -30 kPa, the olives in each level were irrigated. The irrigation volume was determined by the irrigation time, which was calculated by two equations: $t = [G \times (SWC_2 - SWC_1)] / (V \times n)$ and $G = 3.14 \times R^2 \times H \times k$ (Yan et al., 2015). (SWC_2 represents the proportion of soil moisture that accounts for field capacity, whereas SWC_1 refers to the soil moisture before irrigation, measured by the oven-drying method. V represents the rate of emitter flow per hour, which was 2 L·h⁻¹. n is the number of emitters within the designated moisture radius. G represents the weight of the designated moisture volume. R represents the designated moisture radius, which was 100 cm. H represents the depth of the designated moisture, which was 60 cm. k represents the soil bulk density, which was 1.37 g·cm⁻³). The experiment implementation overview in trial sites are shown in Table 2.

Sampling design. Soil samples were taken with an auger (8 cm of inner material and 20 cm of length) at the end of Oct. 2014 (the end of growing season). In the horizontal direction, the samples were taken at distances of 30, 60, and 90 cm from the tree trunks in four directions (east, south, west, and north of the trees). In the VD, the total soil volume was extracted at three soil depths (20, 40, and 60 cm) for each horizontal sampling distance (Fig. 2). Those samples from two directions

(east and west) paralleling the drip line were marked as the PD, whereas the samples from the other two directions (south and north) perpendicular to the drip line were marked as the VD. The samples were dipped in water and then sieved by a 0.8-mm mesh sifter to separate the roots from most of the soil, organic matter, and other impurities. All living roots were handled with tweezers and net spoons in water.

Photographs were taken using an Epson Twain Pro roots scanning system for each root sample, and the images were analyzed using the WinRhizo root image analyzer software to obtain the length, surface area, volume and mean diameter of the root segments individually for each sample.

Data analysis. The Shapiro–Wilk and Levene tests showed that the data conformed to the normal distribution and had equal variance. Excel 2013 and SPSS 20.0 statistical software programs were used for the statistical analysis. A one-way analysis of variance and the Duncan test were performed to analyze the variance and for multiple comparisons ($\alpha = 0.05$). Plots were constructed with Origin 9.2 and Surfer 8.0 software programs.

Results

Root growth response to irrigation. The RLD, RSA, RV, and root mean diameter (RMD) are important indexes for measuring root morphology characteristics. The changes of these root morphology characteristics are shown in Fig. 3, and the root growth indexes of olive trees showed obvious regularity with irrigation levels. However, the regulation was different between the two varieties. In 'Arbosana', the RLD, RSA, and RV increased when the irrigation was between 35% and 75% of field capacity but decreased when the irrigation was between 75% and 100% (T3 > T2 > T4 > T1). Each variable value of T2, T3, and T4 was markedly higher than those of T1 ($P < 0.05$). However, the differences between T2 and T3 and between T2 and T4 were not significant. For example, the RLD in T1 was 0.1129 cm·cm⁻³, whereas in T2, T3, and T4, the RLD values were 0.353, 0.390, and 0.280 cm·cm⁻³, respectively, which were 3.1, 3.4, and 2.5 times greater than that in T1, respectively.

The RLD, RSA, and RV all increased with increasing irrigation amount, reaching a maximum value when the soil water content was maintained at 100% of the field capacity (T4) in 'Arbequina'. Each variable value of T2, T3, and T4 was markedly higher than those of T1 ($P < 0.05$), but the value of RLD with no significant difference observed

Table 2. The experiment implementation overview in trial sites.

Treatment time (mo./d)	Treatment	SWC ₂ (%)	SWC ₁ (%)	Irrigation volume (kg)
3.16	T1	12.1	23.4	0
	T2	19.1	23.4	0
	T3	26.0	23.4	67.1
	T4	34.7	23.4	291.7
3.25	T1	12.1	9.7	61.9
	T2	19.1	9.8	240.0
	T3	26.0	13.9	312.3
	T4	34.7	23.4	291.7
4.5	T1	12.1	6.3	149.7
	T2	19.1	8.9	263.3
	T3	26.0	14.1	307.1
	T4	34.7	23.4	291.7
4.14	T1	12.1	6.1	154.9
	T2	19.1	8.8	265.9
	T3	26.0	14.2	304.6
	T4	34.7	23.4	291.7
4.27	T1	12.1	6.5	144.5
	T2	19.1	9.2	255.5
	T3	26.0	14.6	294.2
	T4	34.7	23.4	291.7
5.5	T1	12.1	5.7	165.2
	T2	19.1	8.4	276.2
	T3	26.0	13.1	333.0
	T4	34.7	23.4	291.7
5.12	T1	12.1	5.4	172.9
	T2	19.1	8.2	281.3
	T3	26.0	13.1	333.0
	T4	34.7	23.4	291.7
5.18	T1	12.1	4.9	188.4
	T2	19.1	7.8	291.7
	T3	26.0	12.7	343.3
	T4	34.7	23.4	291.7
5.24	T1	12.1	4.8	188.4
	T2	19.1	7.7	294.2
	T3	26.0	12.3	353.6
	T4	34.7	23.4	291.7
6.5	T1	12.1	4.6	193.6
	T2	19.1	7.4	302.0
	T3	26.0	12.2	356.2
	T4	34.7	23.4	291.7
0.11	T1	12.1	4.7	191.0
	T2	19.1	7.3	304.6
	T3	26.0	12.3	353.6
	T4	34.7	23.4	291.7
6.25	T1	12.1	5.3	175.5
	T2	19.1	8.4	276.2
	T3	26.0	13.6	320.1
	T4	34.7	23.4	291.7
7.11	T1	12.1	5.0	183.3
	T2	19.1	8.1	283.9
	T3	26.0	13.3	327.8
	T4	34.7	23.4	291.7
8.12	T1	12.1	23.1	0
	T2	19.1	23.1	0
	T3	26.0	23.3	69.7
	T4	34.7	23.4	291.7
9.4	T1	12.1	17.2	0
	T2	19.1	20.4	0
	T3	26.0	22.6	87.8
	T4	34.7	23.4	291.7
9.24	T1	12.1	8.9	82.6
	T2	19.1	11.4	198.7
	T3	26.0	15.1	281.3
	T4	34.7	23.4	291.7
10.3	T1	12.1	7.2	126.5
	T2	19.1	9.1	258.1
	T3	26.0	13.7	317.5
	T4	34.7	23.4	291.7
10.17	T1	12.1	7.0	131.6
	T2	19.1	8.9	263.3
	T3	26.0	13.4	325.2
	T4	34.7	23.4	291.7

SWC₂, the proportion of soil moisture that accounts for field capacity; SWC₁, the soil moisture before irrigation.

between T3 and T4, there was no significant difference in the RSA between T2 and T4. Although there were no significant differences among T2, T3, and T4, the RV values in T2, T3, and T4 were 1.9, 2.3, and 2.4 times greater than that in T1 ($P < 0.01$), respectively. However, the RMD of both varieties decreased with increasing irrigation amount. In 'Arbosana', the RMD in T1 was significantly different from that in T4 ($P < 0.05$), whereas the RMD in 'Arbequina' showed no significant differences among irrigation amounts.

Vertical distribution of olive root responses to irrigation in one dimension. In the VD, the RLD and RSA of the different treatments responded to irrigation by obeying an obvious and similar rule (Figs. 4 and 5). At the same irrigation level, both the RLD and RSA showed a tendency to decrease with increasing soil depth. The RLD and RSA values at the 0- to 20-cm depth were 1.3–2.6 times greater than those at the 20- to 40-cm depth and 1.6–4.0 times greater than those at the 40- to 60-cm depth. In addition, the RLD and RSA in the VD were 12% to 86% greater than those in the PD. With the exception that the RLD and RSA showed no significant differences among soil depths in T4 for 'Arbosana', both variables at the 0- to 20-cm depth were significantly higher than those at the other depths ($P < 0.05$) at each irrigation level for both varieties, but there was no significant difference between the 20- to 40-cm and the 40- to 60-cm depths ($P > 0.05$). In addition, there was a significant difference between the VD and PD.

When comparing different irrigation levels at the same depth, irrigation changed the RLD and RSA of the olive roots, but the responses to irrigation differed between the two varieties. In 'Arbosana', the variables increased at first but then decreased with increasing irrigation amount. In 'Arbequina', the RLD and RSA increased monotonically with the increasing irrigation amount, reaching a maximum value in T4. In both varieties, the two variables in T2, T3, and T4 were significantly higher than those in T1. These results also indicated that the irrigation was not responsible for the significant differences of root variables among the three soil depths. However, water had a greater influence at the 20- to 40-cm and 40- to 60-cm depths than at the 0- to 20-cm depth, and there was a larger influence on the variables in the VD than those in the PD. For example, in 'Arbequina', compared with the variable at the three soil depths in T1, the RLD in T2, T3, and T4 increased by 150%, 168%, and 197% in the PD, respectively, whereas it increased by 199%, 292%, and 233% in the VD, respectively.

Horizontal distribution of olive root responses to irrigation in one dimension. The RLD and RSA showed similar regulation in the horizontal direction among the different treatments (Figs. 6 and 7). The horizontal distribution of roots was significantly related to the radial distance. The RLD and RSA decreased with increasing radial distance. The roots were mostly distributed within

Fig. 2. Layout of root sampling. (A) Top view of study site and root sampling. (B) Root sampling profile.

Fig. 3. The effect of root length density, root surface area, root volume, and root mean diameter under different irrigation treatments. Different letters in different treatments indicate significant differences ($P = 0.05$) according to the Duncan test.

a radial distance of 30 cm. In this area, the RLD ranged from 0.133 to 0.623 cm/cm^3 , accounting for 40% to 78% of the total in each direction, whereas at radial distances of 60 and 90 cm, the RLD values accounted for 15% to 38% and 7% to 28%, respectively. The RSA of the 30-cm radial region ranged from 0.024 to 0.104 cm^2/cm^3 , accounting for 42% to 75% of the total in each direction. In

addition, the 60-cm radial region accounted for 18% to 37%, whereas the 90-cm radial region accounted for 6% to 26%. The values of RLD and RSA in the VD were greater than those in the PD at each radial distance, with the exception of 30 cm. For example, in T3 of Arbosana, the RLD accounted for 55% in the PD and 40% in the VD. In addition, the difference between the 30- and 60-cm and

60- and 90-cm radial areas in the PD was larger than that in the VD.

The contrast analysis showed that between different water conditions at the same radial distance, irrigation changed the RLD and RSA at the same radial distance, but in 'Arbosana', the RLD reaching a maximum in T3. In 'Arbequina', however, the RLD increased with the irrigation amount, reaching

Fig. 4. The vertical distribution of root length density under different irrigation treatments. Different small letters in different treatments indicate significant differences in different soil layers of same process; different capital letters indicate significant differences among different treatments of the same soil layer ($P = 0.05$) according to the Duncan test.

Fig. 5. The vertical distribution of the root surface area under different irrigation treatments. Different small letters in different treatments indicate significant differences in different soil layers of same process; different capital letters indicate significant differences among different treatments of the same soil layer ($P = 0.05$) according to the Duncan test.

a maximum in T4. The RLD and RSA in T1 were significantly lower than those in T2, T3, and T4 ($P < 0.05$), but the differences among T2, T3, and T4 were not significant. With increasing irrigation amounts, the RLD and RSA in the 30-cm radial area accounted for a larger proportion, and the variables in the VD changed less than those in the PD. Such as the RLD in 'Arbequina', T1 and T4 accounted for 44% and 59% of the total in the PD, respectively, and 40% and 42% in the VD, respectively.

Two-dimensional distribution of olive root responses to irrigation. Figure 8 shows the two-dimensional distribution of the RLD and RSA under different irrigation treatments (at a depth of 0–60 cm and radial distance of 0–90 cm) in 'Arbosana' and 'Arbequina'. Irrigation did not change the two-dimensional distribution of the two indexes. In addition to

the values of RLD and RSA having a similar tendency, a rather large spatial variation occurred in which the roots gradually increased and assembled toward the soil surface, mainly concentrating within a radial distance of 60 cm and a depth of 20 cm. In addition, the values of RLD and RSA were higher in the VD than in the PD. For example, in T3 of 'Arbosana', the total RLD value in the VD was $4.941 \text{ cm} \cdot \text{cm}^{-3}$, which was 1.4 times greater than that in the PD ($3.485 \text{ cm} \cdot \text{cm}^{-3}$).

Figure 8 more directly shows how irrigation affects the RLD and RSA of olive trees and how different varieties respond to the irrigation amount. It also indicates that roots are distributed more intensively with increasing irrigation amounts, causing most roots to spread in the soil surface around the trunk. For example, in T3 of 'Arbosana', the total RLD and RSA values within the radial

distance of 0–60 cm and at a depth of 0–20 cm accounted for 41% and 42% of the total, respectively, whereas in T1, they only accounted for 35% and 38%, respectively.

Discussion

Root distribution response to irrigation amount. Under different irrigation amounts, the RLD and RSA values decreased within a soil depth of 60 cm. The irrigation over the ground did not change the vertical distribution pattern of olive roots within the 60-cm soil depth. This agrees with previous findings in olive and other trees (Fernández et al., 1991; Zhang et al., 2013). This phenomenon may occur because under the four irrigation amounts, the availability of soil resources gradually decreases with increasing soil depth because the differences in availability

Fig. 6. The horizontal distribution of root length density under different irrigation treatments. Different small letters in different treatments indicate significant differences at different radial distances of same process; different capital letters indicate significant differences among different treatments of the same radial distance ($P = 0.05$) according to the Duncan test.

Fig. 7. The horizontal distribution of root surface area under different irrigation treatments. Different small letters in different treatments indicate significant differences at different radial distances of same process; different capital letters indicate significant differences among different treatments of the same radial distance ($P = 0.05$) according to the Duncan test.

in the soil among different soil depths leads to differences of RLD in the vertical distribution (Mei et al., 2006), and RSA is positively correlated with RLD (Zhu et al., 2009). Therefore, we can conclude that surface drip irrigation did not change the different availability of soil resources in the vertical distribution. In addition, irrigation was not the main limiting factor affecting the vertical distribution of olive roots. It has been indirectly demonstrated that the vertical root distribution is mainly influenced by the combination of the hereditary characters and the availability of soil resources (Chen et al., 2005).

In the different irrigation treatments, the olive roots were mainly distributed in the surface soil layer (0–20 cm), and their proportion reached 40% to 78% of the total. Both

Fernández et al. (1991) and Searles et al. (2009) reported the same conclusion. The possible reasons for olive root distribution in the surface soil layer are as follows: First, olive hereditary characteristics influence root distribution. During evolution, olive trees were constantly adapting to the climate of the area of origin (the Mediterranean), and the species could have formed special hereditary characteristics in which the roots tend to be distributed toward the soil surface to better absorb and use surface water and rainwater (Fernández and Moreno, 1999). Second, the surface soil layer contains more nutrition because dry branches and fallen leaves have been decomposed by soil microorganisms and protozoa (An et al., 2007), adding to the suitable soil bulk density and texture (Burke et al., 1991), moisture, and temperature

(Pregitzer et al., 1995). Third, the drip irrigation system plays a role. Many studies have indicated that drip irrigation can cause roots to be distributed in the surface layer because the surface soil is moist and roots have a positive water tropism (Zhao et al., 2012).

The RLD, which is significantly influenced by radial distance, decreased with increasing radial distance, as did the RSA. This phenomenon has also been observed in *E. angustifolia* (Zhao et al., 2012) and *Juglans regia* (Wang et al., 2013). These root characteristics may be mainly dependent on the hereditary properties of its own developmental construction (Pregitzer et al., 2002). Most olive roots were distributed in the 30-cm radial area, and the proportion of roots there increased with irrigation amount. The possible reasons are as follows. First, the

Fig. 8. Two-dimensional distribution of root length density (shaded blue to white areas) and root surface area (black isoline, $\text{cm}^2 \cdot \text{cm}^{-3}$) under different irrigation treatments. The solid line in the middle indicates the tree position.

hereditary properties of root development construction play a role (Pregitzer et al., 2002). Second, because the soil around the drip irrigation line was heavily influenced by the drip irrigation and because the irrigation line was arranged at the 30-cm radial distance, the water condition was of high quality there, boosting the availability of water and nutrients in soil, improving the soil structure (Burton et al., 2000; King et al., 2002; Xi et al., 2012) and accelerating root growth.

Root response to irrigation. In different treatments, the morphological variables of olive roots (RLD, RSA, RV, and RMD) responded positively to irrigation. This indicated that a certain amount of irrigation can effectively promote the growth of olive roots. Dichio et al. (2002) also observed that olive root growth responded positively to irrigation, mainly because irrigation vastly improved the availability of soil water (Xi et al., 2012) and perfected the soil structure and the availability of soil resources. The development of the availability of soil

resources can promote carbon transfer to the underground parts of trees, therefore promoting the growth of tree roots and development of the roots in absorbing water and nutrients (Burton et al., 2000; King et al., 2002). In addition, roots tend to grow toward water. Thus, increasing the irrigation amount promotes root growth.

In the VD, the irrigation amount had a stronger effect on the 20- to 40-cm and 40- to 60-cm layers than on the 0- to 20-cm soil layer, possibly because more irrigation led to more usable water in the deeper soil. Irrigation improved the availability of soil resources (Burton et al., 2000; King et al., 2002) and accelerated the root growth. In addition, the olive roots were mainly distributed in the soil surface. Thus, the irrigation amount had a greater effect on the deeper layers (20–40 cm and 40–60 cm).

In each soil layer, there were higher RLD and RSA values in the VD of the drip irrigation line than in the PD, which may be related to the water difference that soil

acquires in the two directions. Because the area in the VD was below the drip line, the soil there could obtain more water than in areas of the PD. Because the tree roots tended to be distributed around water, there were some differences in each root variable between the two directions.

In the horizontal direction, roots of the 30-cm radial area accounted for more proportion in the direction parallel to the drip line than in the VD. In addition, there were more significant root differences among radial distances, and the irrigation amount had a greater effect on the roots in the PD. This result may occur because the area moistened by drip irrigation is a circle that gradually spreads outside the emitter center. Thus, the soil could receive less water in the PD than in the VD, and this difference constantly increased with increasing radial distance. Therefore, roots of the 30-cm radial area accounted for more proportion in the PD than in the VD, and there were more significant root differences among radial distances. With

the increasing irrigation amount, the area in which water diffused was constantly expanding, and thus, soil in the PD received more water, promoting the growth of roots. Therefore, the irrigation amount had a greater effect in the PD than in the VD.

Variety differences in root response to irrigation. Under different irrigation treatments, the different varieties showed different responses to irrigation amounts in terms of the RLD, RSA, RV, and RMD. In 'Arbosana', each root variable increased but then decreased with irrigation amount, reaching a maximum in T3, whereas in 'Arbequina', these variables increased monotonically. The possible reasons are as follows. Plant roots can respond accordingly to water regimes (Feng et al., 1996; Wei et al., 2006), but this type of adaption ability is limited (Li et al., 2010). When 'Arbosana' is fully irrigated, the ventilation conditions worsen, and the water content of the rhizosphere is saturated. With poor air and water conditions, water-logging and lack of oxygen may reach the roots. This would cause low root activity and moisture absorption rates, leading to poor root growth. The same conclusion has been reported in tomato root growth responding to irrigation amounts (Lavado et al., 1999; Yang et al., 2016). However, when 'Arbequina' trees are fully irrigated, their roots adapt to the water regime and maintain growth.

This study suggests that irrigation did not change the spatial distribution pattern of olive roots, which were mainly distributed at a radial distance of 0–60 cm and a depth of 0–20 cm; conversely, irrigation did accelerate root growth. However, different responses to irrigation amounts were observed in the different varieties. 'Arbosana' trees should be irrigated until the water content reaches 75% of the field capacity, whereas 'Arbequina' trees should be irrigated until the water content reaches 100%. Therefore, surface drip irrigation is appropriate for olive trees, and most water should be provided within the 30-cm radial distance from the trunk, and irrigation depth is not easy to more than 20 cm. In addition, different irrigation management regimes should be employed for different varieties.

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