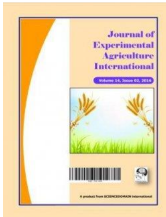


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# Irrigation Scheduling Optimisation in Olive Groves

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***Authors' contributions***

*This work was carried out in collaboration between both authors.*

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## ABSTRACT

**Introduction:** The diffusion of irrigation in olive orchards requires accurate scheduling of the application of water.
**Objectives:** To evaluate the efficiency of different modes of irrigation scheduling for mature olive trees grown at different plant densities and in different soil types and irrigated under different systems and strategies.
**Methodology:** We compare the irrigation scheduling with variable quantities and intervals (OPT), optimised by the water balance-evapotranspiration method (WB-ET) by evaluating the use of variable quantities and different fixed intervals (3, 7, 14 and 28 days) as well as a fixed interval and quantity (FIX). These scheduling scenarios were applied to high-density and super-high density groves in medium to fine textured and moderately coarse to medium textured soils irrigated by sprinkler, microjets and drip irrigation systems under full and deficit (sustained, SDI and regulated, RDI) irrigation strategies in a Mediterranean environment (Calabria Region, Italy). Three sets of measured meteorological data (2016, 2017 and the mean values of the 2001-2017) were used for simulations.
**Results:** OPT scheduling showed maximum efficiency. Three-day and weekly intervals show acceptable performance in terms of efficiency as well as water and energy requirements, whereas

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FIX scheduling shows very low efficiency. SDI and RDI permit mean savings of approximately 36%-54% of water and energy compared to full irrigation. High-density orchards drip irrigated under the SDI strategy show minimum water and energy requirements.

**Conclusions:** The traditional irrigation strategy at fixed quantity and interval is not adequate to achieve high efficiency in the irrigation of olive orchards, from both the agronomic (reduction of crop water stress) and economic (reduction of water and energy requirements) point of view. The optimisation of the irrigation scheduling requires the estimate of the water quantity to deliver in each irrigation in both the irrigation management at variable and fixed interval. The WB-ET model is an efficient and (relatively) simple tool to foresee the quantities and the dates of irrigation during the irrigation season.

*Keywords: Energy irrigation requirements; evapotranspiration; irrigation efficiency; irrigation scheduling; olive orchards; water balance.*

## 1. INTRODUCTION

Olive trees are among the most important and common plants in the Mediterranean basin. Although this species (*Olea europaea* L.) has been traditionally cultivated under rainfall conditions, irrigation also plays an important role, especially in soils with limited water storage to stabilise yields in years of low rainfall [1,2,3,4,5]. In particular, irrigation is needed in new orchards planted at very high densities (1000-2000 trees/ha) [3,6].

However, olive-growing areas are often located in arid or semi-arid regions where water reservoirs are already highly exploited and the development of new water resources is not economically or environmentally viable [7,8]. Improving irrigation efficiency and applying deficit irrigation are the main strategies to save water.

Due to the reduction of soil evaporation and deep losses, localised irrigation systems are potentially able to achieve high efficiencies [9,10,11].

Deficit irrigation strategies (DI), such as the application of irrigation in quantities below total crop evapotranspiration ($ET_c$), are potentially able to improve efficiency and maximise profits in several crops [12]. The literature describes a variety of DI strategies [13,14]. Experiments examining two main strategies have been conducted in olive groves: regulated deficit irrigation (RDI) and sustained deficit irrigation (SDI) [6,14,15,16,17,18]. Under RDI, quantities of water close to $ET_c$ are applied at the phenological stages most sensitive to water stress, while irrigation is reduced, or even interrupted, for the rest of the growing season. Under SDI, a deficit is applied throughout the season. Recent evidence has shown that the qualitative characteristics of olives and the profitability of super high density (SHD) olive orchards can be optimised using DI strategies [3,19,20,21,22].

However, the adoption of localised systems together with DI is not a guarantee of success. Only well-designed and well-managed irrigation systems can ensure high efficiency [10,11,23]. In particular, in irrigation management, significant improvements can be achieved through the proper scheduling of irrigation [8,24].

The most common definition of irrigation scheduling simply involves two questions: when and how much to irrigate a crop [25,26]. The four main methods informing an appropriate irrigation schedule rely on evapotranspiration (ET) and water balance (ET-WB), soil tension or soil moisture along the rooting depth, measurements of plant stress, and simulation models [27,28,29].

Although there is a wide body of literature on scientific irrigation scheduling in reference works, journal articles, symposium proceedings and extension publications, irrigators generally do not adopt effective methods [8,25,27,30]. Due to the need for substantial investments in management capacity as well as in improving or replacing irrigation systems, the majority of growers worldwide still manage irrigation applications based on rigid calendars determined by external factors [26,31]. There is a difference in the approach to irrigation scheduling between farmers and scientists. Scientists depict irrigation scheduling as an accurate process, with the timing of irrigation being defined as a precise date or time, while from a practical point of view, irrigation scheduling sometimes needs to be adjusted in association with many other farm activities and based on constraints [32]. Furthermore, in olive orchards, water irrigation doses and frequencies seem to influence the development of *Verticillium* wilt [33,34]. Despite a significant lack of information about the influence of irrigation management on the diffusion of this disease [35], low frequency irrigation is recommended [3].

The types of irrigation that are scheduling-applicable in practice are as follows: i. irrigation with variable intervals and quantities of water; ii. irrigation with a fixed interval and variable quantities of water; and iii. irrigation with a fixed interval and a fixed quantity of water. The first type requires that water is available upon demand in terms of both quantities and intervals. Scheduling with a fixed interval and variable quantities requires that water is available upon demand for quantities but not for interval, which can simplify irrigation management. Most farmers prefer the third method because it is easy to manage. Furthermore, this method is the most common in areas supplied with collective irrigation systems.

The objective of the present work is to evaluate the efficiency of different modes of irrigation scheduling for mature olive trees grown at different plant densities and in different soil types and irrigated under different systems and strategies. The study mainly uses data from an important Mediterranean area for oil production, the Calabria Region in Italy, but also analyses other conditions that are not widespread in the area to allow the results to be generalised for the Mediterranean environment. The general aim of the study is to enable producers to apply appropriate irrigation practices to olive, a crop with a relatively recent history of irrigation.

## 2. MATERIALS AND METHODS

### 2.1 Data Used for Simulations

Different combinations of meteorological data, growing systems, soil types, and irrigation strategies and systems were considered to test the efficiency of irrigation scheduling.

The following cases were considered (Table 1):

Three sets of meteorological data: for 2016, 2017, and the mean values of the 2001-2017 period;

Two growing systems: high density (HD) and super-high-density (SHD) groves;

Two soil types: medium to fine texture (sandy clay loam, loam, silty loam, clay loam to silty clay loam), with a high water-holding capacity (Fsoil); and moderately coarse to medium texture (sandy loam to fine sandy loam, sandy clay loam, loam, silty loam), with an intermediate water-holding capacity (Msoil);

Three types of irrigation strategies: full irrigation (100% $ET_c$, Full); RDI 50% $ET_c$, with the deficit concentrated in the summer period, from pit hardening until the end of the summer [9,11]; and SDI 50% $ET_c$, with the deficit distributed evenly throughout the irrigation season;

Three types of irrigation system; a sprinkler system (SIS), localised irrigation with microjets (MIS) and localised irrigation with drippers (DIS).

The meteorological, soil and crop data came from an Italian area of particular importance for oil production. The area considered is located in Lametia in the Calabria region. Calabria is the second largest producer of olive oil in Italy, accounting for almost one-third of national production [36]. The characteristics of the irrigation systems considered in this study are standard for well-designed and well-managed irrigation systems for cultivated olives [9,11]. The SHD growing system, the SDI and the RDI irrigation strategies, and the sprinkler irrigation system were added to the simulation to allow the results of this study to be generalised, despite not being widespread in the study area. For the same reason, the simulations were replicated for the three series of meteorological data.

### 2.2 Estimation of Irrigation Requirements

Irrigation requirements were estimated using a daily soil water balance model (WB), implemented in a spreadsheet, specifically developed during this study. In the WB method, an estimate of evapotranspiration (ET) coupled with the WB equation enables the calculation of the soil water deficit, which is then compared with the readily available water in the soil (RAW). When water depletion exceeds RAW, an irrigation event returns the soil water content (θ) to field capacity ($\theta_{FC}$).

The water balance ET based method (WB-ET) is a well-established, simple, robust method [37] with a long history [38]. For this reason, we describe only the main concepts and the specific assumptions applied in this study.

According to Allen et al. [38], the equation for daily soil WB is as follows:

$$D_{r,i} = D_{r,i-1} - (P - RO)_i - I_{net,i} - CR_i + ET_{c,i} + DP_i \quad (1)$$

where D (mm) is the depletion of water from the root zone; i is the current day; i − 1 is the previous day; P (mm) is daily precipitation; RO (mm) is the runoff; $I_{net}$ (mm) is the net irrigation depth; CR (mm) is the capillary rise from the groundwater table; $ET_c$ (mm) is the crop evapotranspiration; and DP (mm) is the deep percolation.

Considering the conditions inherent to the crop and the area examined and the objective of the study, we assumed the following:

The quantity of rainfall stored in the root zone $(P-RO-DP)_i$ can be represented by the effective rainfall, $P_e$ (mm); for the estimation of $P_e$, $P \leq 0.3$ mm was ignored, while RO was considered negligible, and DP was considered negligible when the soil water content in the root zone was below $\theta_{FC}$ and was considered equal to $P-\theta_{FC}$ when the soil water content was higher than $\theta_{FC}$;

CR was considered negligible (the depth of the water table is greater than 5 m);

$ET_c$ was calculated as follows:

$$ET_c = ET_0 \times K_c \quad (2)$$

where $ET_0$ is the reference evapotranspiration estimated according to the FAO Penman-Montieth equation, and $K_c$ is the crop coefficient [38];

Two other coefficients, a coefficient of localisation ($K_l$) and a stress coefficient ($K_s$), were used to adjust equation (2) for localised irrigation systems and deficit irrigation strategies, respectively; equation (2) was therefore modified as follows:

$$ET_c = ET_0 \times K_c \times K_l \times K_s \quad (2a)$$

The value used for $K_c$ was 0.65 until the end of May and 0.55 from June onward [3].

The coefficient of localisation $K_l$ was estimated as [9]:

$$K_l = P_c/100 + 0.5*(1 - P_c/100) \quad (3)$$

where $P_c$= mean ground coverage by canopy (%) measured in the field.

The values for the stress coefficients ($K_s$) (see Table 1) where established according to the irrigation strategy simulated (full irrigation, RDI and SDI).

RO for irrigation water was considered negligible, and DP was accounted for by the potential irrigation system efficiency (PAE, % [42]); $I_{net}$ was therefore replaced by $I_{gross}$, which was estimated as $I_{net}$/(PAE/100).

These assumptions simplify equation (1) as follows:

$$D_{r,i} = D_{r,i-1} - Pe_i - I_{gross} + ET_{c,i} \quad (1a)$$

The total available water (TAW) is the quantity of water stored in the root zone that a plant can utilise and is calculated as follows [38]:

$$TAW = (\theta_{FC} - \theta_{PWP}) \times Z \quad (4)$$

Where $\theta_{FC}$ is the field capacity (mm/m); $\theta_{PWP}$ is the permanent wilting point (mm/m); and Z is the root zone depth (m).

To prevent permanent physiological damage to the crop, irrigation is usually applied before the soil water content is equal to $\theta_{PWP}$. The fraction of TAW that a crop can extract without suffering water stress is the readily available soil water (RAW)

$$RAW = p \ x \ TAW \ x \ \frac{S_w}{100} \quad (5)$$

where p is the average fraction of TAW that is depleted before moisture stress and is equal to 0.65 for olives [38]; and $S_w$ is the wetted surface area (%), which was equal to 100% in SIS and was below 100% for the localised systems (MIS and DIS).

Table 1 shows the values used in this study for PAE, $\theta_{FC}$, $\theta_{PWP}$, Z and Sw.

The hydrological characteristics of the soils were estimated by pedotransfer functions based on sand, silt, clay and organic carbon soil contents and on bulk density using the software SOILPAR 2.00 [39]. The Calabria soil map [40] was overlapped to the land use map [41] by a GIS to identify the soil types, and their physical-chemical characteristics, in the areas cultivated with the crop of interest in the agricultural areas observed.

**Table 1. Variables used in the simulations for the different types of soil, growing systems (plant density), irrigation systems and irrigation strategies**

| | **Soil type** | **Field capacity ($\theta_{FC}$, mm/m)** | **Permanent wilting point ($\theta_{PWP}$, mm/m)** | **Readly available water (RAW, mm/m)** | **Wetted width[1] (m)** |
|---|---|---|---|---|---|
| 1 | Medium to fine texture, high water holding capacity (Fsoil) | 300 | 170 | 84 | 0.8 |
| 2 | Moderately coarse to medium texture, medium water holding capacity (Msoil) | 200 | 100 | 65 | 0.6 |

| | **Plant density** | **Plant age (years)** | **Root depth (Z, m)** | **Plant spacing in the row (m)** | **Row spacing (m)** | **Ground coverage by canopy (%)** |
|---|---|---|---|---|---|---|
| 1 | High density (HD) (286 trees/ha)[3] | 15 | 0.8 | 5 | 7 | 45 |
| 2 | Super high density (SHD) (1667 trees/ha) [3] | 4 | 0.6 | 1.5 | 4 | 82 |

| | **Irrigation system** | **Mean number of emission point per plant** | | **Wetted surface ($S_w$, %)** | | **Emitter characteristics** | |
|---|---|---|---|---|---|---|---|
| | | HD | SHD | HD | SHD | mean discharge (L/h) | working pressur head (kPa) |
| 1 | Sprinkle (SIS) (PAE[2]= 80% [9, 39] | 0.25 | 0.06 | 100 | 100 | 1080 | 300 |
| 2 | Microjets (single lateral system) (MIS)(PAE(2)= 85%)[9,39] | | | | | | |
| | Fsoil | 1 | 1 | 32.4 | 100 | 75 | 150 |
| | Msoil | 1 | 1 | 29.1 | 88.5 | 75 | 150 |
| 3 | Drip (double lateral system) (DIS)(PAE(2)= 90%)[9,39] | | | | | | |
| | Fsoil | 7.7 | 2.3 | 22.1 | 36.7 | 4 | 100 |
| | Msoil | 10 | 3 | 16.2 | 28.3 | 4 | 100 |

| | **Irrigation strategy** | **Coefficient of stress $K_s$** | |
|---|---|---|---|
| | | until June, 30th | after June |
| 1 | Full irrigation, 100% $Et_c$ (Full) | 1 | 1 |
| 2 | Regulated deficit irrigation, with deficit (50% $Et_c$) concentrated in the summer period, from pit hardening until the end of the summer season (RDI) | 1 | 0.5 |
| 3 | Sustained deficit irrigation, 50% $ET_c$, with deficit distributed evenly throughout the whole irrigation season (SDI) | 0.5 | 0.5 |

*[1] diameter of the circular area wetted by a single emitter in drip systems. [2] PAE= potential irrigation system efficiency [9,39]*

Considering the Mediterranean climate, the WB-ET model was run from April 1st to October 31th.

## 2.3 Irrigation Scheduling

In this study, we define "optimal irrigation scheduling" as irrigation management that ensures that irrigation is applied at the time when RAW is depleted ($D_{r,i} \leq RAW$). This type of scheduling, which implies variable intervals and quantities of water, is "optimal" from both the agronomic (no water stress in the crop) and the hydrological (no water losses beyond that considered by PAE, due to deep percolation) points of view. In contrast, irrigation management at fixed intervals and variable water quantities or at fixed intervals and water quantities may not achieve high efficiency.

Six different types of irrigation scheduling were simulated in this study: (a) optimal irrigation scheduling (OPT), (b) irrigation at three days intervals and variable quantities (three days), (c) irrigation at weekly intervals and variable quantities (weekly), (d) irrigation at 14 days intervals and variable quantities (14 days), (e) irrigation at 28 days intervals and variable quantities (28 days) and (f) irrigation with a fixed interval and quantity (FIX).

Both the water quantity and irrigation dates for scheduling type (a) and only the quantity of water for cases (b) to (e) were established based on the WB-ET method.

For strategy (f), the fixed quantity of water was determined by using the RAW corrected by the irrigation system efficiency (PAE):

$$RAW_g = \frac{RAW}{PAE/100} \tag{5}$$

The fixed interval (F) was obtained as follows:

$$F = IS_{lm}/IrriN \tag{6}$$

$$IrriN = WR_s/RAW_g \tag{7}$$

where F is the fixed irrigation interval (days); $IS_l$ is the irrigation season length, which is defined as the total number of days between the first and last irrigation event in a year (days); IrriN is the total number of irrigation events in the season; $WR_s$ is the gross seasonal water requirement (mm); and $RAW_g$ is the gross readily available water (mm).

$IS_{lm}$ was fixed at approximately 110 days because the farmers, in the area examined, generally irrigate their olive orchards from mid-June to September. $WR_s$ was calculated based on the mean values of $ET_0$ and P estimated from the climatic data measured by a meteorological station located near the study area over the period from 1925-2017. The values calculated for $WR_s$ were 241, 227 and 215 mm for SIS, MIS and DIS, respectively.

Approximately 650 simulations, derived from the combination of the numbers of scheduling modes, growing systems, soil types, irrigation strategies, irrigation systems and meteorological datasets, were therefore performed and analysed.

## 2.4 Irrigation Management Efficiency

To determine the efficiency of water application, the results of the simulations for 3, 7, 14 and 28 days intervals and FIX irrigation scheduling were compared to those for OPT scheduling. With this aim, in addition to the gross irrigation ($I_{gross}$, mm), the total number of irrigation events (IrriN) applied over the irrigation season and the irrigation season length ($IS_l$, days), the following indices were calculated and are discussed:

Total energy applied;
Irrigation adequacy;
Scheduling efficiency.

The total energy applied was estimated as follows:

$$Ener = \frac{Q\ x\ H}{E_p x\ 102}\ x\ I_d \tag{8}$$

where Ener is the total energy applied (kWh/ha); Q is the system discharge (L/s); H is the total operating head (m); $E_p$ is the engine pump efficiency (decimal); 102 is the conversion constant; and $I_d$ is the total time of irrigation in the irrigation season (h/ha).

The irrigation adequacy (IA) quantifies the ability of irrigation management to supply sufficient irrigation to meet plant water demands without stress [43, 44]. We distinguished two types of stress: light stress, which occurs when the soil moisture content is lower than RAW but higher than $\theta_{PWP}$, and severe stress, which occurs when the soil moisture content is below $\theta_{PWP}$.

Three indices were used to evaluate IA:

$$IA_1 = \frac{(IS_l - DS_T)}{IS_l} x100 \quad (9)$$

$$IA_2 = \frac{(IS_l - DS_S)}{IS_l} x100 \quad (10)$$

$$IA_3 = \frac{(IS_l - DS_e)}{IS_l} x100 \quad (11)$$

where $IA_1$ (%) represents the days of the irrigation season without any stress (both light and severe) in fully irrigated plants; $IA_2$ (%) represents the days of the irrigation season without severe stress in fully irrigated plants; $IA_3$ (%) represents the days of the irrigation season without extra stress beyond that specified in the deficit irrigation strategy (RDI or SDI); $IS_l$ (days) is the length of the irrigation season; $DS_T$ (days) is the total number of crop stress days (sum of light and severe stress days); $DS_S$ is the number of severe crop stress days; and $DS_e$ is the number of stress days beyond those due to the deficit irrigation strategy (RDI or SDI).

The scheduling efficiency (SchE) is defined as the ability of a management method to achieve irrigation without drainage or runoff (similar to the SWAT procedure described by [43]). The SchE index represents the percentage of the total gross irrigation retained in the root zone and is calculated in the irrigation season with the following equation:

$$SchE = \frac{(I_{gross} - Surplus)}{I_{gross}} x100 \quad (12)$$

where SchE (%) is the scheduling efficiency index; $I_{gross}$ (mm) is the sum of gross irrigation applied over the irrigation season; and Surplus (mm) is the depth of water above the field capacity leading to deep percolation (runoff was assumed to be zero due to the effectively designed irrigation systems).

## 3. RESULTS AND DISCUSSION

### 3.1 Meteorological Characteristics

The maximum (Tmax) and minimum (Tmin) temperatures during the period from April 1st to October 31st were approximately 25°C and 17°C, respectively (mean of the three datasets). Tmax and Tmin showed higher values in 2017 (37.5°C) and for the mean period (approximately 10°C), respectively, while lower values were observed in 2016 for Tmax (14.6°C) and in 2017 for Tmin (2.8°C) (Figures 1 a, b, c). Tmin showed higher variability than Tmax, with coefficients of variation (CV) of 22, 29 and 20% for the 2016, 2017 and 2001-2017 datasets, respectively. The corresponding values of CV for Tmax were 14, 17 and 14%.

Precipitation was the most variable characteristic, with total precipitation of 457, 193 and 325 mm being observed for the 2016, 2017 and 2001-2017 datasets, respectively. Exceptionally high daily precipitation (61.7 mm) was recorded in 2016 (Fig. 1a).

The daily mean values of $ET_0$ ranged from 3.50 mm (in 2001-2017 dataset) to 4.56 mm (in 2016); the corresponding values of accumulated $ET_0$ from April to October were 750 mm (2001-2017) and 956 mm (2016). As expected for the environment examined [45], the average values (2001-2017) showed an upward trend of $ET_0$ up to July and then a decreasing trend. Between the two individual years considered, 2016 exhibited a normal trend of $ET_0$, while in 2017, peaks of $ET_0$ were recorded in the second half of June.

### 3.2 Optimal Irrigation Scheduling

The gross irrigation applied over the irrigation season ($I_{gross}$) ranged between 279 and 550 mm for full irrigation and was 191-401 and 118-256 mm for the RDI and SDI deficit strategies, respectively (Table 2). CV between the different hypothesised conditions was approximately 20% for the full irrigation, RDI and SDI strategies (Table 2). The total energy applied over the irrigation season varied between 182 and 959 kWh/ha for full irrigation (Table 2). The energy savings assured by the deficit strategies were of the same order of magnitude described for $I_{gross}$ (40% for RDI, 113% for SDI, and 53% for SDI with respect to RDI). The coefficient of variation of approximately 50% is higher than $I_{gross}$ due to the influence of the irrigation duration and the number of irrigation events in the season (IrriN) on energy consumption.

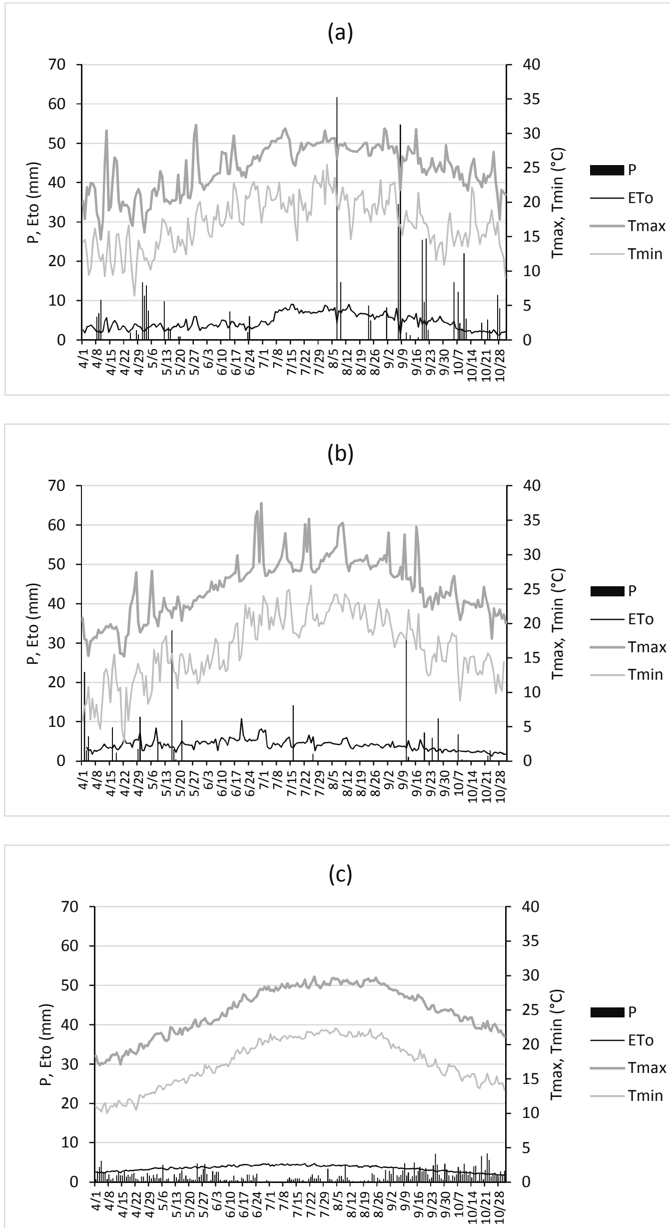



**Fig. 1. Meteorological characteristics of the S. Eufemia Lametia (Calabria, Italy) station (a=2016; b= 2017; c= mean 2001-2017) (P= precipitation; ETo= reference evapotranspiration; Tmax= maximum temperature; Tmin= minimum temperature)**

Due to the different irrigation systems considered, the total number of irrigation events in the irrigation season (IrriN) is the most variable parameter (CV of approximately 60%). On average, IrriN ranged from 11 to 24 irrigation events for drip systems (DIS), from 6 to 13 for microjet systems (MIS), and from 3 to 7 for sprinkler systems (SIS) (Table 2). Among the different irrigation strategies, the lowest values corresponded to SDI, followed by RDI, and the highest corresponded to full irrigation.

The mean irrigation season length ($IS_l$) was 166, 152 and 127 days for the full, RDI and SDI systems, respectively (Table 2). The corresponding CV values were 10, 14 and 21% (Table 2).

The date of the first irrigation event varied from April 22nd to May 2nd for both full and RDI irrigation (under RDI, the deficit was applied starting in July) and from May 14th to May 29th for SDI (data not shown). Irrigation generally ended in September or October (data not shown).

Due to the different irrigation system efficiencies (PAE in Table 1), both $I_{gross}$ and Ener were, as expected, highest in SIS, followed by MIS, and they were lowest in DIS (Table 2). DIS required approximately 10% (1-18%) and 19% (9-40%) less water and 37% (30-42%) and 52% (43-66%) less energy on average than MIS and SIS, respectively.

On the other hand, the total number of irrigation events (IrriN) and the irrigation season length ($IS_l$) were greatest for DIS, followed by MIS and SIS. Due to the low percentage of wet surfaces that distinguish DIS (see Table 1), the differences between the different types of irrigation systems were high for IrriN (DIS required approximately 2.5 and 1.9 times the number of irrigation events in SIS and MIS, respectively). In contrast, $IS_l$ was less variable due to the influence of the less variable weather conditions. DIS required a 13-36% longer irrigation season (depending on the irrigation strategy considered) than SIS and a 4-9% longer season than MIS.

In this study, the WB-ET model was less sensitive to soil type, mainly in terms of the scheduling parameters $I_{gross}$, Ener and $IS_l$, i.e., for the same growing and irrigation system type, the differences between the two soil types considered were small (with a few exceptions; less than 10% for $I_{gross}$, Ener and $IS_l$, and less than 50% for IrriN).

With regard to the growing system, SHD olive orchards required more water and energy and a greater number of irrigation events than the HD systems (Table 2); e.g., under the same conditions, in Fsoil fully irrigated by DIS, $I_{gross}$, IrriN and Ener were approximately 30% higher in the SHD orchard compared to the HD orchard. These differences were mainly due to greater ground coverage by the canopy of the trees grown in SHD (systems (Table 1).

Neither the IA indices nor the SchE index is shown (Table 2) because they were always equal to 100%, due to the rules fixed in the WB-ET model, which specify that both the irrigation interval and the quantity of water are calculated to result in zero deep losses and zero days of plant stress.

## 3.3 Irrigation Management at Fixed Intervals and Variable Quantities

For this type of scheduling, SchE was always 100% (no deep percolation) due to the optimisation of quantities based on the WB-ET model, similar to OPT scheduling. Instead, IA depends on the length of the interval. For the 3 days interval, the IA indices are not shown (Table 3) because they were always 100% for all the cases simulated. In all the cases considered, the 3 days interval was therefore sufficient to supply irrigation without stress.

For the weekly interval, with only a few exceptions, $IA_1$, $IA_2$ and $IA_3$ were 100% for sprinkler system (SIS) and microjet system (MIS) (Table 3). For drip system (DIS), both $IA_1$ and $IA_2$ (referring to full irrigation) were less than 100% in most cases, mainly in Msoils and in the 2016 and 2017 datasets. Under these conditions (HD) groves in Msoils), the 2016 dataset showed the minimum values ($IA_1$ ranging from 65 to 79%, Table 3). For the same cases, stress was mostly of light type, with $IA_2$ being approximately 90% or higher (Table 3). This result indicates that the crop was under severe stress for only approximately 10% (=100-$IA_2$) of the irrigation season. For the deficit strategies, $IA_3$ was always 100% for RDI (any day of extra stress) and was always higher than 97% for SDI (Table 3).

For the 14 days interval, the IA indices were still 100% for the SIS cases. Under MIS, the crop experienced a certain degree of stress, mainly in HD groves with full irrigation in Msoil, whereas $IA_1$ sometimes exhibited values below 80% (Table 3). However, the percentage of days of severe stress generally did not exceed 10% ($IA_2$ $\cong$ 90%). In deficit conditions, some values of $IA_3$ were approximately equal to or lower than 90% (Table 3), leading to a certain incidence of extra stress days, mainly for RDI. This interval was sufficient only for olives under full irrigation by DIS for 36-78% of the irrigation season. For Msoils in particular, $IA_1$ was very low, reaching values below 50% in both HD and SHD groves (Table 3). For the same cases, $IA_2$ values ranging from 59 to 70% (Table 3) showed a high incidence of severe stress. In deficit conditions, it therefore seems reasonable to apply DIS irrigation with a 14-day interval under only the SDI strategy and in Fsoils ($IA_3$ of 94-100%, Table 3).

**Table 2. Parameters of irrigation for the optimised irrigation scheduling (Over the irrigation season)**

| Year | Growing system | Soil type | Irrigation system | Gross irrigation (mm) | | | Total number of irrigation | | | Total energy (kWh/ha) | | | Irrigation season length (days) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Full | RDI | SDI | Full | RDI | SDI | Full | RDI | SDI | Full | RDI | SDI |
| 2016 | HD | Fsoil | DIS | 358 | 227 | 155 | 20 | 13 | 9 | 234 | 148 | 101 | 158 | 142 | 115 |
| | | | MIS | 376 | 262 | 183 | 14 | 10 | 7 | 348 | 243 | 170 | 145 | 170 | 140 |
| | | | SIS | 431 | 256 | 170 | 5 | 3 | 2 | 752 | 447 | 296 | 136 | 91 | 58 |
| | | Msoil | DIS | 369 | 241 | 169 | 35 | 24 | 17 | 241 | 157 | 111 | 176 | 168 | 151 |
| | | | MIS | 400 | 261 | 183 | 21 | 14 | 10 | 370 | 241 | 169 | 178 | 159 | 141 |
| | | | SIS | 466 | 328 | 197 | 7 | 5 | 3 | 812 | 571 | 344 | 173 | 178 | 94 |
| | SHD | Fsoil | DIS | 471 | 320 | 203 | 20 | 14 | 9 | 308 | 209 | 133 | 173 | 182 | 122 |
| | | | MIS | 494 | 364 | 241 | 8 | 6 | 4 | 458 | 337 | 223 | 150 | 162 | 113 |
| | | | SIS | 525 | 387 | 256 | 8 | 6 | 4 | 915 | 674 | 446 | 150 | 162 | 113 |
| | | Msoil | DIS | 481 | 317 | 220 | 35 | 24 | 17 | 314 | 207 | 144 | 188 | 177 | 150 |
| | | | MIS | 505 | 331 | 251 | 12 | 8 | 6 | 468 | 307 | 232 | 161 | 144 | 136 |
| | | | SIS | 550 | 350 | 248 | 11 | 7 | 5 | 959 | 610 | 431 | 165 | 141 | 119 |
| 2017 | HD | Fsoil | DIS | 352 | 249 | 154 | 20 | 14 | 9 | 230 | 163 | 101 | 180 | 153 | 146 |
| | | | MIS | 375 | 265 | 157 | 14 | 10 | 6 | 347 | 246 | 146 | 173 | 143 | 121 |
| | | | SIS | 428 | 341 | 169 | 5 | 4 | 2 | 746 | 595 | 295 | 152 | 151 | 62 |
| | | Msoil | DIS | 355 | 263 | 162 | 34 | 25 | 16 | 232 | 172 | 106 | 184 | 178 | 166 |
| | | | MIS | 383 | 285 | 164 | 20 | 15 | 9 | 354 | 264 | 152 | 183 | 176 | 138 |
| | | | SIS | 395 | 327 | 197 | 6 | 5 | 3 | 689 | 571 | 343 | 138 | 145 | 106 |
| | SHD | Fsoil | DIS | 442 | 324 | 203 | 19 | 14 | 9 | 289 | 212 | 132 | 174 | 156 | 149 |
| | | | MIS | 486 | 362 | 241 | 8 | 6 | 4 | 450 | 335 | 223 | 162 | 137 | 137 |
| | | | SIS | 516 | 384 | 256 | 8 | 6 | 4 | 899 | 670 | 447 | 162 | 137 | 137 |
| | | Msoil | DIS | 453 | 339 | 207 | 33 | 25 | 16 | 296 | 222 | 135 | 185 | 180 | 160 |
| | | | MIS | 505 | 377 | 249 | 12 | 9 | 6 | 467 | 349 | 231 | 183 | 165 | 164 |
| | | | SIS | 504 | 401 | 248 | 10 | 8 | 5 | 878 | 699 | 432 | 158 | 161 | 137 |
| Mean 2001-2017 | HD | Fsoil | DIS | 279 | 191 | 119 | 16 | 11 | 7 | 182 | 125 | 78 | 170 | 138 | 133 |
| | | | MIS | 298 | 215 | 131 | 11 | 8 | 5 | 276 | 199 | 121 | 158 | 150 | 125 |
| | | | SIS | 342 | 256 | 169 | 4 | 3 | 2 | 595 | 447 | 295 | 127 | 107 | 79 |
| | | Msoil | DIS | 285 | 201 | 118 | 28 | 20 | 12 | 186 | 132 | 77 | 178 | 161 | 130 |
| | | | MIS | 298 | 225 | 127 | 16 | 12 | 7 | 276 | 208 | 117 | 161 | 171 | 116 |
| | | | SIS | 329 | 262 | 196 | 5 | 4 | 3 | 574 | 457 | 342 | 130 | 129 | 156 |
| | SHD | Fsoil | DIS | 347 | 250 | 156 | 15 | 11 | 7 | 227 | 163 | 102 | 156 | 138 | 127 |
| | | | MIS | 425 | 302 | 181 | 7 | 5 | 3 | 393 | 279 | 167 | 181 | 142 | 97 |
| | | | SIS | 452 | 320 | 192 | 7 | 5 | 3 | 787 | 558 | 334 | 181 | 142 | 97 |
| | | Msoil | DIS | 365 | 268 | 166 | 27 | 20 | 13 | 239 | 175 | 108 | 177 | 172 | 151 |
| | | | MIS | 417 | 290 | 204 | 10 | 7 | 5 | 386 | 269 | 189 | 183 | 137 | 153 |
| | | | SIS | 448 | 298 | 196 | 9 | 6 | 4 | 780 | 519 | 342 | 184 | 123 | 115 |
| Minimum | | | | 279 | 191 | 118 | 4 | 3 | 2 | 182 | 125 | 77 | 127 | 91 | 58 |
| Maximum | | | | 550 | 401 | 256 | 35 | 25 | 17 | 959 | 699 | 447 | 188 | 182 | 166 |
| Mean | | | | 414 | 295 | 190 | 15 | 11 | 7 | 471 | 338 | 217 | 166 | 152 | 127 |
| Standard deviation | | | | 74 | 56 | 40 | 9 | 7 | 4 | 244 | 180 | 116 | 17 | 21 | 26 |
| Coefficient of variation (%) | | | | 18 | 19 | 21 | 62 | 61 | 62 | 52 | 53 | 53 | 10 | 14 | 21 |

Full= full irrigation; RDI= regulated deficit irrigation; SDI= sustained deficit irrigation; HD= high density grove; SHD= super high density grove; Fsoil= fine to medium texture; Msoil= moderately coarse to medium texture; DIS= drip irrigation system; MIS= microjet irrigation system; SIS= sprinkle irrigation system.

For the 28 days interval, only irrigation by SIS in Fsoils resulted in high values (generally >90%) of the IA indices (Table 3). In Msoils, $IA_1$ was sometimes lower than 90%, mainly for SHD growth. In deficit conditions, $IA_3$ was generally approximately 100% for SDI and ranged between 88-100% for RDI; the minimum values were associated with SHD groves in Msoils under the RDI strategy ($IA_3$ = 77-88%, Table 3). For both the microirrigation systems (MIS and DIS), the percentage of stress days was generally higher than 50% ($IA_1$<50% in most cases, Table 3) for the full irrigation strategy. For DIS in particular, the percentage of severe stress days was also generally higher than 50% ($IA_2$ lower than or approximately equal to 50%, Table 3). For RDI, the percentage of stress days beyond those scheduled was higher than 50% ($IA_3$<50%) for DIS and ranged from 3-51% ($IA_3$=97-49%, Table 3) for MIS. With a few exceptions, $IA_3$ was generally >80% for the SDI strategy applied with MIS; in contrast, $IA_3$ values were always <80% for DIS.

Overall, the data illustrated above suggest when irrigation is carried out with long intervals (more than a week), the worst conditions in terms of water stress are associated with the full irrigation strategy, Msoils and localised irrigation systems, especially DIS. As expected, this effect depends on the low soil-holding capacity of Msoils and the low percentage of surfaces wetted by the emitters in DIS.

Although the IA and SchE for the 3-day and, under most conditions, weekly intervals were similar to those for OPT management, water and energy consumption should be different. Fig. 2 shows the ratios between $I_{gross}$ applied in 3-day and weekly intervals and the same variable under OPT scheduling ($I_{gross}$3-day/$I_{gross}$OPT or $I_{gross}$weekly/$I_{gross}$OPT). These relationships assume the same value for the total energy applied in the irrigation season (Ener). Compared to OPT scheduling, water and energy consumption was generally higher under the 3- and weekly interval management schemes (Fig. 2). However, the increases were less than 10% for both the microirrigation systems (DIS and MIS, Fig. 2) but were higher for sprinkling in most cases, mainly for the deficit strategies (RDI and SDI) in the year with the maximum water requirement (2016). In cases involving sprinkling with RDI or SDI in 2016, water and energy consumption could even be 30-48% higher than that under OPT scheduling (Fig. 2).

### 3.4 Irrigation Management with a Fixed Interval and Quantity

The water quantity and interval were lowest for the HD growing system in Msoil irrigated by DIS (9 mm and 5 days, respectively, Table 4), due to the lower values for RAW and the wetted surface (Table 1). For the opposite reasons, the water quantity and interval were greatest for Msoil and SIS , which showed the highest RAW and a wet surface area of 100%.

For this type of irrigation scheduling, IA was generally very poor (Table 5). Under full irrigation, the crops were stressed for almost the entire irrigation season, mainly under the 2017 meteorological conditions ($IA_1$=2-50%), when the percentage of severe stress days was also very high ($IA_2$ =63-85%, Table 5). The deficit SDI strategy and the drip irrigation system (DIS) resulted in the lowest incidence of stress days ($IA_3$ approximately equal or higher than 80%, Table 5). Intermediate values of $IA_3$ occurred under the RDI strategy (Table 5).

As expected, the fixed interval, which should be adequate during the initial and final parts of the irrigation season, generally resulted in a lower IA than the optimal value during the central part of the irrigation season, which is the period of maximum water requirement under the Mediterranean climate.

SchE was always 100% (any deep loss) under full irrigation and varied from 41 to 100% and 50 to 94% for RDI and SDI, respectively (Table 5). Under full irrigation, the fixed interval indeed always resulted higher than that optimised by the WB-ET method applied to the three meteorological datasets used in this study. Under deficit irrigation strategies, deep losses were high under drip systems (DIS) (SchE=41-92%, Table 5) due to the low percentage of wetted area, which did not permit the soil to retain the fixed quantity of irrigation.

### 3.5 Comparison between the Different Irrigation Scheduling Methods

The irrigation scheduling at variable quantities and intervals (OPT) resulted the most adequate and efficient (no water stress to the plants, no water losses by deep percolation over those due to distribution uniformity) because of the optimisation of both water quantities and intervals determined via the WB-ET method.

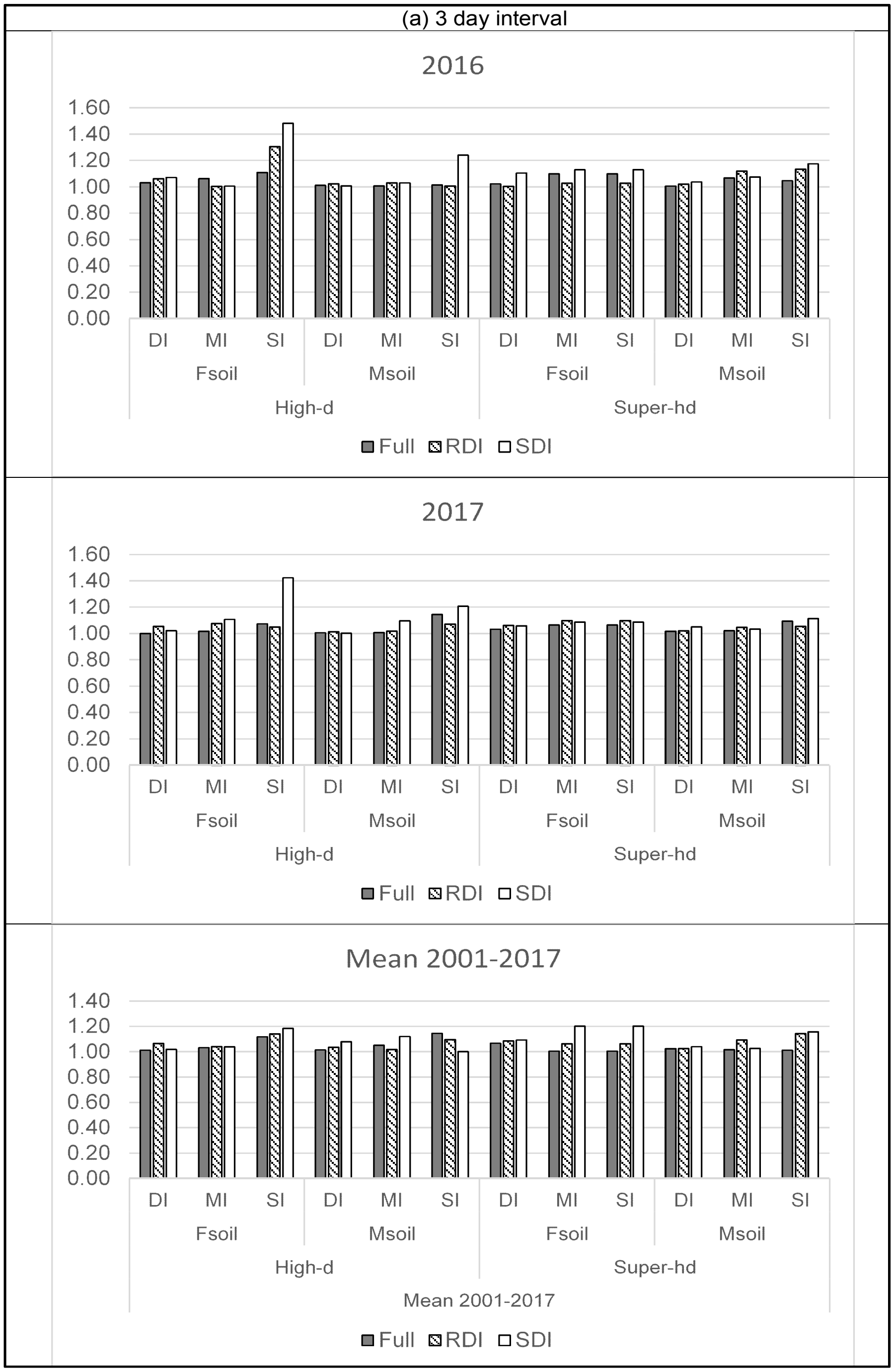
For this type of irrigation management, drip systems require less water and energy, allowing considerable savings of approximately 10% and 19%, respectively, of water and 37% and 52%, respectively, of energy compared to microjet and sprinkler systems.

**Table 3. Irrigation adequacy ($IA_1$, $IA_2$ and $IA_3$) for irrigation scheduling at variable quantities and weekly, 14-day and 28-day intervals. ($IA_1$ (%) represents the days of the irrigation season without any stress -both light and severe- in fully irrigated plants; $IA_2$ (%) represents the days of the irrigation season without severe stress in fully irrigated plants; $IA_3$ (%) represents the days of the irrigation season without extra stress beyond that specified in the deficit irrigation strategy RDI or SDI)**

| Year | Growing system | Soil type | Irrigation system | Weekly | | | | 14-days | | | | 28 days | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Full | | RDI | SDI | Full | | RDI | SDI | Full | | RDI | SDI |
| | | | | $IA_1$ | $IA_2$ | $IA_3$ | $IA_3$ | $IA_1$ | $IA_2$ | $IA_3$ | $IA_3$ | $IA_1$ | $IA_2$ | $IA_3$ | $IA_3$ |
| 2016 | HD | Fsoil | DIS | 95 | 100 | 100 | 100 | 63 | 86 | 86 | 94 | 30 | 49 | 53 | 61 |
| | | | MIS | 100 | 100 | 100 | 100 | 86 | 95 | 99 | 100 | 48 | 67 | 68 | 82 |
| | | | SIS | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 98 | 100 | 100 | 100 |
| | | Msoil | DIS | 65 | 86 | 100 | 97 | 37 | 59 | 57 | 69 | 21 | 33 | 31 | 38 |
| | | | MIS | 95 | 100 | 100 | 100 | 66 | 86 | 85 | 95 | 37 | 51 | 49 | 61 |
| | | | SIS | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 93 | 100 | 100 | 100 |
| | SHD | Fsoil | DIS | 96 | 100 | 100 | 100 | 70 | 88 | 87 | 95 | 37 | 53 | 51 | 61 |
| | | | MIS | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 82 | 96 | 97 | 100 |
| | | | SIS | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 82 | 96 | 97 | 100 |
| | | Msoil | DIS | 71 | 89 | 100 | 99 | 36 | 55 | 49 | 73 | 19 | 34 | 29 | 43 |
| | | | MIS | 100 | 100 | 100 | 100 | 92 | 100 | 100 | 100 | 58 | 79 | 80 | 92 |
| | | | SIS | 100 | 100 | 100 | 100 | 97 | 100 | 100 | 100 | 67 | 87 | 88 | 96 |
| 2017 | HD | Fsoil | DIS | 98 | 100 | 100 | 100 | 66 | 87 | 78 | 97 | 34 | 52 | 52 | 68 |
| | | | MIS | 100 | 100 | 100 | 100 | 87 | 99 | 91 | 100 | 49 | 71 | 69 | 88 |
| | | | SIS | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 99 | 100 | 99 | 100 |
| | | Msoil | DIS | 74 | 91 | 100 | 99 | 37 | 59 | 61 | 75 | 16 | 29 | 32 | 39 |
| | | | MIS | 98 | 100 | 100 | 100 | 69 | 88 | 82 | 98 | 36 | 52 | 56 | 70 |
| | | | SIS | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 95 | 100 | 97 | 100 |
| | SHD | Fsoil | DIS | 99 | 100 | 100 | 100 | 71 | 90 | 82 | 98 | 36 | 54 | 56 | 72 |
| | | | MIS | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 84 | 98 | 89 | 100 |
| | | | SIS | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 84 | 98 | 89 | 100 |
| | | Msoil | DIS | 79 | 93 | 100 | 99 | 43 | 59 | 66 | 78 | 20 | 29 | 34 | 42 |
| | | | MIS | 100 | 100 | 100 | 100 | 96 | 99 | 96 | 100 | 63 | 82 | 76 | 97 |
| | | | SIS | 100 | 100 | 100 | 100 | 98 | 100 | 98 | 100 | 68 | 90 | 77 | 98 |
| Mean 2001-2017 | HD | Fsoil | DIS | 100 | 100 | 100 | 100 | 77 | 95 | 87 | 100 | 42 | 61 | 65 | 76 |
| | | | MIS | 100 | 100 | 100 | 100 | 96 | 100 | 97 | 100 | 61 | 81 | 81 | 95 |
| | | | SIS | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| | | Msoil | DIS | 84 | 98 | 100 | 100 | 45 | 66 | 67 | 84 | 25 | 38 | 39 | 51 |
| | | | MIS | 100 | 100 | 100 | 100 | 75 | 96 | 86 | 100 | 44 | 62 | 62 | 76 |
| | | | SIS | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| | SHD | Fsoil | DIS | 100 | 100 | 100 | 100 | 78 | 97 | 87 | 100 | 44 | 63 | 64 | 79 |
| | | | MIS | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 93 | 100 | 97 | 100 |
| | | | SIS | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 93 | 100 | 97 | 100 |
| | | Msoil | DIS | 87 | 98 | 100 | 100 | 50 | 68 | 70 | 85 | 26 | 40 | 42 | 51 |
| | | | MIS | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 71 | 94 | 83 | 100 |
| | | | SIS | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 79 | 98 | 88 | 100 |
| Minimum | | | | 65 | 86 | 100 | 97 | 36 | 55 | 49 | 69 | 16 | 29 | 29 | 38 |
| Maximum | | | | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| Mean | | | | 96 | 99 | 100 | 100 | 82 | 91 | 89 | 96 | 59 | 73 | 72 | 82 |
| Standard deviation | | | | 9.22 | 3.30 | 0 | 0.53 | 22.1 | 14.4 | 14.4 | 8.73 | 27.9 | 25.2 | 23.6 | 21.6 |
| Coefficient of variation (%) | | | | 9.64 | 3.34 | 0 | 0.53 | 27.1 | 15.9 | 16.1 | 9.14 | 47 | 34.4 | 32.8 | 26.4 |

Full= full irrigation; RDI= regulated deficit irrigation; SDI= sustained deficit irrigation; HD= high density grove; SHD= super high density grove; Fsoil= fine to medium texture; Msoil= moderately coarse to medium texture; DIS= drip irrigation system; MIS= microjet irrigation system; SIS= sprinkle irrigation system.Full= full irrigation; RDI= regulated deficit irrigation; SDI= sustained deficit irrigation; Fsoil= fine to medium texture; Msoil= moderately coarse to medium texture; DIS= drip irrigation system; MIS= microjet irrigation system; SIS= sprinkle irrigation system.

SDI was found to be the lowest consumption irrigation strategy in terms of both water and energy. SDI permitted average savings of approximately 36% and 54% for water and energy compared to RDI and full irrigation, respectively. Compared to HD orchards, SHD orchards required approximately 32% more water and energy on average. In reference to the mean meteorological conditions, HD orchards (approximately 280 plants/ha) drip irrigated under the SDI strategy showed minimum water and energy requirements of approximately 120 mm



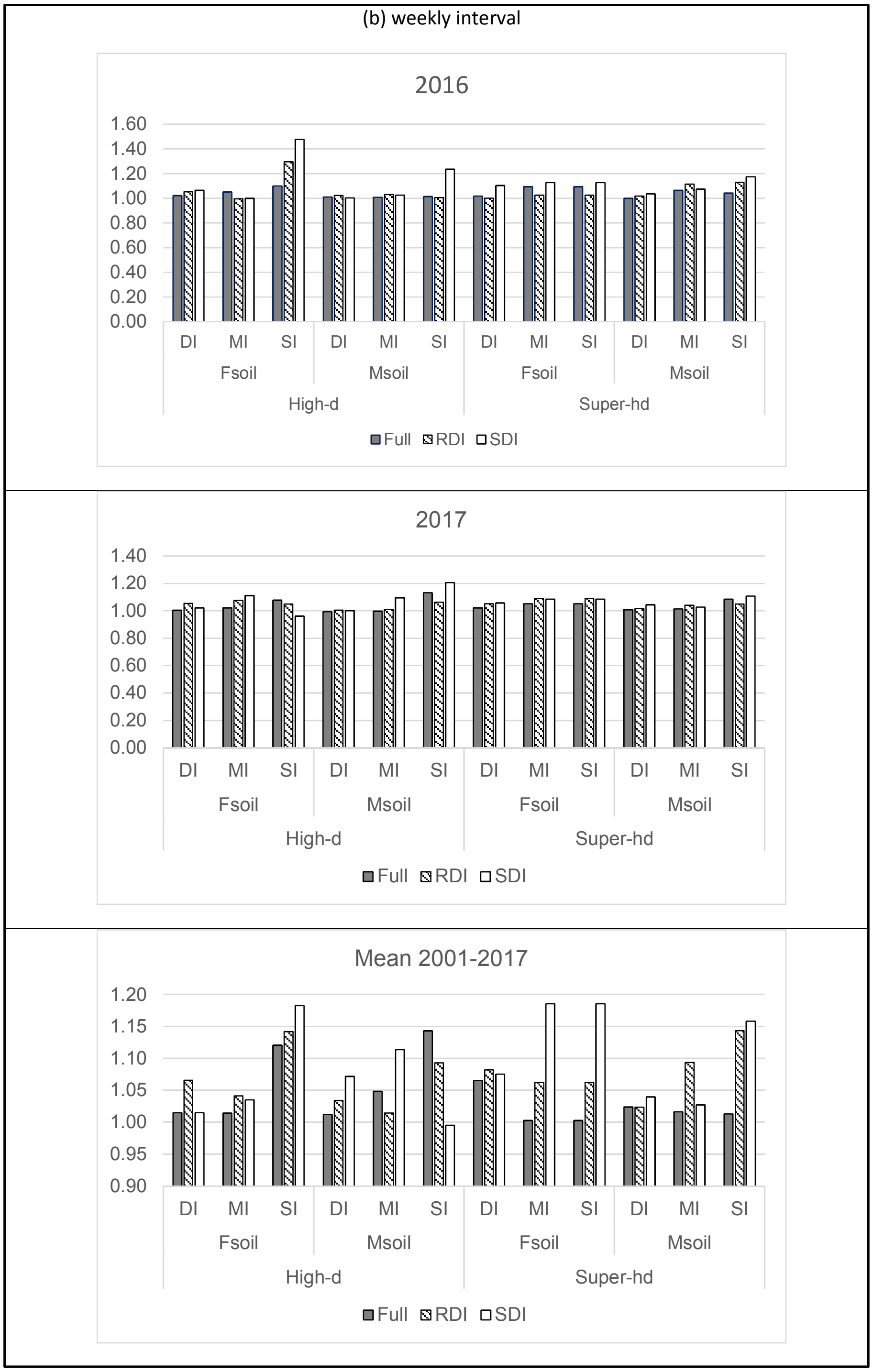



**Fig. 2. Gross irrigation used for management with variable amounts and fixed intervals relative to optimised scheduling. (a) 3 day interval; (b) 7 day interval (DI= drip irrigation system; MI= microjet irrigation system; SI= sprinkle irrigation system; Fsoil= fine to medium texture; Msoil= moderately coarse to medium texture; High-d= high-density grove; Super-hd= super-high-density grove; Full= full irrigation; RDI= regulated deficit irrigation; SDI= sustained deficit irrigation)**

**Table 4. Irrigation parameters for irrigation scheduling at a fixed quantity and interval**

| Growing system | Soil type | Irrigation system | Fixed amount (mm) | Total number of irrigation | Fixed interval (days) |
|---|---|---|---|---|---|
| HD | Fsoil | DIS | 17 | 13 | 9 |
| | | MIS | 26 | 9 | 14 |
| | | SIS | 85 | 3 | 42 |
| | Msoil | DIS | 9 | 23 | 5 |
| | | MIS | 18 | 13 | 9 |
| | | SIS | 65 | 4 | 33 |
| SHD | Fsoil | DIS | 22 | 10 | 12 |
| | | MIS | 60 | 4 | 32 |
| | | SIS | 63 | 4 | 32 |
| | Msoil | DIS | 12 | 18 | 7 |
| | | MIS | 41 | 6 | 22 |
| | | SIS | 49 | 5 | 24 |
| Minimum | | | 9 | 3 | 5 |
| Maximum | | | 85 | 23 | 42 |
| Mean | | | 39 | 9 | 20 |
| Standard deviation | | | 25 | 6 | 12 |
| Coefficient of variation (%) | | | 64 | 70 | 61 |

*HD= high density grove;*
*SHD= super high-density grove;*
*Fsoil= fine to medium texture;*
*Msoil= moderately coarse to medium texture;*
*DIS= drip irrigation system;*
*MIS= microjet irrigation system;*
*SIS= sprinkle irrigation system*

and 80 KWh/ha, respectively. In contrast, SHD orchards (approximately 1700 plants/ha) fully irrigated by DIS showed higher water and energy requirements (approximately 350 mm and 230 KWh/ha, respectively). A typical HD olive orchard drip irrigated under the RDI strategy required approximately 200 mm of water and 180 KWh/ha of energy. The irrigation requirements are of the same order of magnitude as those suggested in Andalucia, Spain [4].

Under irrigation scheduling with variable quantities and fixed intervals, the 3 days interval ensured performance similar to the OPT scheduling in terms of efficiency, but with a slight increase (less than 10%) in water and energy requirements. The weekly interval resulted in high scheduling efficiency (SchE), but with light water stress for HD groves in Msoils fully irrigated by drip systems. Due to the high percentage of stress days (both light and severe), drip and microjet irrigation were not feasible for 14- and 28-day intervals under most of the conditions examined. With a 14 days interval, microjet systems were acceptable under only the SDI strategy. Sprinkler systems resulted in a low percentage of stress days and a high SchE, but water and energy requirements were up to 40% higher than those with OPT scheduling.

For all the conditions examined, irrigation scheduling with a fixed quantity and interval resulted in a high percentage of stress days. Furthermore, water losses due to deep percolation were high for both the RDI and SDI strategies.

It should be noted that early water deficit was detected in all the three meteorological periods analysed (2016, 2017 and mean 2001-2017). In fact, the date of the first irrigation event varied from April 22$^{nd}$ to May 2$^{nd}$ for both full and RDI irrigation and from May 14$^{th}$ to May 29$^{th}$ for SDI, in contrast with the traditional irrigation scheduling according to farmers, in the area examined, irrigate olive orchards from mid-June to September.

**Table 5. Irrigation adequacy ($IA_1$, IA2 and $IA_3$) and irrigation scheduling efficiency for irrigation management at a fixed quantity and interval ($IA_1$ (%) represents the days of the irrigation season without any stress -both light and severe- in fully irrigated plants; $IA_2$ (%) represents the days of the irrigation season without severe stress in fully irrigated plants; $IA_3$ (%) represents the days of the irrigation season without extra stress beyond that specified in the deficit irrigation strategy RDI or SDI).**

| Year | Gro-wing system | Soil type | Irrigation system | Irrigation adequacy (%) | | | | Scheduling efficiency (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Full | | RDI | SDI | Full | RDI | SDI |
| | | | | $IA_1$ | $IA_2$ | $IA_3$ | $IA_3$ | | | |
| 2016 | HD | Fsoil | DIs | 14 | 27 | 70 | 85 | 100 | 89 | 70 |
| | | | MIs | 15 | 29 | 79 | 96 | 100 | 89 | 75 |
| | | | SIs | 28 | 64 | 79 | 96 | 100 | 89 | 82 |
| | | Msoil | DIs | 12 | 23 | 60 | 68 | 100 | 61 | 70 |
| | | | MIs | 12 | 26 | 73 | 79 | 100 | 61 | 69 |
| | | | SIs | 12 | 48 | 75 | 88 | 100 | 71 | 78 |
| | SHD | Fsoil | DIs | 8 | 23 | 64 | 75 | 100 | 78 | 89 |
| | | | MIs | 13 | 31 | 70 | 87 | 100 | 83 | 93 |
| | | | SIs | 13 | 31 | 70 | 87 | 100 | 83 | 93 |
| | | Msoil | DIs | 5 | 16 | 47 | 48 | 100 | 78 | 90 |
| | | | MIs | 10 | 23 | 67 | 77 | 100 | 85 | 94 |
| | | | SIs | 12 | 24 | 68 | 79 | 100 | 80 | 90 |
| 2017 | HD | Fsoil | DIs | 2 | 20 | 56 | 85 | 100 | 72 | 59 |
| | | | MIs | 3 | 30 | 48 | 76 | 100 | 78 | 64 |
| | | | SIs | 50 | 83 | 55 | 77 | 100 | 92 | 67 |
| | | Msoil | DIs | 1 | 8 | 41 | 66 | 100 | 41 | 57 |
| | | | MIs | 7 | 34 | 55 | 78 | 100 | 55 | 58 |
| | | | SIs | 7 | 34 | 66 | 82 | 100 | 66 | 68 |
| | SHD | Fsoil | DIs | 2 | 9 | 39 | 76 | 100 | 92 | 74 |
| | | | MIs | 7 | 34 | 58 | 81 | 100 | 95 | 80 |
| | | | SIs | 7 | 34 | 63 | 81 | 100 | 100 | 80 |
| | | Msoil | DIs | 1 | 4 | 23 | 63 | 100 | 93 | 74 |
| | | | MIs | 4 | 13 | 48 | 76 | 100 | 98 | 80 |
| | | | SIs | 5 | 17 | 55 | 77 | 100 | 93 | 77 |
| Mean 2001-2017 | HD | Fsoil | DIs | 51 | 85 | 76 | 97 | 95 | 61 | 52 |
| | | | MIs | 53 | 87 | 77 | 97 | 100 | 67 | 57 |
| | | | SIs | 73 | 88 | 78 | 97 | 100 | 77 | 68 |
| | | Msoil | DIs | 31 | 58 | 60 | 75 | 95 | 61 | 50 |
| | | | MIs | 52 | 81 | 73 | 87 | 94 | 61 | 51 |
| | | | SIs | 68 | 83 | 75 | 87 | 100 | 71 | 62 |
| | SHD | Fsoil | DIs | 4 | 19 | 64 | 86 | 100 | 78 | 65 |
| | | | MIs | 27 | 74 | 70 | 86 | 100 | 83 | 72 |
| | | | SIs | 27 | 74 | 70 | 86 | 100 | 83 | 72 |
| | | Msoil | DIs | 2 | 10 | 47 | 48 | 100 | 78 | 90 |
| | | | MIs | 9 | 36 | 67 | 77 | 100 | 85 | 94 |
| | | | SIs | 15 | 57 | 68 | 79 | 100 | 80 | 90 |
| Minimum | | | | 1 | 4 | 23 | 48 | 94 | 41 | 50 |
| Maximum | | | | 73 | 88 | 79 | 97 | 100 | 100 | 94 |
| Mean | | | | 18 | 40 | 63 | 80 | 100 | 78 | 74 |
| Standard deviation | | | | 20 | 26 | 13 | 11 | 1 | 14 | 13 |
| Coefficient of variation (%) | | | | 107 | 66 | 21 | 14 | 1 | 17 | 18 |

Full= full irrigation; RDI= regulated deficit irrigation; SDI= sustained deficit irrigation; HD= high density grove; SHD= super high density grove; Fsoil= fine to medium texture; Msoil= moderately coarse to medium texture; DIS= drip irrigation system; MIS= microjet irrigation system; SIS= sprinkle irrigation system.

## 4. CONCLUSION

The main results of the research showed that the traditional irrigation strategy at fixed quantity and interval is not adequate to achieve high efficiency in the irrigation of olive orchards, from both the agronomic (reduction of crop water stress) and economic (reduction of water and energy requirements) point of view.

The optimisation of the irrigation scheduling requires the estimate of the water quantity to deliver in each irrigation in both the irrigation management at variable and fixed interval. The evapotranspiration-water balance model is an efficient and (relatively) simple tool to foresee the quantities and the dates of irrigation during the irrigation season.

The adoption of a fixed interval, which is preferred by the farmers for practical reasons, is feasible after verifying that it is adequate for the type of soil, plant density and irrigation system used. In the case of drip systems, it is not advisable to adopt intervals longer than one week. A means of lengthening the interval would be to increase the wetted area through the installation of more than two laterals per row, but this strategy is not feasible for practical and economic reasons as it can make irrigation costs prohibitive for a crop such as olive, in which large gains are not possible. When water agencies supply water at intervals longer than a week, the farmers should build storage facilities.

The irrigation season length should be longer respect the traditional one. Early water deficit (at the end of April or in the first decade of May) were detected in all the meteorological periods studied. Similarly, the results of the simulation showed that the irrigation season ends in October, mainly when localised irrigation systems were used. In contrast, with the traditional irrigation scheduling, farmers, in the area examined, irrigate olive orchards from mid-June to September.

Overall, in the area examined or in similar climatic conditions, considering also the risks to development of diseases such as *Verticillium*, drip irrigation systems and a weekly interval are advisable for olive groves, as highlighted by Gucci and Fereres [3].

From the methodological point of view, the simulated cases can be considered representative of both the real and potential conditions experienced by olive grown in the Southern Italy environment.

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## COMPETING INTERESTS

Authors have declared that no competing interests exist.

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