Water Use Efficiency of Surface Drip Irrigation versus an Alternative Subsurface Drip Irrigation Method

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Abstract: In semiarid regions where water resources are scarce, irrigation water use efficiency is an important issue. Although subsurface drip irrigation is a very efficient irrigation method, it has had relatively limited expansion due to several disadvantages such as the clogging of emitters and the difficulty of detecting leakages and repairing them. Recently, an alternative subsurface irrigation method that is able to avoid most of the aforementioned drawbacks has been introduced in southern Spain. The objective of this work is to assess the performance of this method and to compare it to a surface drip-irrigation system. To achieve this objective, a three-year field experiment was carried out in an organic olive orchard (Olea europaea L.) located in the province of Almería, Spain. The water-use efficiency of both irrigation methods was analyzed under three different irrigation water supplies. The results show that the alternative subsurface irrigation method seems to perform better than the drip irrigation one because the yield and the irrigation water use efficiency were higher for the first one. DOI: 10.1061/(ASCE) IR.1943-4774.0000745. This work is made available under the terms of the Creative Commons Attribution 4.0 International license, http://creativecommons.org/licenses/by/4.0/.

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Introduction and Objectives

The Mediterranean climate is characterized by scarce and variable precipitation. The average annual rainfall in some areas in southeastern Spain is less than 300 mm per year. Proper management of the irrigation systems is essential for achieving maximum efficiency of irrigation water use. The use of subsurface drip irrigation (SDI) systems may provide an improvement in irrigation water use efficiency. These systems apply irrigation water directly inside the ground instead of on the surface (Ayars et al. 1999). This procedure reduces soil water evaporation losses from the wet bulb as the soil surface is not wetted, especially in low-density crops. Bonachela et al. (2001) measured the soil-direct evaporation from the wet bulb for surface drip-irrigated olive orchards. They estimated that this evaporation represented a fraction of seasonal orchard evapotranspiration ranging from 4 to 12% for a mature orchard and from 18 to 43% for a young orchard, depending mainly on the fraction of soil surface wetted.

Camp (1998) reviewed the results of some previous works that compared the crop yield both in subsurface and other different methods of surface irrigation. He concluded that crop yields for subsurface drip systems were equal to or better than the other systems in all cases, including different crops, soils, and cropping conditions. Water and nutrients are used more efficiently, and yields and product quality are often significantly improved (Phene et al. 1987).

Other additional advantages of underground irrigation have also been described: the increase in the working life of the system as vandalism and solar radiation degradation are avoided; ploughing and other cropping practices are facilitated, and the development of weeds and fungal diseases are diminished. As a result of these advantages, this technique is being used in several crops such as fruits, citrus, tobacco and especially in olive orchards. Olives are one of the most widespread crops in the Mediterranean basin. Traditionally, olives are cultivated under rainfed conditions; however, many studies have shown that the application of irrigation water results in a significant increase in yield and a considerable reduction of the problem of alternate bearing (Moriana et al. 2003; Melgar et al. 2008). For this reason, in recent years, there has been an enormous increase in irrigated olive land area using drip-irrigation systems.

Although, subsurface irrigation methods have been used since ancient times (Bainbridge 2001), their expansion is quite limited despite its high water use efficiency and numerous advantages. This is mainly due to the fact that current subsurface drip-irrigation systems, which consist of burying both the laterals and emitters, also have serious drawbacks. These shortcomings include the higher cost of the system, emitters clogging and breakage problems due to the intrusion of roots or the suction of solid particles from the soil matrix, and the difficulty of detecting and repairing potential leakage problems.

Another drawback of these systems has also been observed by several researchers (Lazarovitch et al. 2006; Provenzano 2007; Gil et al. 2011). The hydraulics properties of the soil can reduce the discharge of the emitters due to the positive pressures that may develop during irrigation in the soil near the dripper. This variation of emitter discharge can seriously influence the overall system irrigation uniformity (Lazarovitch et al. 2006; Rodríguez-Sinobas et al. 2009a, b).

An alternative subsurface drip irrigation method (SDI system), which is able to avoid most of the abovementioned drawbacks, has been recently developed. This system is being introduced in southern Spain to irrigate olive orchards. It consists of installing the water distribution network and the emitters on the soil surface, as if it were a conventional drip-irrigation system, but the emitters discharge to atmosphere and pour the water into a perforated plastic pipe vertically inserted into a hole in the ground (Fig. 1). In this way, the wet bulb is formed inside the soil, just at the bottom end of the perforated pipe. If the depth of the perforated pipe is...
high and its diameter is small enough, the evaporation losses from the wet bulb can be considered negligible. As a consequence, the proposed alternative SDI system has most of the advantages of a conventional SDI system but without most of its drawbacks.

The system is easy to install and relatively economical, although it entails an additional installation cost, as compared to a DI system, due to the placement of the perforated pipes below each emitter. However, it avoids the cost of burying the irrigation laterals as it occurs in others SDI system. Maintenance of the system is much simpler than in other SDI systems, as clogged emitters can be more easily detected and replaced at a lower cost.

The objective of this work is to evaluate experimentally the performance of this alternative subsurface irrigation method in comparison with a traditional surface drip-irrigation system (DI system). Its effect on the crop yield and irrigation water use efficiency will be analyzed and the possible water savings with this new method will be assessed. A field experiment has been performed to evaluate and compare the response of both irrigation systems under different irrigation water amounts.

**Experimental Site**

This paper describes a three-year experiment (2005–2007) carried out in an organic olive orchard (*Olea europaea* L. cv. Arbequina), located in the municipality of Tabernas, in Almería, Spain. The experimental plot is located in Universal Transverse Mercator (UTM) zone 30S, and its UTM coordinates are $X = 561,661$ m and $Y = 4,108,276$ m (30N 561661 4108276).

This area has a Mediterranean semiarid climate, with an average annual rainfall of 260 mm and a wide dry period during the summer months. Average monthly temperatures range from 8°C in January to 26°C in July, which means that winters are mild and the risk of frost is very low as the absolute minimum temperature is above 0°C. The average wind speed is about 2 m/s, and the relative humidity has a monthly average of 60%, with minimum values in the warmer months.

The olive trees were planted in January 2001 and the tree spacing was $7 \times 5$ m$^2$. The soil is a calcareous Cambisol with a sandy loam texture, high pedregosity and a bulk density of $1.64$ g/cm$^3$.

The irrigation water comes from a private well located on the farm. According to Ayers and Westcot (1994), the irrigation water quality is good, as its electrical conductivity is approximately 1.1 dS/m with a moderate risk of alkalinization as the adjusted Sodium adsorption ratio is 4.78

**Material and Methods**

**Experimental Design**

To test the performance of the SDI system and to compare it to the DI system, an experiment was conducted based on a randomized blocks design with two factors: irrigation system type (SDI system and DI system) and irrigation water supply. Three different irrigation water supplies were considered in the experiment: 100% net irrigation water requirements (NIR), 80% NIR and 60% NIR. NIR is equal to the crop evapotranspiration ($ET_c$) minus the effective precipitation ($P_{ef}$). As a result, there were six different treatments...
in the experiment. Treatments T1, T2, and T3 correspond to the SDI system with 100, 80, and 60% NIR, respectively and treatments T4, T5, and T6 correspond to the DI system with equivalent water supplies.

Three replicates were carried out for each treatment (R1, R1, and R3), which resulted in a total of 18 experimental units. The experimental units were randomly distributed throughout the plot. Every experimental unit was composed of a total of nine trees. The three central ones were collected to measure the olive yield while the rest were considered as border trees. Fig. 2 shows the described experimental layout.

Some researchers have studied the effect of different controlled deficit-irrigation strategies on the crop yield (Goldhamer 1999; Moriana et al. 2003; Caruso et al. 2013; Garcia et al. 2013; Gispert et al. 2013). However, in this work and with the aim of comparing both irrigation methods, a uniformly distributed deficit-irrigation strategy has been carried out in the deficit-irrigation treatments.

Irrigation System Description

The experimental olive orchard is irrigated by a drip-irrigation system. A representative irrigation subunit was chosen to conduct the experiment. Experimental units were randomly distributed within the selected irrigation subunit. Therefore, the irrigation system layout was the same for both systems in order to compare them under similar conditions.

New pressure-compensating emitters with a working interval ranging from 50 to 400 kPa were installed in the irrigation subunit. Their flow rate was 4 L/h. A sample of these emitters was tested on a test bench with the aim of assessing their manufacturing variability. A manufacturer’s coefficient of variation of 2.27% was obtained experimentally, which means that the uniformity of the emitters’ flow is high [ISO 9261:2004 (2004)].

The irrigation subunit had a rectangular shape. It was composed of one manifold pipe and irrigation laterals fed by their extreme. Both manifold and lateral pipes were made of polyethylene. There was one lateral per tree row with 7 m of spacing among laterals and 16 mm of external diameter.

Several works have discussed the emitter spacing for SDI systems (Lamm and Camp 2007; Provenzano 2007; Grabow et al. 2011). However, in this experiment, a common setup in the study area for young olive orchards was used. Two emitters per tree were installed in the direction of the laterals and connected to them with a micro-tube. One dripper was located on each side of the tree. The emitters were separated 0.5 m from the trunk (1 m of spacing between them).

In the SDI treatments (T1, T2, and T3), the same emitter spacing has been maintained but one perforated pipe was placed vertically into a hole on the ground under each emitter. The depth of the hole was approximately 50 cm and its width 11 cm.

Two field evaluations of the irrigation uniformity of the experimental irrigation subunit were conducted at the beginning and at the end of the experiment. These irrigation evaluations were made following the methodology proposed by Bralts and Edwards (1986). The calculated irrigation statistical uniformity (US) was high in both cases (0.91 at the beginning of the experiment and 0.89 at the end).

Irrigation Scheduling

The irrigation water requirements were calculated from actual climatic data taken from the Tabernas agroclimatic station belonging to the network of agroclimatic stations of the government of Andalusia. This station is located very close to the study area (UTM zone: 30S UTM coordinates: X = 562,109, Y = 4,105,362) (30N 562109 4105362) and its elevation is 435 m above sea level. It is equipped with rainfall, temperature, radiation, air humidity, and wind-speed sensors.

The crop water requirements calculation methodology used in this work is that proposed by the Food and Agriculture Organization of the United Nations (FAO) (Allen et al. 1998). According to this methodology, crop evapotranspiration is calculated by the following equation:

\[
ET_c = ET_o \times K_c \times K_r
\]

where \(ET_o\) = reference evapotranspiration (mm), \(K_c\) = crop coefficient, and \(K_r\) = ground cover reduction coefficient.

The reference evapotranspiration, \(ET_o\), has been calculated using the Penman-Monteith equation (Allen et al. 1998).

The calculation of \(K_c\) values for olive trees is a complex issue as it depends on many factors: ground cover, precipitation, irrigation method, and irrigation scheduling. Several researchers have proposed different sets of values for the crop coefficient depending on the type of olive orchard and the climate (Goldhamer et al. 1994; Allen et al. 1998) or complex models to estimate these values (Orgaz et al. 2006; Allen and Pereira 2009). The \(K_c\) values used in this research were those proposed by Orgaz and Fereres (1999) for mature olive trees with a ground cover of 50% at least (0.50 in July and August; 0.55 in May, June and September; 0.60 in April and October; and 0.65 from November to March). These values were obtained from climatic conditions similar to those of the experimental site.

Several works have analyzed the effect of incomplete tree canopy cover on crop evapotranspiration (Ritchie 1972; Villalobos et al. 2000; Testi et al. 2004). The experimental crop is a young olive orchard with a ground cover fraction of approximately 12% during the study period. Using the formula proposed by Fereres et al. (1981), a \(K_c\) value of 0.24 has been obtained.

There are several methods to calculate the effective precipitation from the actual rainfall (Dastane 1976). In this work, effective precipitation has been calculated by applying an empirical coefficient of 0.24, taking into account that the olives trees are young without fully developed root distribution, that the terrain is relatively sloped, and precipitations are scarce and torrential.

The irrigation scheduling performed in this experiment was based on a water balance approach. A specific spreadsheet program
was designed to calculate the crop water requirements and to perform the irrigation scheduling for every treatment. The irrigation scheduling was based on applying constant irrigation water amounts and variable time intervals between irrigations depending on the crop water requirements. The time interval between irrigations was the same for all treatments. In the control treatment (100% NIR) the irrigation water dose was 40 L/tree. In the deficit-irrigation treatments, the irrigation time was reduced proportionally in order to apply the desired irrigation volume per treatment: 32 L/tree (for 80% NIR) and 24 L/tree (for 60% NIR). The time interval between irrigations was recalculated weekly using actual climatic data with the aim of matching the applied irrigation water to the crop water requirements.

**Soil Moisture Measurement**

To evaluate the performance of the irrigation operations, capacitive sensors (ECH2O of Decagon Devices) were installed to measure soil moisture. According to the manufacturer’s information, the resolution of this sensor is 0.002 m/m and has a margin of error of about 2%. Two 20-cm probes were installed per treatment. They were placed vertically and positioned at different depths. These two sensors were set at a horizontal distance of 20 cm from the emitters, following the direction of the laterals. As the size and shape of the wet bulb differs in both methods, the depth at which the sensors were placed was different. In the DI system, the midpoint of the most superficial sensor (Probe 1) was placed 30 cm deep (depth range between 20 and 40 cm) and the deepest sensor (Probe 2) was placed 50 cm deep (depth range between 40 and 60 cm). In the SDI system, both sensors were placed 10 cm deeper than in the DI system so that the midpoints of the probes were located at 40 depth (depth range from 30 to 50 cm) and 60 cm (from 50 to 70 cm), respectively. Thus, the upper sensor is above the point of application of water to the ground while the deeper probe is below it. This arrangement allows analyzing both upward and downward flows. The reading and storage of the data were carried out using data loggers, which also served as the electrical power supply for the probes. The data were collected periodically using a laptop computer.

**Cropping Techniques**

All other cropping techniques such as pruning, phytosanitary treatments, fertilizer applications, and tillage were identical for all treatments. Pruning was carried out every two years, just after harvesting. In the study period, the olive trees were pruned twice, at the end of each cropping season. The driest year of the series was the first year of study. The other two years were less dry, especially the third one with a total rainfall of almost 300 mm/year.

The calculated average NIR were 131.5 mm. The maximum NIR value exceeded 160 mm and occurred in the driest year of the series, mainly due to the lower amount of rainfall (143.6 mm). The irrigation scheduling was based on a water balance approach. The time interval between irrigations was recalculated.

**Water Use Efficiency Indices and Statistical Analysis**

The main purpose of this paper is to assess the influence of the irrigation method and the amount of water applied on the olive trees yield and productivity.

The irrigation water use efficiency can be defined as the yield of plant product per unit of irrigation water used and it is a measure of the productivity of the irrigation water. With the aim of assessing the influence of the irrigation method and amount of water on the operational efficiency of the irrigation water use, two different water use efficiency performance indices have been considered:

1. WUE$_{f} = \frac{m_1}{P}$: Ratio between olive yield and the amount of irrigation water applied (kg of olives/m$^2$)
2. WUE$_{o} = \frac{m_2}{P}$: Ratio between olive oil yield and the amount of irrigation water applied (kg of olive oil/m$^2$)

To assess the influence of the considered factors on the performance indices, several multifactor analyses of variance have been performed. The irrigation water amount and the irrigation method have been considered as factors. The olive yield, olive oil yield, WUE$_{f}$, and WUE$_{o}$ have been taken as dependent variables. The Statgraphics Plus for Windows 4.0 Windows statistical package was used to carry out these statistical analyses.

**Results and Discussion**

**Weather Conditions and Irrigation Scheduling**

Table 1 summarizes the main climatic data of the study area and irrigation scheduling variables during the three years of research.

The reference evapotranspiration was relatively steady throughout the three-year study. The average value was 1,404.2 mm with only a coefficient of variation of 2.9%. Rainfall was very scarce, which is usual in the area. The average annual rainfall was 239.2 mm, but its variability was considerably higher (34.85%).

| Year | $R_{f}$ (MJ/m$^2$) | $P$ (mm) | $ET_{o}$ (mm) | NIR (mm) | $I$ (mm) | $\epsilon$ (%) |
|------|-------------------|----------|--------------|----------|---------|---------------|
| 2005 | 6,941.2           | 143.6    | 1,450.8      | 160.2    | 162.3   | 1.31          |
| 2006 | 6,446.2           | 277.2    | 1,386.3      | 120.2    | 125.1   | 4.08          |
| 2007 | 6,545.7           | 296.8    | 1,375.6      | 114.0    | 131.4   | 15.26         |
| Mean | 6,644.4           | 239.2    | 1,404.2      | 131.5    | 139.6   | 6.88          |
| SD   | 261.8             | 83.4     | 40.7         | 25.1     | 19.9    | 7.39          |
| CV   | 3.94              | 34.85    | 2.90         | 19.07    | 14.26   | 7.39          |
| 2005 | 6,941.2           | 143.6    | 1,450.8      | 160.2    | 162.3   | 1.31          |
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| Mean | 6,644.4           | 239.2    | 1,404.2      | 131.5    | 139.6   | 6.88          |
| SD   | 261.8             | 83.4     | 40.7         | 25.1     | 19.9    | 7.39          |
| CV   | 3.94              | 34.85    | 2.90         | 19.07    | 14.26   | 7.39          |

Note: CV = coefficient of variation; $ET_{o}$ = reference evapotranspiration; $I$ = annual irrigation water applied; NIR = net irrigation requirements; $P$ = total rainfall; $R_{f}$ = measured annual solar radiation; SD = standard deviation; $\epsilon$ = relative deviation between $I$ and NIR.
weekly based on actual climatic data measurements. Fig. 3 shows the cumulative values of the variables involved in the irrigation water balance ($ET_c$, $Pef$, NIR, and $I$) for the three years of study. For this reason, the irrigation water applied ($I$) in the full irrigation treatment matched fairly well the theoretical crop irrigation requirements (NIR), especially in the first two years. In the third year the water input was slightly greater than the irrigation needs. This bias between applied water and crop water requirements was due to the additional input of water provided by the unexpected high precipitations that occurred in the last period of that year as it is depicted in Fig. 3.

**Soil Water Distribution**

Fig. 4 shows the evolution of the soil moisture ($\theta_v$) in the 60% NIR treatments during the irrigation season measured by the two capacity probes installed (a) in the DI system and (b) in the SDI system during the first year of research.

These graphs show that the measured soil moisture responded to the irrigation cycles. The results were a rapid increase in moisture immediately after an irrigation event and a gradual decrease due to the redistribution of water in the soil, the absorption of water by the plant, and the loss of water from the soil by evaporation. As is depicted in Fig. 4(a), the soil moisture oscillations measured in the DI system were greater in the most superficial sensor (Probe 1). This was due to the closer proximity to the water emission point. Soil moisture increases immediately after an irrigation (up to 30% of volumetric water content) and decreases due to infiltration and the drying of the soil surface as a consequence of direct evaporation (until 10%). In the deepest probe (Probe 2), the observed soil moisture variations are considerably lower (ranging between 20 and 30% in most cases).

However, as is shown in Fig. 4(b), the soil moisture variations in the most superficial probe (Probe 1) were very small and the average soil water content was relatively low. This indicates that water flow upwards is significantly lower than the water flow downwards. This can be due to the force of gravity, whose effect is relatively greater than the matrix forces in the light textured soil of the experimental site. For this reason, in the SDI system, the wet bulb is formed in the interior of the soil and does not reach the soil surface as it does with surface drip irrigation. It can be concluded that the SDI system prevents evaporation water losses. The better soil moisture distribution near the tree active roots and the absence of evaporation losses could explain the experimentally observed higher productivity in this type of irrigation system.
### Olive Production and Water Use

Table 2 shows the olive and oil yield results. Values of the olive yield (kg/tree) and oil content (%) are shown in this table for all the experimental units during the three years of research.

The results of the multifactor analyses of variance are discussed in the following sections.

### Influence of the Irrigation Method and Amount of Irrigation Water on Olive Yield

Table 3 shows the multifactor analysis of variance results obtained for olive yield and Fig. 5 depicts the least-squares means for olive yields and the 95% confidence intervals obtained for the three years of study for both irrigation methods and irrigation water applied.

#### Table 2. Olive and Oil Yield Data for All the Experimental Units

| Irrigation system | Water supply (%NIR) | Year | Yield (kg/tree) | Oil content (%) |
|-------------------|---------------------|------|-----------------|-----------------|
| SDI system        | 100                 | 2005 | 23.00           | 31.29           |
|                   | T1R1                |      | 23.00           | 27.46           |
|                   | T1R2                |      | 21.70           | 29.05           |
|                   | T1R3                |      | 24.00           | 29.65           |
|                   | 80                  |      | 20.30           | 29.95           |
|                   | T2R1                |      | 17.30           | 30.74           |
|                   | T2R2                |      | 17.00           | 26.18           |
|                   | T2R3                |      | 15.00           | 28.39           |
|                   | 60                  |      | 17.00           | 29.72           |
|                   | T3R1                |      | 23.70           | 25.73           |
|                   | T3R2                |      | 18.00           | 29.37           |
|                   | T3R3                |      | 13.30           | 29.55           |
|                   | 80                  |      | 18.30           | 30.10           |
|                   | T5R1                |      | 17.00           | 26.89           |
|                   | T5R2                |      | 15.00           | 28.39           |
|                   | T5R3                |      | 15.00           | 28.39           |
|                   | 60                  |      | 16.00           | 28.35           |
|                   | T6R1                |      | 17.00           | 26.18           |
|                   | T6R2                |      | 15.00           | 28.39           |
|                   | T6R3                |      | 15.00           | 30.05           |
| DI system         | 100                 | 2005 | 23.70           | 25.73           |
|                   | T4R1                |      | 23.00           | 28.25           |
|                   | T4R2                |      | 18.00           | 29.37           |
|                   | T4R3                |      | 13.30           | 29.55           |
|                   | 80                  |      | 18.30           | 30.10           |
|                   | T5R1                |      | 17.00           | 26.18           |
|                   | T5R2                |      | 15.00           | 28.39           |
|                   | T5R3                |      | 15.00           | 28.39           |
|                   | 60                  |      | 16.00           | 28.35           |
|                   | T6R1                |      | 17.00           | 26.18           |
|                   | T6R2                |      | 15.00           | 28.39           |
|                   | T6R3                |      | 15.00           | 30.05           |

#### Table 3. Analysis of Variance for Olive Yield

| Year | Source | Sum of squares | Df | Mean square | F-ratio | P-value |
|------|--------|----------------|----|-------------|---------|---------|
| 2005 | Main effects A: irrigation system | 16.63 | 1 | 16.63 | 2.03 | 0.1793 |
|      | B: water supply | 73.47 | 2 | 36.74 | 4.49 | 0.0349 |
|      | Interactions | | | | | |
|      | AB | 12.05 | 2 | 6.02 | 0.74 | 0.4990 |
|      | Residual | 98.08 | 12 | 8.17 | | |
|      | Total | 200.23 | 17 | | | |
| 2006 | Main effects A: irrigation system | 47.44 | 1 | 47.44 | 20.69 | 0.0007 |
|      | B: water supply | 32.32 | 2 | 16.16 | 7.05 | 0.0094 |
|      | Interactions | | | | | |
|      | AB | 6.07 | 2 | 3.04 | 1.32 | 0.3023 |
|      | Residual | 27.51 | 12 | 2.29 | | |
|      | Total | 113.34 | 17 | | | |
| 2007 | Main effects A: irrigation system | 4.60056 | 1 | 4.60056 | 0.35 | 0.5640 |
|      | B: water supply | 47.2933 | 2 | 23.6467 | 1.81 | 0.2058 |
|      | Interactions | | | | | |
|      | AB | 3.20444 | 2 | 1.60222 | 0.12 | 0.8857 |
|      | Residual | 156.867 | 12 | 13.0722 | | |
|      | Total | 211.965 | 17 | | | |

Note: Df = degree of freedom; P-value = significance.
depth applied was statistically significant for the first two years of study but not for the third.

Again, two homogeneous groups can be observed. Oil yield was very similar for the control and 80% NR treatments (approximately 5.9 and 6.4 kg/tree in the first and second year, respectively), while the oil yield dropped to 4.6 and 5.7 kg/tree in the more restrictive treatment (reductions of 22 and 11%, respectively). In the third year the oil yield reduction for the 60% treatment was 18% with respect to the control treatment (3.56 kg/tree), although in that year the oil yield in the 80% treatment was abnormally low.

Regarding the irrigation method, the SDI system produced greater olive-oil yield every year, although the differences were not statistically significant. The increases in oil yield with respect to the SDI were 12, 6, and 7% for the three years of study, respectively. The increases in oil yield were always lower than the increases in olive yield. This is due to the inverse relationship between the olive yield and the oil content observed in this research and in previous works (Lavee and Wodner 2004). Several factors contribute to this inverse relationship. Among them, the maturity of the fruits, which is usually more advanced for low yields, and the mesocarp/endocarp (pulp/pit) ratio, which is also greater for low yields due to the greater size of the fruits.

The results of this experiment show that the use of the SDI system with a uniform cutoff of 20% of the calculated NIR seems to be a good strategy to save water and achieve an appropriate productive level.

### Influence of the Irrigation Method and Water Amount

#### of Water on the Irrigation Water Use Efficiency

Table 4 shows the result of the multifactor analysis of variance obtained for WUE<sub>f</sub>, and Fig. 6 depicts the mean values of the WUE<sub>f</sub> and the 95% confidence intervals as a function of the irrigation method and irrigation water amount for the three years of study.

The results of the analysis show that the irrigation water amount was a statistically significant variable in the first two years but not in the third year, although there were clear differences. There is an inverse relationship between the irrigation water amount and the irrigation water use efficiency.

The maximum olive productivity ratio was obtained in the second year (7.3 kg of olives/m<sup>3</sup>). The values of this index were lower in the first and third year (4.2 and 3.1 kg/m<sup>3</sup>, respectively). This was due to the higher yield in the second year and the higher precipitation that diminished the irrigation needs. Similar WUE<sub>f</sub> values can be derived from the data obtained by Moriana et al. (2003) in an experimental essay carried out in a 6 × 6 m<sup>2</sup> mature

### Table 4. Analysis of Variance for WUE<sub>f</sub>

| Year | Source                      | Sum of squares | Df  | Mean square | F-ratio | P-value |
|------|-----------------------------|----------------|-----|-------------|---------|---------|
| 2005 | Main effects                |                |     |             |         |         |
|      | A: irrigation system        | 0.64           | 1   | 0.64        | 1.98    | 0.1846  |
|      | B: water supply             | 3.89           | 2   | 1.95        | 6.01    | 0.0156  |
|      | Interactions                |                |     |             |         |         |
|      | AB                          | 0.30           | 2   | 0.15        | 0.46    | 0.6446  |
|      | Residual                    | 3.89           | 12  | 0.32        |         |         |
|      | Total                       | 8.72           | 17  |             |         |         |
| 2006 | Main effects                |                |     |             |         |         |
|      | A: irrigation system        | 3.64           | 1   | 3.64        | 13.29   | 0.0034  |
|      | B: water supply             | 24.09          | 2   | 12.04       | 44.00   | 0.0000  |
|      | Interactions                |                |     |             |         |         |
|      | AB                          | 0.09           | 2   | 0.05        | 0.17    | 0.8481  |
|      | Residual                    | 3.28           | 12  | 0.27        |         |         |
|      | Total                       | 31.10          | 17  |             |         |         |
| 2007 | Main effects                |                |     |             |         |         |
|      | A: irrigation system        | 0.29           | 1   | 0.29        | 0.26    | 0.6209  |
|      | B: water supply             | 8.21           | 2   | 4.11        | 3.66    | 0.0573  |
|      | Interactions                |                |     |             |         |         |
|      | AB                          | 0.22           | 2   | 0.11        | 0.10    | 0.9055  |
|      | Residual                    | 13.43          | 12  | 1.12        |         |         |
|      | Total                       | 22.17          | 17  |             |         |         |

Note: Df = degree of freedom; P-value = significance.
olive orchard in the province of Córdoba, Spain. From their biennial yields and irrigation water applied data, \( WUE_F \) values can be calculated for two consecutive biennial periods (1997–1998 and 1998–1999). \( WUE_F \) values ranging from 2.4 kg of olives/m³ (for a 100% ET, irrigation treatment) to 7.6 kg of olives/m³ (for a 75% ET, irrigation treatment) can be obtained for the first biennial period. However, it must be taken into account that precipitation was much higher than that occurred in the experiment presented in this paper. \( WUE_F \) were significantly lower for the second biennial period. Lower average \( WUE_F \) values have been reported for low-density olive orchards in Portugal (Ramos and Santos 2010).

The irrigation method also had a relevant influence on the irrigation water use. This influence was only statistically significant in the second year. The efficiency of the irrigation water use was higher with the SDI system than with the DI system, especially in the second year. In that year the productivity values were 7.75 kg/m³ in the SDI system versus 6.85 kg/m³ in the DI system. This corresponds to a percentage increase in productivity of 13.1% with the SDI system with respect to the DI system. No significant interactions were found between the irrigation system and the amount of water applied.

The inverse value of the water use efficiency represents the amount of water applied per unit of product yield. The calculated values of this variable indicate that 0.247, 0.146, and 0.337 m³ of water were needed to produce one kilogram of olives in the three years of study respectively, with the DI system, while only 0.226, 0.129, and 0.31 m³ of water were used with the SDI system. This means that water savings of 0.021 m³ (8.5%), 0.017 m³ (11.6%), and 0.027 m³ (8%) were achieved with the new SDI system. These water savings were even larger for the full irrigation (100% NIR) treatment in which the water savings reached approximately 20%.

Similar results were found when the \( WUE_o \) was considered. The most significant factor affecting the irrigation water use efficiency was the amount of irrigation water. A statistically significant relationship was found in the first two years of study. The irrigation method also has a relevant influence on the irrigation water use (\( WUE_o \)), although this relationship was not statistically significant. The SDI system was more efficient in the irrigation water use than the DI system for any irrigation water amount or year of study.

Conclusions

A field experiment was conducted to assess the performance of an alternative subsurface drip irrigation method (SDI system) and to compare it to a surface drip irrigation method (DI system). It was experimentally observed that the olive and oil yields were always higher with the SDI system than with the DI system for any year and irrigation amount. These differences were statistically significant in one out of the three years of study.

It has been also tested that the SDI system has improved the irrigation water use efficiency in comparison with a traditional DI system. The SDI system provided relevant yield increases for the same irrigation water use. In this experimental research, water savings up to 20% have been achieved with this new irrigation method.

The increase in yield and water savings experimentally observed in the SDI system could be due to the absence of water losses caused by evaporation from the soil and the better water redistribution in the wet bulb.

The irrigation water amount has proved to be a very significant factor affecting crop yield, in terms of both olives and oil. The 100% NIR and 80% NIR treatments provided very similar results. However, in the most restrictive treatment (60% NIR) the yield was significantly reduced.

The results found in this work seem to indicate that the use of the new SDI systems together with the application of controlled...
deficit irrigations (about 80% NIR) could be a recommendable option to save water in areas where water resources are particularly scarce without compromising the crop yield.

The new proposed irrigation method has many advantages and is easy to install. For this reason, its expansion could contribute to relevant water savings in areas where water is especially scarce.

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Notation

The following symbols are used in this paper:

\[ \text{ET}_\text{o} = \text{crop evapotranspiration}; \]
\[ \text{ET}_\text{o} = \text{reference evapotranspiration}; \]
\[ I = \text{annual irrigation water applied}; \]
\[ K_r = \text{crop coefficient}; \]
\[ K_r = \text{ground cover reduction coefficient}; \]
\[ \text{NIR} = \text{net irrigation requirements}; \]
\[ P = \text{precipitation}; \]
\[ P_{\text{ef}} = \text{effective precipitation}; \]
\[ R_s = \text{annual solar radiation}; \]
\[ US = \text{statistical uniformity}; \]
\[ \text{WUE}_\text{f} = \text{ratio between the olive yield and the amount of water used}; \]
\[ \text{WUE}_\text{f} = \text{ratio between the oil yield and the amount of water used}; \]
\[ \varepsilon = \text{relative deviation between the irrigation water applied} I \text{ and the net irrigation requirements} \text{NIR}; \]
\[ \theta_e = \text{volumetric soil moisture}. \]

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