Urban Forestry & Urban Greening 60 (2021) 127053

Contents lists available at ScienceDirect

Urban Forestry & Urban Greening

journal homepage: www.elsevier.com/locate/ufug

Root adaptation of urban trees to a more precise irrigation system: Mature olive as a case study

Fahime Mohamadzade [a], Mahdi Gheysari [a,*], Mina Kiani [b,*]

[a] Department of Water Engineering, College of Agriculture, Isfahan University of Technology, Isfahan, Iran
[b] Department of Agricultural Sciences, University of Helsinki, Helsinki, Finland

ARTICLE INFO

Handling Editor: A Alessio Fini

Keywords:
Forest park
Root distribution
Urban irrigation system
Urban mature trees
Urban water
Water scarcity

ABSTRACT

Water scarcity encourages municipalities to use more precise irrigation systems in arid urban landscapes. However, major concerns are associated with the adaptation of mature trees to new irrigation systems after they have matured under traditional management. We investigated the adaptation of mature olive trees to a change in irrigation system from a traditional surface to an automatic drip irrigation system in a coarse-textured urban forest park. The growth indices of eight-year-old olive trees were monitored for the period of 2012–2014 under three irrigation systems: (1) automated drip irrigation (ADI) for trees that matured under traditional basin-surface irrigation (TSI), (2) TSI since plantation, and (3) traditional drip irrigation (TDI) irrigating the trees depending on water availability since the time of planting. We additionally determined the spatial pattern of root development by collecting 156 soil samples from each irrigation system with a 20 × 20-cm grid system (120 cm width × 80 cm depth) in the soil profile. Results showed no significant differences in terms of fruit productivity between TSI and recently established ADI systems. Automated drip irrigation resulted in the maximum root density with a uniform root distribution pattern, where roots expanded all over the soil profile. In TSI, however, the roots were distributed irregularly, with the highest density close to the irrigation basin. The wide spacing between drippers in the TDI system created large gaps between the wetted zones in the soil with a low water-holding capacity, leading to a discrete small root system. The present study highlights the positive response of mature olive trees to the replacement of the irrigation system in an urban forest park with limited available water and low soil quality. Our findings will help municipalities to properly preserve mature urban trees and the ecosystem services for their inhabitants.

1. Introduction

Urban forest parks play an important role in the well-being of city dwellers (McPherson et al., 1997). They may also provide various ecosystem services such as carbon sequestration, erosion prevention, and air purification (Cilliers et al., 2014; Mexia et al., 2017). The water crisis in arid regions has forced municipal irrigation managers to replace traditional surface irrigation with more precise irrigation systems in urban landscapes. However, one main concern of government officials is that this replacement may negatively affect the growth of mature trees, thus increasing their mortality risk. Olive (*Olea europaea*, L.) trees are used in urban landscapes and urban forestry (Ferrini et al., 2017) and are considered green urban infrastructure that affects the shading and cooling of the environment. The olive is known as a highly drought-resistant tree, which can attain acceptable production even under deficit water conditions (Fernandez et al., 1991; Santos et al., 2007). However, a paucity of information exists regarding the response of mature olive trees to changing the traditional surface irrigation to an automated drip irrigation system in water-limiting conditions.

An appropriately designed and managed irrigation system can simulate the development of the plant root system, which is especially important in perennial plantations such as urban forest parks (Sokalska et al., 2009). Designing such irrigation systems depends on considerations such as wetted area, the number of drippers needed, and the spatial pattern of the root system. Knowledge of root distribution is even more important when the irrigation system is installed on a site where mature plants have previously grown under a rainfed or another type of irrigation system (Fernandez et al., 1991). In general, the olive root system adjusts to the deep soil structure (Bini, 1984). However, in an arid area with limited precipitation, root system penetration into the soil

* Corresponding authors.
E-mail addresses: Gheysari@cc.iut.ac.ir (M. Gheysari), mina.kiani@helsinki.fi (M. Kiani).

https://doi.org/10.1016/j.ufug.2021.127053
Received 22 August 2020; Received in revised form 15 February 2021; Accepted 18 February 2021
Available online 23 February 2021

depends on the soil wetting pattern. Irrigation system (Al Ibrahem et al., 2010; Xi et al., 2013), soil physical and chemical properties (Salgado and Cautin, 2008; Al Ibrahem et al., 2010), water quality (Al Ibrahem et al., 2010), irrigation management (Ben Ahmed et al., 2007), tree age (Purbopuspito and Van Rees, 2002), and soil limitation (Fernandez et al., 1991) are among the factors with important effects on root distribution. The few available previous studies concerning the root distribution of macauba trees (Moreira et al., 2019), olive trees (Searles et al., 2009; Sorgonà et al., 2018), apple trees (Neilsen et al., 2000; Sokalska et al., 2009; Gan et al., 2010; Song et al., 2018), avocado trees (Cantuarias et al., 1995), and grapevines (Araujo et al., 1995) showed that the root system under drip irrigation concentrated in the soil wetted zone beneath the emitter discharge with a regular pattern. However, no comprehensive study exists regarding the response of the shoots and roots of mature olive trees irrigated by drip irrigation after the plants have become adults under the surface irrigation system in an urban landscape.

Moreover, soil quality and soil texture play important roles in soil water content and, in turn, in tree root distribution (Salgado and Cautin, 2008; Martínez-Gimeno et al., 2018). Urban landscapes usually have low soil quality (e.g., high gravel content and low organic matter) and are challenging substrates for tree development (Scharenbroch et al., 2013). Coarse soils with a high percentage of gravel have a low water-holding capacity, which is a particularly important parameter in irrigation management under water shortage (Rawlins, 1973). Evaluating the root response of mature trees is therefore crucial in such soil conditions where changing the irrigation system may significantly affect the soil water content, root development, and growth of mature olive trees.

Climate change affects both the quantity and pattern of precipitation, causing uncertainty in water resource availability. Competition for this limited resource has directed municipal managers toward using drip irrigation systems instead of traditional surface irrigation in urban forest parks. The specific objective of this study was to investigate the adaptation of mature olive trees to the change of system from basin-surface to drip irrigation in a coarse-textured urban forest park through i) quantifying the response of root growth and distribution in the soil profile and ii) determining the effects of irrigation systems on yield and growth indices of olive tree in water-limited conditions. The results of our current study will help develop comprehensive assessment tools for changing the irrigation system for mature trees.

2. Materials and methods

2.1. Description of the experimental site

The experiment was conducted in an urban forested park with mature olive trees located in an arid area at the Isfahan University of Technology, Isfahan, Iran (32°42′ N, 51°32′ E, 1637 m above sea level) over a 3-year period. According to Köppen's climatic classification, Isfahan has a cold desert climate with hot summers (Assari and Mahesh, 2011). Based on 50 years of meteorological data (1970–2019) obtained from Isfahan meteorological station, the annual minimum and maximum air temperature averages are 9.4 °C and 23.3 °C, respectively. The long-term average annual precipitation is 104 mm, which mostly occurs during the fall and winter months.

In a uniform olive-forested park with an area of 5 ha, olive trees were irrigated by three irrigation systems as follows: i) the traditional basin-surface (TSI) and ii) traditional drip irrigation (TDI) systems, since plantation, and iii) an automated drip irrigation (ADI) system which replaced TSI system eight years after planting in 2011. The olive trees averaged 3 m in height and 6.5 m^2 in shaded areas. The three irrigation systems were displayed in a completely randomized design with three replications. Each treatment had thirteen trees per row. The three central trees of each row were used for fruit yield and physiological measurements while the other trees served as border trees.

The experimental soil was Petrogypsic Anhyorthels (Soil Survey Staff, 2010) with a sandy clay loam texture in the upper 20 cm and a sandy loam texture at a 20–60-cm soil depth with a considerable (60.3 ± 10.5 %) gravel content (Table 1). The field capacity was 13.8 % by volume, measured on-site (Romano et al., 2002) and 17.9 % for 2-mm sieved soil using the pressure plate (McIntyre, 1974). Soil infiltration was tested by the falling-head method using a double-ring infiltrometer (with inner and outer ring diameters of 25 and 35 cm, respectively), as described by Bouwer (1986). The average soil infiltration was 60 mm h^{-1} (Fig. S1), which was twice as rapid as the estimated value by FAO for sandy loam soils (20–30 mm h^{-1}). The difference may be due to the high percentage of over 2-mm particles on the study sites causing rapid downward water loss through the preferential flow pathways (Cole et al., 2017).

2.2. Irrigation management and systems operation

The irrigation management approach in the studied forested urban park was aimed at preserving olive trees as landscape trees rather than maximizing the fruit yield due to the limited quantity of available water. Therefore, the TSI supplied water through a furrow with an application of approximately 60 % of the ET_c with a periodicity of five days, allowing for partial depletion of soil water content. The radius of the basin around the trunk was 0.4 m and the furrow width was 0.6 m. The trees under the TDI system were irrigated depending on water availability (up to a 20-day gap between irrigations) through a loop layout, including four drippers (4 L h^{-1}) for each tree, with the drippers spaced 1.0 m apart.

One year prior to sampling, the ADI system was established on the site, which was first irrigated using TSI for eight years. A Weathermatic Smartline Irrigation Controller (Weathermatic Inc., Garland, TX, USA) was used to automate the irrigation watering at 60 % of ET_c. With the aim of designing a suitable drip irrigation system for mature olive trees, the number of drippers and their suitable discharge were selected in order to wetting 40 % of tree shaded area. The wetting patterns of the drippers with different discharge rates were determined on the study site. The best model was fitted to estimate the wetting pattern with respect to the dripper discharges and the time of irrigation:

$$w = (0.49t + 8.32) \times q + (5.25t + 25.5), \; R^2 = 0.92 \qquad (1)$$

where w is the width of the wetted zone at a depth of 30 cm, t is the time of irrigation, q is the discharge of the drippers, and R^2 is the coefficient of determination of the equation. As a result, five drippers (4 L h^{-1}) per tree were selected to wet 40 % of the shading tree area in the ADI system. The water was supplied using one drip line for each tree row placed on the furrow path of the previous surface irrigation system, with the drippers spaced 0.65 m apart. The drip line was set out on the previous furrow water pathway. Volumetric flow meters were used to measure the quantity of irrigation water applied to the TSI and ADI systems.

The FAO Penman-Monteith method was used to estimate reference evapotranspiration (ET_0) (Allen et al., 1998).

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\left[\frac{900}{T+273}\right]U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)}, \qquad (2)$$

where ET_o is the reference evapotranspiration (mm day^{-1}), R_n is net radiation at the crop surface (MJ m^{-2} day^{-1}), G is soil heat flux density (MJ m^{-2} day^{-1}), T is air temperature at a 2 m height (℃), U_2 is wind speed at a 2-m height (m s^{-1}), e_s is saturation vapor pressure (kPa), e_a is actual vapor pressure (kPa), e_s-e_a is saturation vapor pressure deficit (kPa), Δ is the slope vapor pressure curve (kPa ℃$^{-1}$), and γ is the psychrometric constant (kPa ℃$^{-1}$).

Olive tree evapotranspiration was calculated as follows:

$$ET_c = ET_0 \times K_c, \qquad (3)$$

Table 1
Soil properties of an urban forest park in the 0–80 cm layer of the soil profile.

Depth (cm)	Texture	Clay (%)	Silt (%)	Sand (%)	Gravel (%)	Bulk density (gr/cm^3)	Organic matter (%)
0–20	Sandy clay loam	21.00	24.33	54.67	45.43	1.11	0.71
20–40	Sandy loam	14.34	16.33	69.33	65.12	1.24	0.06
40–60	Sandy loam	17.68	17.99	64.33	69.22	1.28	0.03
60–80	Sandy clay loam	22.00	15.67	62.33	61.67	1.28	0.03

where ET_c is the olive evapotranspiration (mm d^{-1}) and K_c is the crop coefficient of the olive (dimensionless). The crop coefficient was adjusted based on the climate-specific condition following Allen et al. (1998):

$$K_{cmid} = K_{c\ mid(tab)} + [0 \cdot 04(u_2 - 2) - 0.004(RH_{min} - 45)]\left(\frac{h}{3}\right)^{0.3} \quad (4)$$

where $K_{c\ mid(tab)}$ is the recommended crop coefficient for the olive tree by Allen et al. (1998), U_2 is the mean value of daily wind speed at a 2-m height over grass during the midseason growth stage (m s^{-1}) when 1 m $s^{-1} \leq u_2 \leq 6$ m s^{-1}, RH_{min} is the mean value of daily minimum relative humidity during the mid-season growth stage (%) when 20 % $\leq RH_{min} \leq$ 80 %, and h is mean plant height during the mid-season stage (m) when 0.1 m < h < 10 m. Accordingly, the crop coefficients to convert ET_o into actual crop evapotranspiration were: April (0.63), May (0.68), June (0.71), July (0.75), August (0.75), September (0.75), October (0.74), November (0.70), and December (0.66).

2.3. Growth indices and root measurements

Branch length and the number of new buds were measured in 2012 and 2013 from four one-year-old branches marked in four directions (north, west, east, and south) per tested tree every month. In addition, the weight and volume of 100 fruits per tested tree were measured during three experimental years to assess the response of fruit growth to irrigation treatments. Water-use efficiency was calculated as the ratio between final fruit yield obtained by harvesting all fruits of trees and the water quantity applied via the irrigation system.

In the second year, three trees from both the ADI and TSI sites and two trees from the TDI sites were selected for monitoring root distribution and its density (Fig. 1). A 1 m deep trench with a length of 4.0 m and a width of 0.5 m was prepared at a 0.5-m distance from each trunk. Using a soil core sampler (7.7 cm in diameter and 6.9 cm in height), soil and root samples were collected in a 20 × 20-cm grid system at depth increments of 0–20, 20–40, 40–60, and 60–80 cm, which resulted in 52 samples per tested tree (Fig. 1b). The fresh root weights (FRW) were obtained by segregating the roots from the soil through a hand-washing process (Böhm, 1979). The fresh root volume (FRV) was measured with a graduated cylinder and a pipette based on displacement technique (Böhm, 1979; Sattelmacher, 1987).

2.4. Statistical analysis

Statistical analysis was performed using R v3.5.3 software. The data set was tested using Levene's and Shapiro-Wilk's tests and passed the tests of normality and homogeneity of variances. The statistical analysis was performed based on a completely randomized design to determine the effect of irrigation systems on growth indices (i.e., Cum. branch length and Cum. new buds) and on FRW and FRV. When the F test was statistically significant ($P < 0.05$), the Tukey HSD tests were subsequently run to identify significant differences between the means.

3. Results and discussion

3.1. Weather conditions and water relations

Based on daily meteorological data from Isfahan meteorological

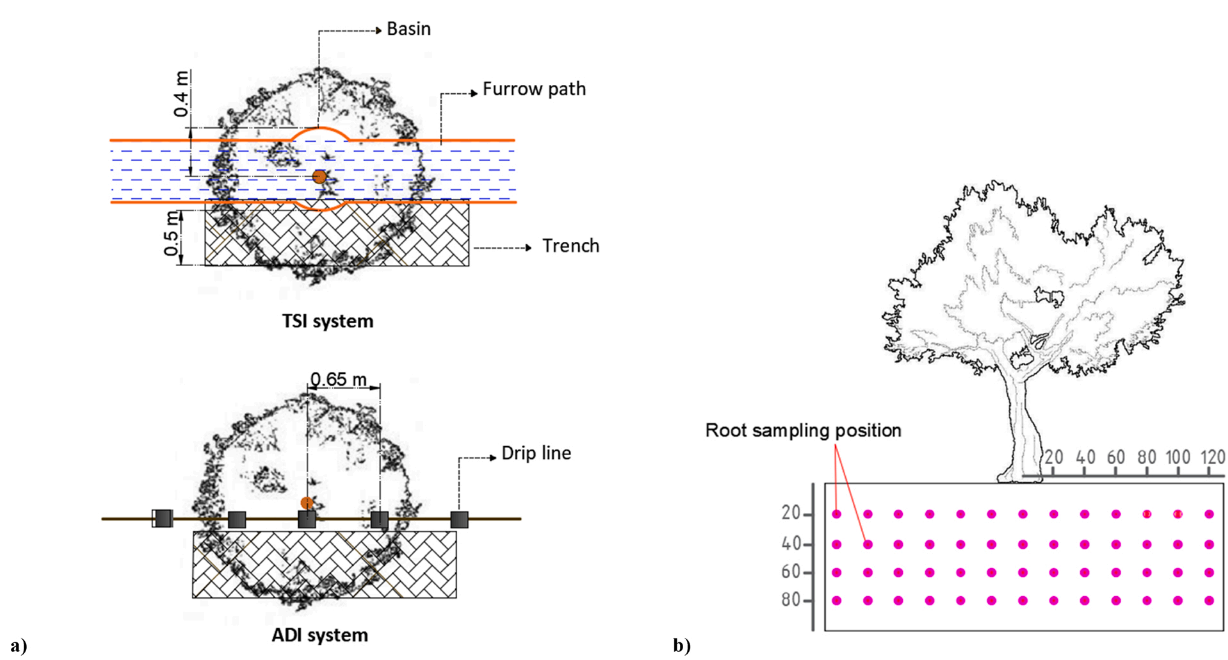

Fig. 1. (a) Arrangement of the experimental sites with mature olive trees under the traditional basin-surface (TSI) and automated drip irrigation (ADI) systems, and irrigation line positions with the trench location in the urban forest park, (b) soil and root sampling positions in TSI, ADI, and traditional drip irrigation (TDI) sites with a 20 × 20-cm grid system in the soil profile.

station, the annual precipitation was 238 mm in 2012, 91 mm in 2013, and 148 mm in 2014 (Fig. 2a), of which only 65, 35, and 14 mm occurred during the spring season and no rain fell in the summer in 2012–2014, respectively. The asymmetric precipitation pattern with annual values lower than 400 mm underlined the need for regular irrigation management to cover the water demand of mature olive trees (Steduto et al., 2012) with an ET_c of 825 mm. The annual precipitation in 2013 was almost half of that in 2012 and 2014, which made olive tree growth rely more on irrigation during that year (Fig. 2). Being able to capture the effect of changing the irrigation system on root development, an effort was made to deliver approximately the same water quantity with a similar irrigation frequency at both the TSI and ADI sites. Consequently, a total of 495- and 519-mm water (~ 60 % ET_c) were applied by the TSI and ADI systems, respectively. Also, the cumulative irrigation depth at the TDI site was reportedly 413 mm (~ 50 % ET_c), which was managed by the director of the urban forest park, leaving no authority for us to adjust the irrigation depth.

3.2. Vertical root adaptation for a more precise irrigation system

The FRWs and FRVs of the olive trees appeared to significantly change in shallow and deep layers of the soil. Irrespective of irrigation system type, FRW and FRV decreased with increasing soil depth, such that approximately 80 % of the roots were in the 0–40-cm soil layer (Fig. 3a and b). A similar result was reported for the root growth of mature olive trees in a sandy loam (Fernandez et al., 1991; Searles et al., 2009) and in a clay loam soil (Sorgonà et al., 2018). The values of FRW and FRV dropped from 22 % in the 40–60 cm layer to approximately 3% at the 60–80-cm soil depth. Root development may be inhibited in deeper layers due to low irrigation depth and soil limitation (i.e., higher soil bulk density and a high gravel content below 60 cm; Table 1). Previous studies reported restricting penetration for root growth in drought-prone gravelly soils (Arachchi, 1998) and when a hardpan layer is present deeper in the soil profile (Romero et al., 2004).

Switching the irrigation system had a significant effect on FRW, particularly in the upper 20 cm of the soil where the olive tree had a double amount of roots in the ADI than in the TSI system ($P < 0.05$; Fig. 3c). At the 20–40 cm and 40–60 cm soil depths, FRW was numerically 1.8 and 3.3 times larger in ADI than in the TSI system, respectively ($P > 0.06$). Likewise, the mature olive tree had a significant threefold larger volume of fresh roots under the ADI system than the TSI in the upper 20 cm of soil. Regarding the deeper layers, replacing the surface irrigation with drip irrigation increased the FRV more than fourfold in the 20–60-cm soil layer (Fig. 3d). That is to say, the automatic drip irrigation facilitated the root development of mature olive trees traditionally grown under TSI. Also, the percentage of FRW ($P < 0.05$) and FRV ($P > 0.06$) at 40–60 cm was over 40 % and 35 % greater in both drip systems, respectively, compared to the TSI system, implying that drip irrigation stimulated deeper root development than the surface system. The few available previous studies also reported more abundant olive tree roots under a drip irrigation system in a sandy loam/clay loam soil in Spain (Fernandez et al., 1991) and for avocado in a coastline area of

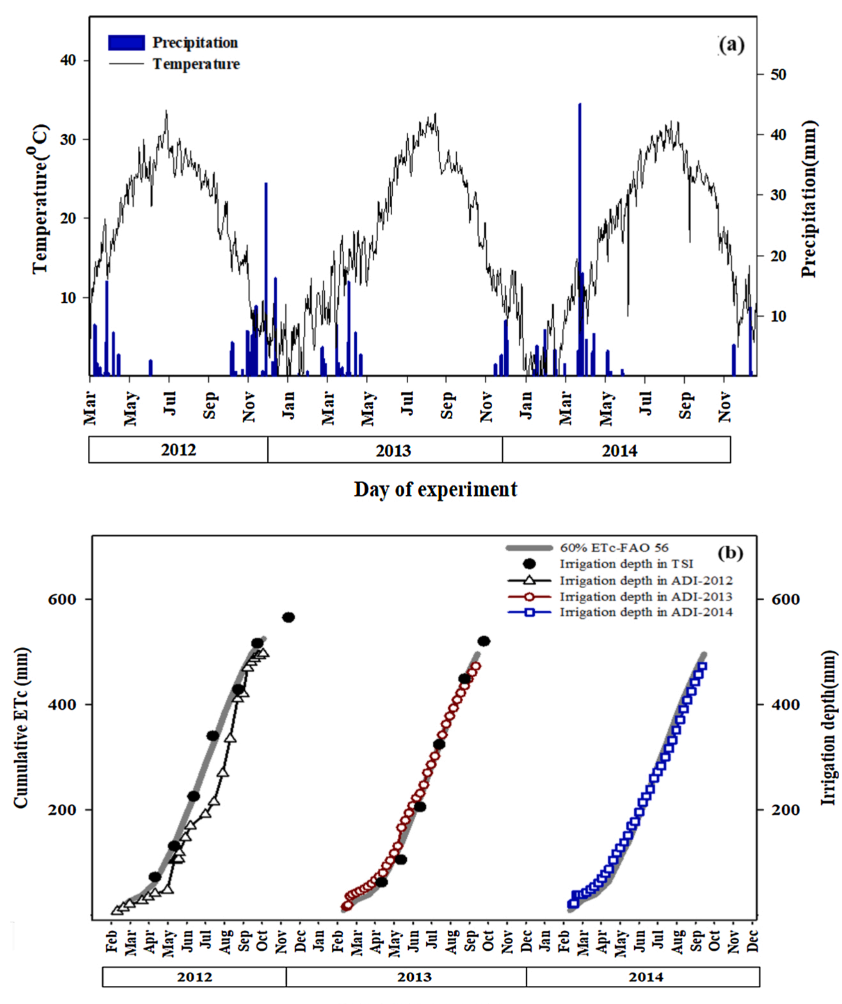

Fig. 2. (a) The average temperature and rainfall registered during the 3-year monitoring period, (b) the cumulative evapotranspiration of olive tree and irrigation depth in automated drip irrigation (ADI) and traditional surface irrigation systems (TSI) in an urban forest park.

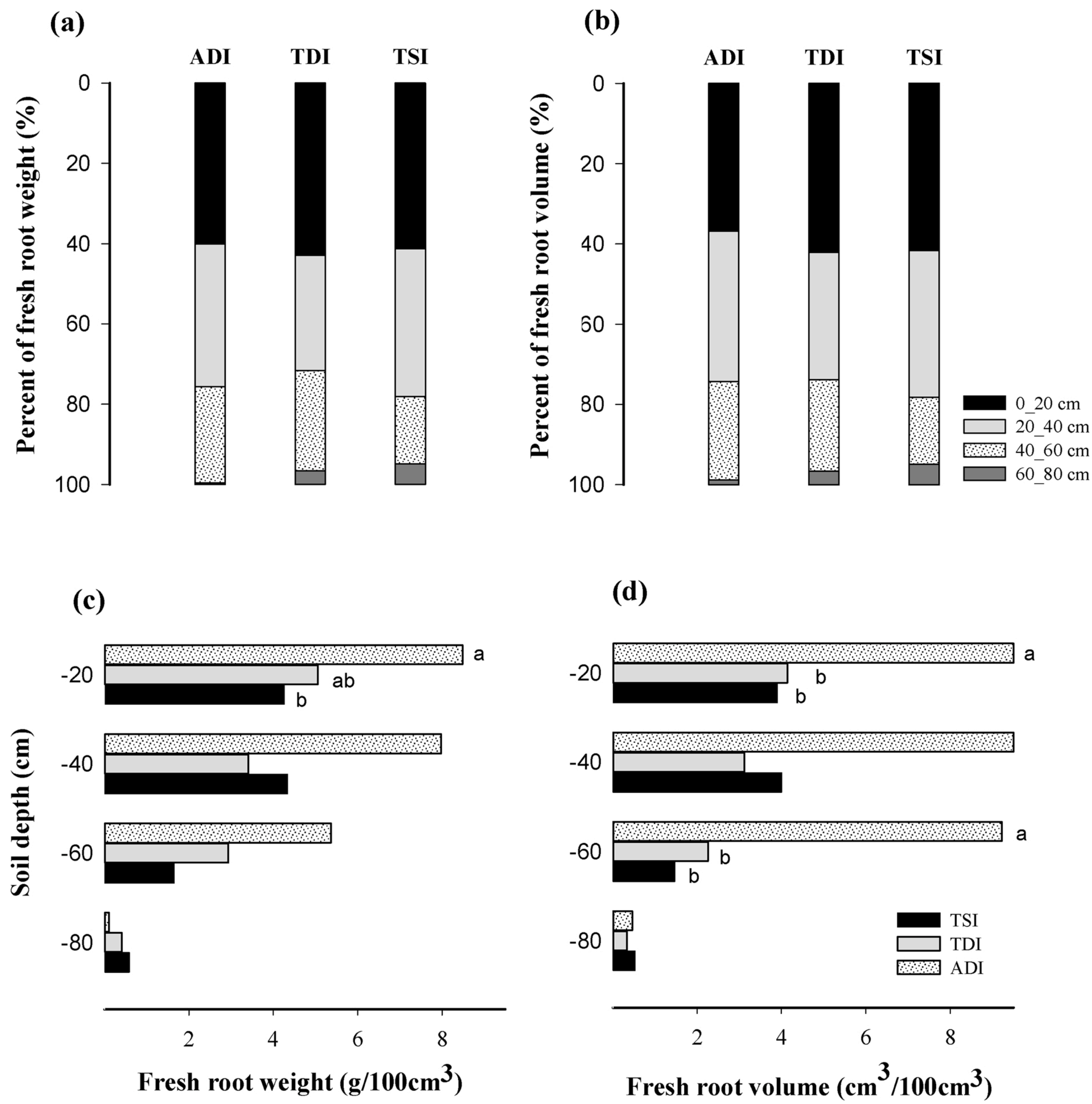

Fig. 3. (a) Proportion of fresh root weight and (b) fresh root volume of olive trees, and (c) the average values of fresh root weight and (d) fresh root volume in the 0–80-cm soil depth under automated drip irrigation (ADI), traditional basin-surface irrigation (TSI), and traditional drip irrigation (TDI) in 2013 in an urban forest park. Different letters within each row indicate significant differences at $P \leq 0.05$.

Chile with a Mediterranean climate (Salgado and Cautín, 2008).

Soil texture plays an important role in soil water content and, in turn, in tree root distribution (Salgado and Cautin, 2008). In the current sandy loam site with the majority of roots located in the upper 40 cm of soil, ADI was able to distribute a consistent low volume of water to the root zone of the olive trees. However, a considerable water quantity may be evaporating from the water's surface in the furrow of the TSI system and may percolate to deep layers due to a very high infiltration rate from the tree's basin (Fig. 2c), thereby decreasing root growth. We recorded a high percentage of gravel (> 60 %) from the studied sites, which may cause a rapid depletion of water flooded by the TSI system from the root zone in the upper soil layer. Similarly, Searles et al. (2009) found that the absolute values of soil moisture content were low in loamy sand soil with high gravel and most of the olive roots were located in the upper soil layer. Our results revealed that a well-designed drip irrigation system (e.g., a wetted pattern covering 40 % of the shaded area and a short irrigation interval) can enhance the root development of mature olive trees in coarse soils with a high gravel content.

Moreover, the olive trees irrigated by TDI had half the FRW in the soil profile compared to ADI (Fig. 3c). Also, less than 30 % FRV was observed in the 40–80-cm soil depth. The difference between TDI and ADI implied that changing the irrigation system will not necessarily yield promising results unless the system is properly designed based on soil and tree properties. In TDI, water was applied when it was available in the canal, which caused a lengthy gap between irrigations (up to 20 days). Also, the drippers were placed at longer intervals on the line (1.0 m in TDI with loop layout vs. 0.65 m in ADI with line layout). Thus, the appropriate soil moisture variations in the root development zone affected olive root growth. However, ADI provided a constant adequate water quantity (the gap between field capacity and permanent wilt) with a short irrigation interval. Our study extends the existing literature by documenting the clear root adaptation of mature trees to a well-designed drip irrigation system.

3.3. Horizontal root distribution under different irrigation systems

Irrespective of the irrigation system, the horizontal distribution of roots seemed to be more even compared to their vertical distribution under the tree-shaded area (120 cm radius, Fig. 4). This could be due to more uniform water availability (rainfall and irrigation) in the horizon rather than in the deep layers of the soil. A similar result was reported for avocado trees irrigated by drip irrigation in coarse-textured soil (Salgado and Cautin, 2008). The percentages of FRW and FRV ranged between 14 %–22 % in each 20-cm distance increment from the trunk (Fig. 4a and b). Also, ca. 55 % of FRW was distributed to 60 cm from the tree trunk.

Automatic drip irrigation produced a greater horizontal distribution of roots in the soil profile than TSI and TDI (Fig. 4c and d). In detail, FRWs that developed at a 20-cm distance from the trunk in the ADI system were 2 and 1.4 times that of the TSI and TDI systems, respectively (Fig. 4). We observed similar trend between ADI and the other two systems at 20–120 cm from the trunk (2 and 2.4 time, respectively), although the differences were not statistically significant. The ADI system had a fourfold larger FRV at a distance of 0–120 cm from the trunk compared to TSI and TDI ($P < 0.05$, Fig. 5). Comparing these irrigation systems leads us to conclude that replacing the traditional surface system with automatic drip irrigation did not negatively affect root growth but expanded the root weight and volume of mature olive trees.

The spatial root distribution of mature olive trees was tightly coupled with soil water distribution. The maximum root density of olive trees irrigated by TSI was 10.9 g roots in 100 cm^3 soil, located at a 50 cm distance from the trunk at a depth of 40 cm (Fig. 5). This may be caused by the irrigation basin with a radius of 40 cm around the tree (Fig. 1a). The maximum root density in the TDI system was observed beneath the dripper positions (a 100-cm distance from the tree) in the 20–60-cm layer of the soil profile. In this system, wide spacing between drippers in the sandy loam soil with a low water-holding capacity created a large gap in the wetted zones, leading to a discrete small root system (Fig. 5). This notion was further supported by the TDI showing the lowest FRW and FRV values compared to the other systems at a distance of 0–120 cm from the trunk. However, the ADI system (maximum root density of 15.1 g roots in 100 cm^3 soil), with drippers placed at smaller intervals, created a uniform wetted zone and, in turn, a smooth pattern of root distribution in the soil profile (Fig. 5). According to previous studies, dripper arrangement was a very important parameter defining root distribution following the path where water is supplied by drip irrigation (Black and Mitchell, 1974; Searles et al., 2009; Li et al., 2017). Also, automation of the ADI system made it possible to have a regular irrigation schedule with a high frequency. We observed a denser root concentration in the area close to the dripper in both drip irrigations (Fig. 5). However, the more intense water deficit in TDI (413 mm in TDI vs. 495 mm in ADI) stimulated a very dense distribution of absorbing roots in the wetted soil zone while root density was as little as 2 g in 100 cm^3 soil at a 50-cm distance from the dripper. Previous studies also emphasized the importance of irrigation regimes to avoid a sudden decrease of the soil matrix potential in soils with low water-holding capacities, and thus, the inability of plants in regulating their transpiration (Moriana et al., 2002; Searles et al., 2009; Díaz-Espejo et al.,

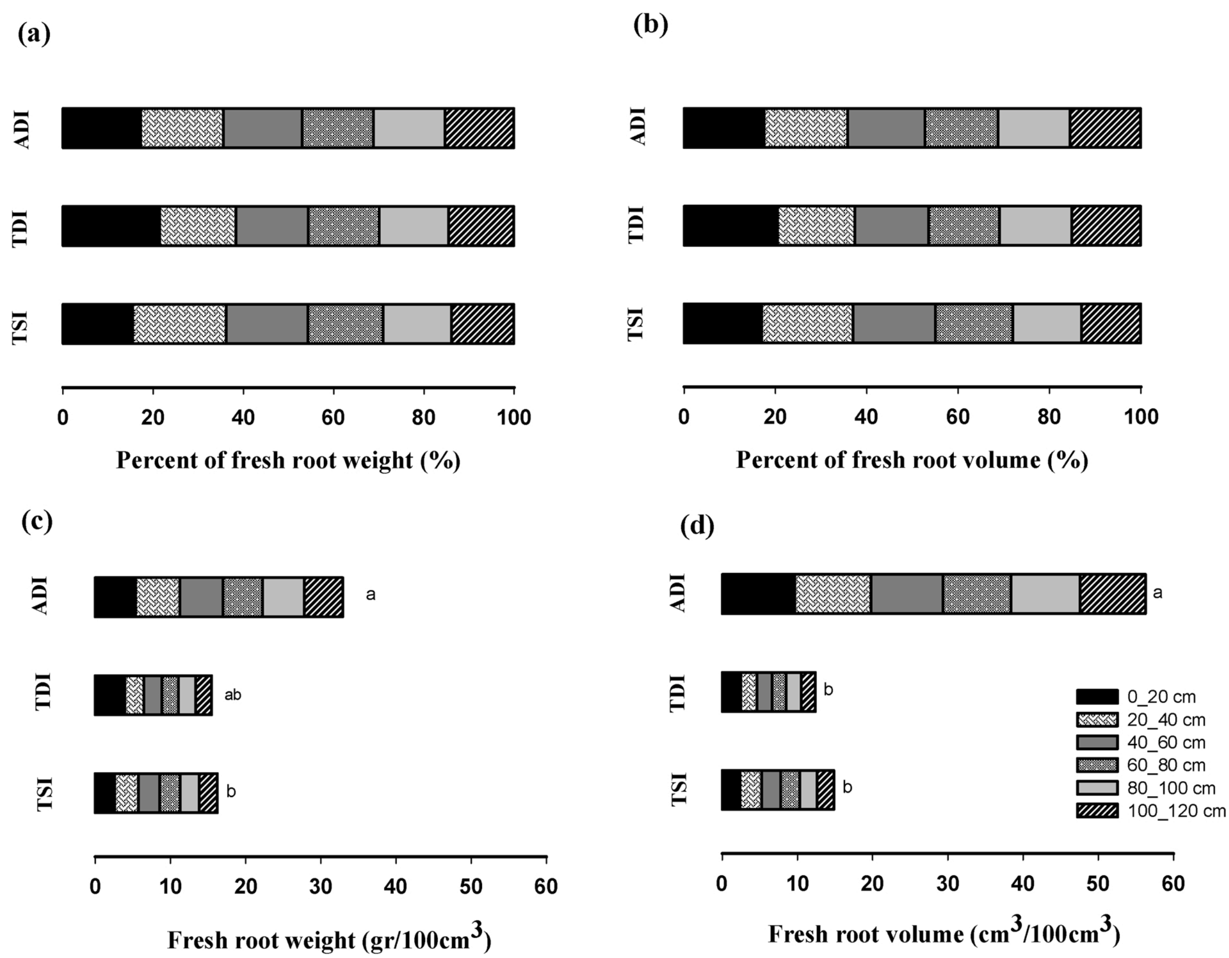

Fig. 4. (a) Proportion of fresh root weight and (b) fresh root volume of olive trees, and (c) the average values of fresh root weight and (d) fresh root volume at a distance of 0–120 cm from tree trunk under automated drip irrigation (ADI), traditional basin-surface irrigation (TSI), and traditional drip irrigation (TDI) in 2013 in an urban forest park. Different letters within each column of sections indicate significant differences at $P \leq 0.05$.

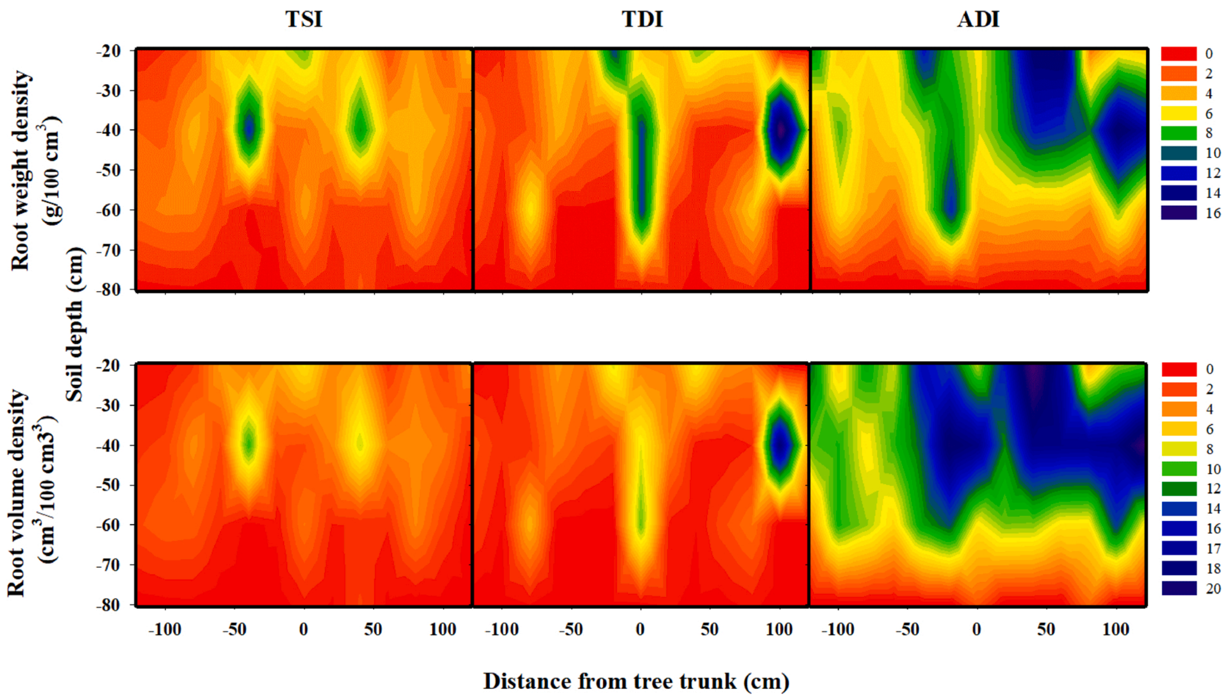

Fig. 5. Olive root weight density and root volume density at a distance of 0–120 cm from the tree trunk and at a depth of 0–80 cm of the soil profile in traditional basin-surface irrigation (TSI), traditional drip irrigation (TDI), and automated drip irrigation (ADI) sites in 2013 in an urban forest park. Values are the averages of three replicates collected with a 20 × 20-cm grid system in the soil profile.

2012). Our results showed that the accurate design, implementation, and operation of a drip irrigation system, including a suitable dripper space and irrigation frequency, may extend mature olive tree roots and result in more uniform root development.

3.4. Olive growth adaptation to a more precise irrigation system

Average fresh fruit weight calculated during the three years ranged between 1.7 and 5.1 g, depending on the irrigation system and measurement year (Table 2). In 2012, one year after changing the irrigation system, we observed no significant difference between the TSI and ADI systems regarding fruit weight ($P > 0.22$). However, in both 2013 and 2014, ADI resulted in more than 40 % heavier fruits compared to the TSI system ($P < 0.05$). Also, fresh fruit volume tended to be 20 % higher in ADI than in TSI (Table 2). Olive trees tend to be alternate bearing, which can be reduced by providing sufficient water and nutrients to increase shoot growth to support the next year's crop (Vossen, 2007). The lowest values of fruit weight and volume in TSI and ADI were registered in 2013 when rainfall conditions were especially limited (Fig. 2). Also, young branch growth, expressed as the cumulative growth of one-year-old branch length, showed significant differences between the TSI and ADI systems in 2013 (Table 2). In 2013, with the lowest rainfall level during the growth period in spring, the nearly fourfold lower branch growth in TSI compared with ADI implies that olive trees irrigated by TSI were affected by water shortage more intensively than trees in the ADI system. Comparing TSI and ADI implied that water-stress symptoms were closely related to irrigation strategy rather than with the quantity of irrigated water (519 mm in TSI vs. 495 mm in ADI). In fact, the positive response shown by the roots to the traditional system being replaced by ADI preserved the vegetative growth of mature olive trees under deficit-irrigation strategies. Consequently, the ADI system enhanced the fruit yield of mature olive trees (~ 6 t ha^{-1}) compared to both the TSI and TDI systems (Table 2). The TDI system resulted in the lowest fruit yield (~ 4 t ha^{-1}), which may be due to long irrigation intervals and more severe water deficit conditions (50 % ET_c) compared to the other systems providing 60 % of the trees' needs.

Moreover, the significantly higher water-use efficiency of ADI than TSI (Table 2) indicated that the water productivity parameter not only depends on water, quantity but also on the irrigation strategy applied (García-Tejero et al., 2011; Gheysari et al., 2015). A reduction in applied irrigation water was not resulted in higher water-use efficiency in our experiment. In other words, the ADI which received higher water levels (495 mm in ADI vs. 413 mm in TDI), had a slightly higher water-use efficiency than TDI. This may relate to long irrigation intervals (up to 20 days) in the TDI system. Similar results were reported previously, where increasing irrigation intervals had a negative feedback on plant growth rate in arid areas (Lahav and Kalmar, 1977; Sepaskhah and Kamgar-Haghighi, 1997; Zhang et al., 2019). The present work emphasized the possibility of switching traditional irrigation to drip irrigation with proper management and a suitable wetting pattern to preserve mature olive trees. Our results on the responses of mature trees to an updated irrigation system may improve the methods through which municipal irrigation officers are better able to preserve urban trees during a water crisis, and this may eventually lead to more sustainable urban ecosystems.

4. Conclusions

In this study, we explored the possibility of replacing traditional surface irrigation with the ADI system for urban mature olive trees under water deficit conditions for three years. Our results revealed that having a well-designed drip irrigation system (appropriate number and position of the drippers) with proper management (automated irrigation) leads to root adaptation without interfering with the growth and production of the mature olive trees in an urban forest park in an arid area. The growth rate and productivity in ADI followed the same trend as in the TSI system. The roots irrigated by ADI, after being irrigated by TSI for eight years, had a uniform spatial pattern where they expanded all over the soil profile (120 cm × 80 cm). However, roots in the TSI were distributed irregularly in the soil profile, with the highest density close to the irrigation basin located around the tree trunk. In TDI, the wide spacing between drippers created a large gap between the wetted zones

Table 2
Effect of irrigation systems on the yield and growth indices of mature olive trees in an urban forest park. Within each column of every section, the treatment means with different letters differ from each other, $P < 0.05$.

Irrigation system	ET_c (mm)	ID (mm)	Cum. branch length (cm)			Cum. new buds			Fresh fruit weight (gr)				Fresh fruit volume (cm^3)				Fruit yield (kg/ha)	IWUE (kg/m^3)
			2012	2013	Mean	2012	2013	Mean	2012	2013	2014	Mean	2012	2013	2014	Mean	2013	2013
ADI	825	495	1.81	1.65 ^{a}	1.73 ^{a}	1.01	2.13	1.57	4.89	2.38 ^{a}	4.55^{a}	3.94 ^{a}	4.43	2.11 ^{a}	3.18	3.24	5978 ^{a}	1.21^{a}
TSI	825	519	1.20	0.44 ^{b}	0.82 ^{b}	1.93	2.30	2.12	5.06	1.68 ^{b}	3.11^{b}	3.28 ^{b}	4.59	1.72 ^{b}	2.57	2.96	4436 ^{ab}	0.85 ^{b}
TDI	825	413	–	–	–	–	–	–	–	–	–	–	–	–	–	–	3911 ^{b}	0.94 ^{ab}
SE			*0.203*	*0.075*	*0.058*	*0.203*	*0.491*	*0.335*	*0.144*	*0.209*	*0.087*	*0.125*	*0.162*	*0.101*	*0.194*	*0.104*	*314.9*	*0.040*

ET_c: crop evapotranspiration; ID: Annual irrigation depth; Cum. branch length: Annual cumulative growth of branch length; Cum. new buds: Annual cumulative number of new buds on the selected branch; IWUE: Irrigation water-use efficiency based on the fruit yield in 2013 and irrigation depth; SE: Standard error.

in the sandy loam soil with a low water-holding capacity, leading to a discrete small root system. Our results on converting TSI to a more precise drip irrigation system may help municipalities and government officials properly preserve urban trees and sustainably develop urban forest parks in areas where available water resources are limited and water demand is growing. Also, in urban landscapes with low-quality soils (i.e., limited depth, coarse texture, high gravel content, and very low organic matter), the establishment and development of the root system of mature urban trees using the ADI system increases the chance of preserving the trees for longer periods of time and ensures the continued production of ecosystem services such as carbon sequestration, erosion prevention, air purification, and habitat quality. It is suggested to explore the effect of replacing traditional surface irrigation with automated drip irrigation systems in a longer period of time and a wider range of urban landscapes.

CRediT authorship contribution statement

Fahime Mohamadzade: Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Writing - original draft. **Mahdi Gheysari:** Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Validation, Visualization, Writing - review & editing. **Mina Kiani:** Formal analysis, Investigation, Methodology, Resources, Visualization, Validation, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The research project was funded by the Isfahan University of Technology (project n. 991148) and Iran National Science Foundation (project no. 97010962). Also, open access was funded by University of Helsinki Library. The authors wish to thank Prof. Shamsollah Ayoubi, Prof. Bahram Baninasab, and Dr. Parvaneh Asgarinia for their insightful comments. The authors also acknowledge Ali Maleki for assisting with the root washing process, and Forough Fazel and Marzie Mohamadian for assisting with the fruit collection process.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.ufug.2021.127053.

References

Al Ibrahem, A., Boulouha, B., Gregoriou, C., El-Kholy, M., Ksantini, M., Serafids, N., Shdiefat, S., 2010. Olive Gap Manual Good Agricultural Practices for the Near East and North Africa Countries. Viale delle Terme di Caracalla, Rome, Italy.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements. Irrigation and drainage paper 56, Rome, Italy.

Arachchi, L.V., 1998. Preliminary requirements to design a suitable drip irrigation system for coconut (Cocos nucifera L.) in gravelly soils. Agric. Water Manage. 38 (2), 169–180.

Araujo, F., Williams, L.E., Grimes, D.W., Matthews, M.A., 1995. A comparative study of young 'Thompson Seedless' grapevines under drip and furrow irrigation. I: root and soil water distributions. Sci. Hortic-Amsterdam 60, 235–249.

Assari, A., Mahesh, T.M., 2011. Demographic comparative in heritage texture of Isfahan City. J. Geogr. Reg. Plann. 4, 463–470.

Ben Ahmed, Ch, Ben Rouina, D., Boukhris, M., 2007. Effects of water deficit on olive trees cv. Chemlali under field conditions in arid region in Tunisia. Sci. Hortic-Amsterdam 113, 267–277.

Bini, G., 1984. Flowering and pollination in olive. Investigations on the pollination period, receptibility of stigma and evolution of the female gametophyte. Adv. Hortic. Sci. 68, 57–69.

Black, J.D., Mitchell, P.D., 1974. Changes in root distribution of mature pear trees in response to trickle irrigation. In: Proceedings 2nd Intern. San Diego (California), pp. 437–438. Drip Irrig Congr.
Böhm, W., 1979. Root parameters and their measurement. In: Methods of Studying Root Systems. Ecological Studies (Analysis and Synthesis), vol 33. Springer, Berlin, Heidelberg.
Bouwer, H., 1986. Intake rate. Cylinder infiltrometer. In: Klute, A. (Ed.), Methods of Soil Analysis, ASA Monograph 9. ASA, Madison, pp. 825–843.
Cantuarias, T., Cohen, Y., Tomer, E., 1995. Improving Avocado. Tree Water Status under Severe Climatic Conditions by Increasing Wetted Soil Volume. The World Avocado Congress III, Israel, pp. 196–204.
Cilliers, S., du Toit, M., Cilliers, J., Drewes, E., Retief, F., 2014. Sustainable urban landscapes: South African perspectives on transdisciplinary possibilities. Landsc. Urban Plan 125, 260–270.
Cole, S., Mikhailova, E., Post, C., Privette, C., Schlautman, M.A., Cope, M., 2017. Comparing SSURGO data with geospatial field measurements to estimate soil texture and infiltration rate classes in glaciated soils. Commun. Soil Sci. Plant Anal. 48 (11), 1309–1318.
Díaz-Espejo, A., Buckley, T.N., Sperry, J.S., Cuevas, M.V., De Cires, A., Elsayed-Farag, S., Martin-Palomo, M.J., Muriel, J.L., Perez-Martin, A., Rodriguez-Dominguez, C.M., Rubio-Casal, A.E., 2012. Steps toward an improvement in process-based models of water use by fruit trees: a case study in olive. Agric. Water Manage. 114, 37–49.
Fernandez, J.E., Moreno, F., Cabrera, F., Arrue, J.L., Martin-Aranda, J., 1991. Drip irrigation, soil characteristics and the root distribution and root activity of olive trees. Plant Soil 133, 239–251.
Ferrini, F., Konijnendijk van den Bosch, C.C., Fini, A., 2017. Routledge Handbook of Urban Forestry. Routledge, London, United Kingdom, p. 574 pages (pg. 18).
Gan, Z.T., Zhou, Z.C., Liu, W.Z., 2010. Vertical distribution and seasonal dynamics of fine root parameters for apple trees of different ages on the Loess Plateau of China. Agric. Sci. China 9 (1), 46–55. https://doi.org/10.1016/S1671-2927(09)60066-3.
García-Tejero, I., Durán-Zuazo, V.H., Muriel-Fernández, J.L., Martínez-García, G., Jiménez-Bocanegra, J.A., 2011. Benefits of low-frequency irrigation in citrus orchards. Agron. Sust. Dev. 31, 779–791.
Gheysari, M., Loescher, H.W., Sadeghi, S.H., Mirlatifi, S.M., Zareian, M.J., Hoogenboom, G., 2015. Water-yield relations and water use efficiency of maize under nitrogen fertigation for semiarid environments: experiment and synthesis. Adv. Agron. 130, 175–229.
Lahav, E., Kalmar, D., 1977. Water requirements of avocado in Israel. II. Influence on yield, fruit growth and oil content. Aust. J. Agric. Res. 28 (5), 869–877.
Li, X., Šimůnek, J., Shi, H., Yan, J., Peng, Z., Gong, X., 2017. Spatial distribution of soil water, soil temperature, and plant roots in a drip-irrigated intercropping field with plastic mulch. Eur. J. Agron. 83, 47–56.
Martínez-Gimeno, M.A., Bonet, L., Provenzano, G., Badal, E., Intrigliolo, D.S., Ballester, C., 2018. Assessment of yield and water productivity of clementine trees under surface and subsurface drip irrigation. Agric. Water Manage. 206, 209–216.
McIntyre, D.S., 1974. In: Loveday, J. (Ed.), Methods of Analysis for Irrigated Soils. Commonwealth Agricultural Bureaux Technical Communication No 54, Farnham Royal, England.
McPherson, E.G., Nowak, D., Heisler, G., Grimmond, S., Souch, C., Grant, R., Rowntree, R., 1997. Quantifying urban forest structure, function, and value: the Chicago Urban Forest Climate Project. Urban Ecosyst. 1 (1), 49–61.
Mexia, T., Vieira, J., Príncipe, A., Anjos, A., Silva, P., Lopes, N., 2017. Ecosystem services: urban parks under a magnifying glass Environmental Research Ecosystem services: urban parks under a magnifying glass. Environ. Res. 160, 469–478. https://doi.org/10.1016/j.envres.2017.10.023.
Moreira, S.L.S., Imbuzeiro, H.M.A., Dietrich, O.H.S., Henriques, E., Pereira Flores, M.E., Pimentel, L.D., Fernandes, R.B.A., 2019. Root distribution of cultivated macauba trees. Ind. Crop Prod. 137, 646–651. https://doi.org/10.1016/j.indcrop.2019.05.064.
Moriana, A., Villalobos, F.J., Fereres, E., 2002. Stomatal and photosynthetic responses of olive (Olea europaea L.) leaves to water deficits. Plant Cell Environ. 25 (3), 395–405.
Neilsen, G.H., Parchomchuk, P., Neilsen, D., Zebarth, B.J., 2000. Drip-fertigation of apple trees affects root distribution and development of K deficiency. Can. J. Soil Sci. 80 (2), 353–361.
Purbopuspito, J., Van Rees, K.C.J., 2002. Root distribution at various distances from clove trees growing in Indonesia. Plant Soil 239, 313–320.
Rawlins, S.L., 1973. Principles of managing high frequency irrigation 1. Soil Sci. Soc. Am. J. 37 (4), 626–629.
Romano, N., Santini, A., Dane, J.H., Topp, G.C., 2002. Water retention and storage: field. Methods Soil Anal. 4, 721–738. Part.
Romero, P., Botia, P., Garcia, F., 2004. Effects of Regulated Deficit Irrigation Under Subsurface Drip Irrigation Conditions on Vegetative Development and Yield of Mature Almond Trees, pp. 169–181.
Salgado, E., Cautin, R., 2008. Avocado root distribution in fine and coarse-textured soils under drip and micro sprinkler irrigation. Agric. Water Manage. 95, 817–824.
Santos, F.L., Valverde, P.C., Ramos, A.F., Reis, J.L., Castanheira, N.L., 2007. Water use and response of a dry-farmed olive orchard recently converted to irrigation. Biosyst. Eng. 98 (1), 102–114.
Sattelmacher, B., 1987. Methods for measuring root volume and for studying root morphology. J. Plant Nutr. Soil Sci. 150, 54–55.
Scharenbroch, B.C., Meza, E.N., Catania, M., Fite, K., 2013. Biochar and biosolids increase tree growth and improve soil quality for urban landscapes. J. Environ. Qual. 42 (5), 1372–1385.
Searles, P.S., Saravia, D.A., Rousseaux, M.C., 2009. Root length density and soil water distribution in drip- irrigated olive orchards in Argentina under arid conditions. Crop Pasture Sci. 60, 280–288.
Sepaskhah, A.R., Kamgar-Haghighi, A.A., 1997. Water use and yields of sugarbeet grown under every-other-furrow irrigation with different irrigation intervals. Agric. Water Manage. 34 (1), 71–79.
Soil Survey Staff, 2010. Keys to soil taxonomy. U.S. Department of Agriculture. Natural Resources Conservation Service, 11th ed. U.S. Government Printing Offices Washington.
Sokalska, D.I., Haman, D.Z., Szewczuk, A., Sobota, J., Dereń, D., 2009. Spatial root distribution of mature apple trees under drip irrigation system. Agric. Water Manage. 96, 917–924.
Song, X., Gao, X., Dyck, M., Zhang, W., Wu, P., Yao, J., Zhao, X., 2018. Soil water and root distribution of apple tree (Malus pumila Mill) stands in relation to stand age and rainwater collection and infiltration system (RWCI) in a hilly region of the Loess Plateau, China. Catena 170, 324–334. https://doi.org/10.1016/j.catena.2018.06.026.
Sorgonà, A., Proto, A.R., Abenavoli, L.M., Di Iorio, A., 2018. Spatial distribution of coarse root biomass and carbon in a high-density olive orchard: effects of mechanical harvesting methods. Trees-Struct. Funct. 32 (4), 919–931.
Steduto, P., Hsiao, T.C., Fereres, E., Raes, D., 2012. Crop Yield Response to Water. FAO Irrigation and Drainage Paper No.66, Rome, p. 505 p..
Vossen, P.M., 2007. Organic Olive: Production Manual, 1st ed. University of California Agriculture & Natural.
Xi, B., Wang, Y., Jili, L., Bloomberg, M., Li, G., Di, N., 2013. Characteristics of fine root system and water uptake in a triploid Populus tomentosa plantation in the North China Plain: implications for irrigation water management. Agric. Water Manage. 117, 83–92.
Zhang, G., Shen, D., Ming, B., Xie, R., Jin, X., Liu, C., Hou, P., Xue, J., Chen, J., Zhang, W., Liu, W., 2019. Using irrigation intervals to optimize water-use efficiency and maize yield in Xinjiang, northwest China. Crop J. 7 (3), 322–334.