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Mandarin irrigation scheduling by means of frequency domain reflectometry soil moisture monitoring

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Abstract

The accurate estimation of plant water needs is the first step for achieving high crop water productivity. The main objective of the work was to develop an irrigation scheduling procedure for mandarin orchards under Mediterranean conditions based on replacing the amount of consumed water using reference values of soil moisture according to different phenological periods. The proposed methodology includes a definition part where the threshold values were established relating the trees' stem water potential and the volumetric soil water content measured with Frequency Domain Reflectometry probes. A second part includes the steps for standardizing measurements from capacitance probes by using the LEACHM hydrological simulation model to take into account the sensor-to-sensor variations. Finally, an extrapolation procedure based on soil water retention curves was used for adapting critical soil water content thresholds to different soil conditions.

Field evaluations were made in a citrus orchard located in eastern Spain during two seasons. Standardized critical soil water contents were: i) 24% vol. for post-harvest, bloom - fruit set and phase III of fruit growth; ii) 27% vol. for phase I of fruit growth, and iii) 29% vol. for phase II of fruit growth with average daily air vapour pressure deficit values ranging between 0.2 - 0.4; 0.9 - 1.1 and 1.1 - 1.3 kPa, respectively. When implemented in the orchard, the sensor-based strategy resulted in water saving of 26% respect to a control treatment, irrigated using the standard FAO-56 approach, without significant differences in yield and increasing the crop water productivity by 33%. In conclusion, we suggest that the determination and use of the critical soil water content is a useful tool for scheduling irrigation. The proposed standardization and extrapolation methodology allows the irrigation strategy to be applied to other mandarin orchards under similar climatic conditions.

1. Introduction

In arid and semi-arid zones, irrigated agriculture is the main user of water resources, reaching a proportion that could exceed 70–80% of the total water abstractions (Fereres and Soriano, 2006). Citrus trees are widely cultivated in south-eastern Spain, where the predominant climate conditions are those typical of a semi-arid zones.

Climate change forecasts an increase in crop water requirements (CWR) and probably more severe drought periods (Menenti et al., 2013). Some scenarios for 2050 predict 30-50% decrease of fresh water availability, while its demand on eastern and southern areas could be doubled (Milano et al., 2013).

In citrus trees, irrigation is essential to guarantee high quality and yield, and an effective water management strategy is crucial to cope with this situation of water scarcity (Garcia-Tejero et al., 2011) and avoid environmental hazards such as groundwater pollution by nitrogen fertilizers (Quiñones et al., 2007). Precision irrigation aims to minimize water losses due to deep percolation during the watering events through increasing the efficiency of systems and using a schedule methodology based on the water exchange in the soil-plant-atmosphere system (Pérez, 2016).

Nowadays, the most widely used system for calculating irrigation needs is based on the water balance proposed in FAO paper number 56 (Allen et al., 1998). This method determines the CWR considering the reference evapotranspiration (ET_0) and the crop coefficients (K_c). Although some studies have adapted the FAO-56 algorithm for irrigation scheduling (Rallo et al., 2011), this strategy has some uncertainty calculating water needs for instance when tree light interception (Consoli et al., 2006) or crop load (Syvertsen et al., 2003; Yonemoto et al., 2004) change over the seasons. Therefore, a substantial improvement in irrigation management can be achieved if soil and plant water status are used for scheduling irrigation in woody perennial crops.

Indirect methods for monitoring soil water status are based on measuring soil matric potential (Ψ_{soil}) or volumetric water content (θ) (Campbell and Campbell, 1982). Amongst the wide range of available devices, probes based on Frequency Domain Reflectometry (FDR) are nowadays the most widely used tools to determine the θ because of their relatively affordable price and ease of use (Fares and Polyakov, 2006). Accuracy of obtained information depends on the probe installation (Evett et al., 2002) which should minimize air gaps between the plastic shell and the soil. Under these circumstances, the accuracy of the FDR sensors can reach values of ±1% vol. with soil specific calibration (Muñoz-Carpena et al., 2004). However, Provenzano et al. (2015) found higher differences in a capacitance probe calibration for a range of soils with different particle size distributions. The field practices used, and particularly those related with the orchard soil management that affects bulk density and organic matter content, can play a significant effect on soil properties invalidating the calibration (Hignett and Evett, 2008; Paraskevas et al., 2012). When absolute θ values are used for scheduling irrigation, using manufacturer default calibration equations might result in inappropriate θ estimations, and a site-specific analysis should be then performed (Evett et al., 2006).

Hydrological simulation could be an alternative tool for calibrating FDR probes and obtaining accurate θ values. The Leaching Estimation And Chemistry Model (LEACHM) is a one-dimensional deterministic model that describes the water and solutes regimes in unsaturated or partially saturated soils (Hutson, 2003). LEACHM model has been widely used for simulating water, nitrogen, salts and pesticide behavior in soils (Ramos and Carbonell 1991; Asada et al., 2013; Nasri et al., 2015; Deng et al., 2017). The model has been used to evaluate water and nitrogen management in citrus orchards (Lidón et al., 1999; Alva et al., 2006; Lidón et al., 2013). It is a mechanistic model that uses the Richards equation (Richards, 1931) to simulate soil moisture variation, being as valid as other agro-hydrological models like SPAW, FAO, SMCR, SIMODIS and Hydrus 2D among others (Minacapilli et al., 2008, Zhang et al., 2010; Rallo et al., 2011; Autovino et al., 2018).

The usefulness of capacitance probes for scheduling irrigation can be increased if plants water status is included. This information integrates the effects of surrounding environmental conditions and the fraction of the water available in the soil for the plant (Moriana et al., 2012). In this sense, midday stem water potential (Ψ_{Stem}) is considered as a benchmark indicator of the degree of plant water stress (Ruiz-Sánchez et al., 2010; Ballester et al., 2011). This indicator is obtained through a destructive measurement, which is time-consuming and needs dedication and currently it is impossible to automate. However, these measurements can play an essential role for irrigation scheduling when comparing it with a reference value, corresponding to an ideal plant water status with full water availability (Spinelli et al., 2017).

The aim of the research was to develop an irrigation scheduling strategy for mandarin orchards under Mediterranean conditions based on replacing the amount of consumed water using reference values of soil moisture at different phenological periods. Threshold values to start irrigation were determined using relationships between Ψ_{Stem} and the volumetric soil water content measured with FDR probes (θ_{FDR}). The methodology includes a procedure for standardizing soil moisture capacitance probes readings and extrapolating scheduling thresholds for plots with different soil characteristics.

2. Materials and methods

2.1. General approach

The methodology followed for scheduling mandarin irrigation by means of the proposed sensor-based strategy comprises three steps: definition, standardization and extrapolation.

The goal of the definition phase is to obtain a reference θ for scheduling irrigation with FDR probes ensuring an adequate plant water status. The critical soil water content threshold ($\theta_{crit-FDR}$) is defined from simultaneous measurements of θ_{FDR} and Ψ_{Stem} in different periods of the crop cycle in which irrigation was withheld.

Secondly, the aim of the standardization phase was to gauge FDR probes minimizing sensor-to-sensor variations for scheduling irrigation with absolute critical soil water content (θ_{crit}) values. This step is needed considering that FDR probes might provide for different readings at the same moisture levels due to lack of calibration. The chosen methodology consists in comparing the soil water content obtained by means of a hydrological simulation software (θ_{SIM}) with the θ_{FDR} and computing the differences with a standardization equation.

And thirdly, in the extrapolation phase, a methodology based on soil water retention curves (SWRC) and the Ψ_{soil} was used for adapting θ_{crit} to different soil physical conditions. The aim of these two last steps (standardization and extrapolation) are fundamental for applying the sensor-based strategy to other mandarin orchards located under similar climatic conditions.

2.2. Experimental plot

The study was carried out during 2015 and 2016 in a commercial citrus orchard located in Alberic in the south of the province of Valencia, Spain (39° 7′ 31.33″ N, 0° 33′ 17.06″ W, 37 m a.m.s.l). The experiment was performed on mature ‘Arrufatina’ mandarin (*Citrus clementina* Hort. ex Tan.) trees grafted onto ‘Carrizo’ citrange (*Citrus sinensis* Osb. × *Poncirus trifoliata* Raf.) rootstock, with a tree spacing of 5.50 m × 4.25 m. Soil textural class, according to the USDA classification, is loam to sandy clay loam with percentages of clay ranging from 22 to 34% within the orchard. Soil organic matter was on average 1.3%. The climate is semi-arid with warm winters and dry summers with average annual precipitation of 400 mm, lower than the ET_0, 1000 - 1300 mm (IGN, 2018). The plot was equipped with a drip irrigation system, automatic control valves and flow meters to monitor the amount of water applied. Water was supplied by two drip laterals with a total 7 emitters per tree (2.2 L h^{-1} AZUD Premier PC AS (Azud, Alcantarilla, Murcia, Spain). Emitters were spaced at 1.2 m apart.

FDR water-content-profile probes (EnviroScan, Sentek, Stepney, Australia) were used for monitoring θ_{FDR} at 0.2, 0.3 and 0.5 m depths where roots are mainly concentrated (Abouatallah et al., 2012) at 30 minutes time-step. A total of 6 FDR probes were installed in the experimental plot. Four probes (noted as Definition (Def) 1 to 4) were installed on four contiguous trees used for establishing the $\theta_{crit-FDR}$ thresholds. Two additional probes (noted as Validation (Val) 1 and 2) were installed under different trees for implementing the sensor-based strategy. All probes were located adjacent to the drip irrigation line and at about 0.10 m from the emitter following the installations recommendations by Bonet et al., (2010).

In order to characterize the soils where the 6 FDR probes were installed, two undisturbed soil cores (0.05 m height and 0.05 m diameter) were collected around the access tubes at 0.2, 0.3 and 0.4 m depths. Soil organic matter content (Walkley and Black, 1934), dry bulk density and soil textural class according USDA classification (Soil Survey Staff, 1975) were determined.

2.3. Critical soil water content definition.

The $\theta_{crit-FDR}$ below which plant water stress occurs, and it is necessary to start irrigation, was obtained by solving linear equations fed with simultaneous measurements of Ψ_{Stem} and θ_{FDR}.Values of Ψ_{Stem} obtained in previous research carried out in the area for solving these equations (Ballester et al., 2014; Martínez-Gimeno et al. 2018) were adapted. The onset of plant water stress was established at -0.8 to -1.0 MPa from mid-September to May and at -1.0 to -1.2 MPa from June to mid-September. Measurements were made during three drought cycles in two consecutive years. Irrigation was withheld from May 4th to May 17th [days of the year (DOY) 124–137, period A1], July 20th to July 26th (DOY 201–207, period B1) and November 12th to January 11th (DOY 316–11, period C1) in 2015–2016; and May 19th to June 8th (DOY 140–160, period A2), August 5th to August 19th (DOY 218–232, period B2) and December 1st to January 13th (DOY 336–13, period C2) in 2016-2017. According to common phenological stages of 'Clementina arrufatina' under climatic conditions of Mediterranean area along the season, period A corresponds with phase I of fruit growth, period B with phase II of fruit growth and period

C with phase III of fruit growth, bloom and fruit set and post-harvest. Definition probes 1 to 4 were used for measuring the θ_{FDR} during these periods. The Ψ_{Stem} was measured in the same four trees equipped with the FDR probes by using a Schölander pressure chamber (Model 600, PMS Instrument Co., USA). Measurements were carried out with high frequency (from daily to weekly) during the drought cycles. For each tree, measurements were made on two leaves that were covered with aluminum foil bags at least one hour before the measurements (Turner, 1981). Average air vapour pressure deficit (VPD) was estimated for each drought cycle.

2.4. Critical soil water content standardization

The adjustment to take into account sensor-to-sensor variation for using the θ_{crit} with any FDR probe was made by contrasting θ_{SIM} and θ_{FDR}. Differences were quantified by solving the linear regression equation expressed as:

$$\theta_{FDR} = a\theta_{SIM} + b \quad [1]$$

where a and b are fitting parameters.

The LEACHM model was used for obtaining θ_{SIM},. Input data includes soil physical and chemical properties of the different soil layers (texture, organic matter, bulk density, water retention parameters), plant data (crop cycle data, crop cover fraction) and weather (rain, temperature, thermal amplitude, potential evapotranspiration). The LEACHM model follows the method proposed by Childs and Hanks (1975) to calculate the ET_0 from the weekly reference evapotranspiration. The partition between evaporation and transpiration is made according to the crop cover fraction and following the equation proposed by Nimah and Hanks (1973).

The soil profile where FDR probes were installed was divided into several horizontal segments. The total simulation period was divided into short time intervals, and equations were solved for each soil layer and each water flow interval, which should be 0.1 day or less. It was necessary to know the relations between hydraulic conductivity, θ and Ψ_{soil}. Those are based on the moisture retention function (Eq. 2) and the unsaturated hydraulic conductivity function (Eq. 3) proposed by Campbell (1974) integrating the modification suggested by Hutson and Cass (1987):

$$\Psi_{soil} = a\left(\frac{\theta}{\theta_s}\right)^{-b} \qquad [2]$$

$$K = K_s\left(\frac{\theta}{\theta_s}\right)^{2b+2+p} \qquad [3]$$

where Ψ_{soil} is the soil matric potential (kPa), a is the air entry water potential (kPa), b is an empirically determined constant (-), θ_s is the volumetric water content at saturation (% vol.), θ is the volumetric water content (% vol.), K is the hydraulic conductivity (mm day^{-1}), K_s is the saturated hydraulic conductivity (mm day^{-1}) and p is an interaction parameter about pore size, the value of which is assumed to be 1 for the LEACHM model. A free-draining lower boundary was assumed.

Although the objective of the work was not to assess the LEACHM model, performance indicators were applied to validate simulations and detect anomalous data in the standardization. Differences between observed values (θ_{FDR}) and predicted values (θ_{SIM}) were evaluated by calculating two model evaluation indicators: i) the root mean square error (RMSE) was selected for quantifying the error in terms of the units of the variable calculated by the model and ii) the relative root mean squared error (RRMSE) was used as indicator which is independent of the units of measurement. The minimum value is 0, being also the optimal value (Loague and Green, 1991). Their definitions are given by:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(O_i-P_i)^2}{N}} \qquad [4]$$

$$RRMSE = \sqrt{\frac{\frac{1}{N}\sum_{i=1}^{N}(O_i-P_i)^2}{\bar{O}}} \qquad [5]$$

where N is the number of measured data, O_i and P_i are the predicted and the measured values and $\bar{O}$ is the mean of the observed values.

Indeed, the approach proposed in the present work offers an alternative methodology to traditional calibration that allows to simulate an unlimited number of water balances from soil samples. Certainly, this standardization methodology proposed could be replaced by any field or laboratory protocols to calibrate FDR sensors (Provenzano et al., 2015).

2.5. Critical soil water content extrapolation

The θ_{crit} should be adapted for scheduling mandarin irrigation under different soil physical conditions for instance by relating Ψ_{soil} and θ using SWRCs. The SWRC allows transferring the θ_{crit} from the conditions where they were obtained (Definition) to other locations (Validation) with different soil physical properties using the corresponding Ψ_{soil} following these steps: i) to construct and to parameterize SWRCs for the surrounding soil where FDR probes where installed; ii) determination of the Ψ_{soil} corresponding to the critical soil water content of Definition FDR probes (θ_{crit}^{Def}); and iii) determination of the critical soil water content of Validation FDR probes (θ_{crit}^{Val}) corresponding to the Ψ_{soil} obtained in the previous step.

Data for SWRC were generated using the pressure plate method (Richards, 1948), where θ corresponding to Ψ_{soil} of 0, -10, -30, -60, -100, -300 and -1000 kPa was determined. Experimental data were fitted by means of the van Genuchten model (van Genuchten, 1980):

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{(1+(\alpha\Psi_{\mathrm{soil}})^n)^m} \qquad [6]$$

where θ is the soil water content (%vol.), θ_r is the soil residual water content (%vol.), θ_s is the soil saturated water content (%vol.), Ψ_{soil} is the soil matric potential (kPa), α is a scale parameter inversely proportional to mean pore diameter (cm^{-1}), and m and n are parameters associated to the shape of the soil water characteristic curve being $m=1-1 \cdot n^{-1}$. θ_r, α and n could be calculated using a least squares objective function with certain restrictions (Schaap et al., 1998; Anlauf, 2014): $0.0 \leq \theta \leq 0.3$ cm^3cm^{-3}; $0.0001 \leq \alpha \leq 1.000$ cm^{-1}, and $1.001 \leq n \leq 10$.

2.5. Irrigation dose computation

The aim of the sensor-based strategy was to restore water losses given by evapotranspiration events and maintaining the soil moisture above the θ_{crit}. Crop water requirements were estimated according to crop evapotranspiration, ET_c, estimated with the single crop coefficient approach (Allen et al., 1998). ET_0 was determined with the Penman - Monteith equation in the version modified by FAO (Allen et al., 1998), by using the meteorological observations acquired by two automatic agro-meteorological stations located nearby the orchard. The K_c varied among months depending on the crop phenological stage. According to the canopy ground cover, K_c was assumed variable from a minimum of 0.36 in May to a maximum of 0.56 in October (Castel, 2000). Irrigation scheduling was programmed twice a week, Monday and Thursday.

The soil moisture was measured with the Validation FDR probes in the root profile (0 - 0.5 m) before each scheduling event. Then, the irrigation required dose (V, mm) was defined as:

$$V = f_m \cdot z \cdot (\theta_{crit-FDR}^{Val} - \theta_{FDR}^{Val}) \quad [7]$$

where f_m (-) is the wetted soil fraction, z (mm) is the bulb depth, θ_{FDR}^{Val} and $\theta_{crit-FDR}^{Val}$ (%vol.) are the current and critical soil water content for scheduling irrigation with Validation FDR probes, respectively. The total dose (V_t, mm) to be applied for *i* days and the time for each irrigation event (IT, s) were calculated as:

$$V_t = \sum_{i=1}^{i=n} CWR_i + V \quad [8]$$

$$IT(s) = \frac{V_t \cdot S}{q_{intake} \cdot n} \quad [9]$$

where S (m^2) is the total irrigated area, q_{intake} ($L\ s^{-1}$) is the total flow delivered to the subunit (irrigation area controlled by pressure regulator) and n (-) is the number of days irrigation was performed for the scheduled interval.

2.6. Irrigation strategy validation

The sensor-based strategy was implemented during 2016 in the same experimental plot where irrigation thresholds were obtained. The treatments applied were Control, irrigated during the whole season at 100% ET_c (Allen et al.,1998;Castel, 2000), and the sensor-based strategy (SB strategy), irrigated following θ_{crit}. For the strategy implementation, the θ_{crit} obtained from the stress cycles were extended to specific developmental crop phenological stages of the trees with similar VPD levels: post-harvest and bloom and fruit-set (Periods C1 and C2), phase I (Periods A1 and A2), phase II (Periods B1 and B2) and phase III (Periods C1 and C2) of fruit growth.

The statistical design for comparing the two irrigation strategies was a randomized complete block with three replicates per treatment. Each sub-plot had four rows with 6 - 7 sample trees per row where perimeter trees were used as guard, leaving 8 - 10 central trees for experimental determinations. Ψ_{Stem} was determined approximately weekly at solar midday in two mature leaves of two trees per experimental unit for assessing plant water status. In the SB strategy, FDR probes Validation 1 and 2 were used for measuring θ and for scheduling irrigation. Yield was determined at the time of commercial harvest in all the sampled trees. This was defined by the grower collaborator following the standard fruit quality protocols used in the area. Juice total soluble solids content, juice titratable acidity and maturity index about 12ºBrix, 7 g/l and 17, respectively. According to Perry et al., (2017), crop water productivity (CWP) was calculated as the crop yield divided by the irrigation volumes applied.

3. Results and discussion

3.1. Critical soil water content determination

During the three drought cycles carried out in 2015 and 2016, Ψ_{Stem} and θ_{FDR} measured with Definition 1 to 4 FDR probes, were compared by using linear regressions (Figure 1). The equations depicted in Figure 1 are indicating the soil water status threshold below which Ψ_{Stem} do not decrease greatly in response to small changes in θ. Differences among the slope of the curve can be observed for the different studied periods. This might be because of the variations in the VPD registered for each period. The most pronounced slopes were found in the summer stress cycles (periods B1 and B2), when VPD reached its maximum values (1.3 kPa) from DOY 201 to 207 in 2015. The most moderate slope was found from DOY 316 in 2015 to DOY 11 in 2016 (period C1), in agreement with low VPD (0.4 kPa), since the atmospheric demand is not a limiting factor and changes in the soil moisture do not result in drastic decreases in the plant water status. However, measurements from DOY 336 in 2016 to 13 in 2017 (period C2) showed a different trend with small variations in the θ_{FDR} resulting in important changes in Ψ_{Stem}. Given the registered VPD values (0.2 kPa), this was an unexpected behavior. It could be a consequence of the low soil temperature probably occurring this winter period, which might have increased water viscosity and root hydraulic resistance hindering water absorption (Kramer, 1942; Runnin and Reid, 1980).

The linear equations that relate Ψ_{Stem} and θ_{FDR} (Figure 1) were solved using the Ψ_{Stem} thresholds proposed in the methodology. Results showed that the $\theta_{crit-\ FDR}^{Def}$ for scheduling irrigation varied on the considered period of the year and the evaporative demand (Table 3A). This is the main advantage of the proposed strategy because irrigation water needs are adapted to the soil water status and the crop phenological stage. It should be noted that the probes Definition 1 and 3 showed higher humidity values than the probes Definition 2 and 4. This fact may be attributed to the lack of calibration of the probes, to the soil characteristics, or even to the differences between plants.

3.2. Critical soil water content standardization and extrapolation

The simulation with LEACHM was performed for a cold period (from DOY 338 in 2015 to 12 in 2016) without irrigation and with low evaporative demand, aiming to minimize the effect of the evapotranspiration rates on the soil water dynamics. Soil physical and chemical properties and crop data inputs are summarized in Tables 1 and 2.

Linear regression equations (Table 4) were calculated to consider differences between θ_{FDR} and θ_{SIM} and to standardize soil moisture values obtained with the FDR probes. The slope of the regression lines (a) give an idea of how well the simulation fits the real measurements. The slope of the regression varied between 0.67 to 1.03, indicating that data trends were reasonably similar and both methods were reproducing comparable soil water dynamics. The fitting constant b, that ranged between 2.68 and 15.63, showed the different levels of soil moisture provided by simulated and measured temporal series. For each probe, θ_{FDR} was higher than θ_{SIM} (data not shown). Other studies corroborate that electromagnetic soil water content sensors could overestimate volumetric water content due to presence of salt in soils (Sevostianova et al., 2015). Standardization equations were characterized by coefficients of determination ranging between 0.93 to 0.72.

The standardization methodology was assessed by means of evaluation indicators. Errors were estimated with θ_{SIM} and θ_{FDR}. RMSE was 1.0 ± 0.4 % vol. and RRMSE was 0.16 ± 0.06. Both statistics are widely affected by the presence of outliers (Viteri, 2013), and simulations performed with LEACHM model sometimes presented these punctual differences at the beginning of the simulated data set (data not shown). In other studies, the estimation of soil water content in the root zone was considered suitable when the RMSE was equal to 2.0 % vol. (Rallo et al., 2011), and the RRMSE was considered as valid when it was lower than 0.40 (Confalonieri and Bechini, 2004; Wallis at al., 2011). The soil water balance simulation with LEACHM, despite the difference with respect to the soil water content of the FDR, accurately reproduce moisture readings. This fact could lay the foundations for future research, where the θ_{crit} may be used directly in the simulations, and thus, reduce the dependency of the equipment on continuous measurement of soil moisture.

There is no consensus in the scientific community regarding to capacitance probes calibration. Some authors ensure that FDR measurements are valid in any soil within wide ranges of soil moisture levels (Thomas, 1966; Hoekstra and Delaney, 1974). However, some studies have demonstrated that capacitance probes were influenced by the soil type (Bell et al., 1987). The proposed standardization, or any other analogous methodology, is indeed considering essential for ensuring the correct use of the SB strategy. Following this procedure, any volumetric water content value from FDR probe sensors could be adjusted at the same reference and data from different sensors could be comparable.

The θ_{crit}^{Def} obtained by means of LEACHM standardization were 26.8, 28.9 and 24.4 %vol. for periods A1 - A2, B1 - B2 and C1 - C2, respectively (Table 3B). A progressive increase of the values is recorded according to the VPD along the season. During the period B1 - B2 (summer), the θ_{crit}^{Def} required to avoid plant stress was the highest, with 29 ± 2% vol., because of the high evaporative demand during this part of the season (VPD = 1.2 kPa). The soil water storage capacity in this period should be enough for avoiding significant water stress (Girona et al., 2002). In contrast, the lowest θ_{crit}^{Def} was determined during the period C1- C2 (winter), 24 ± 3 % vol. when the evaporative demand (VPD = 0.3 kPa) is lower than in the summer. Indeed, the results showed that the critical soil water content to maintain an adequate plant water status was lower during periods of low-evaporative-demand as winter and the beginning of spring.

The seasonal weighted average θ_{crit}^{Def} for the root profile (0 – 0.5 m) was 26 % vol., similar to previous results obtained in grapefruit (Pérez-Pérez et al., 2008) and orange (Pérez-Pérez et al., 2014) irrigated al 100% ET_c, with a volumetric soil water content in the entire soil profile (0 – 1 m) ranging between 21 and 25 % vol. and 24 and 24 % vol., respectively. In these studies, volumetric soil water content was measured using a neutron probe previously calibrated at the experimental site. Differences could be attributed, among others, to the soil properties, measurement depth and citrus variety.

After applying the standardization process, extrapolation was made to adapt the θ_{crit}^{Def} to specific soil conditions where Validation 1 and 2 probes were installed. Extrapolated θ_{crit}^{Val} showed in the Table 5 have been classified in specific phenological stages (post-harvest, bloom and fruit-set and phase I, II and III of fruit growth) in accordance with the registered average VPD during the drought cycles (Table 3) and during the season when the sensor-based strategy was implemented (Table 4). Indeed, the thresholds obtained for Validation probes were similar to the average values obtained for Definition probes probably because the soil homogeneity within the plot.

3.3. Irrigation strategy validation

Irrigation was scheduled by means of the sensor-based strategy during 2016 in the experimental plot using the Validation 1 and 2 FDR probes. The mean annual ET_0 and rainfall for the experimental season was of 1,122 and 716 mm, respectively. The temporal distribution of rainfall and VPD followed the typical patterns of the Mediterranean basin (Fig. 2A). The seasonal variation of rainfall was characterised by a period of great scarcity during phase II of fruit growth (21 mm) and higher precipitation values were registered in the spring and the autumn, during bloom and fruit-set (113 mm) and phase III of fruit growth (548 mm). Mean daily VPD reached the highest values during phase II of fruit growth (1.1 kPa). During the implementation period (from January to November 2016), control trees received 581 mm of irrigation, while in the treatment irrigated following the SB strategy, the applied irrigation water was 429 mm (Fig. 2B). A 27 % water saving was achieved with the SB strategy, reaching the highest reductions (29%) during phase II of fruit growth.

These differences in water application resulted in slightly different plant water status between treatments (Fig. 2C). During post-harvest (DOY 11 and 21), the Ψ_{Stem} registered in both treatments was lower than the thresholds established (-0.8 to -1.0 MPa) most likely because of the effect of low temperatures (12.4°C) which could reduce plant water uptake capacity. However, it should be noted that there were no statistically significant differences between the evaluated irrigation strategies. Later on, during the mid-winter period, plant water status was recovered in the control treatment because of the higher irrigation volume applied during the beginning of the crop season in comparisons with the SB strategy. During this period (DOY 33, 42 and 49), in the SB strategy Ψ_{Stem} was lower than -1.0 MPa with no statistically significant differences between irrigation strategies From DOY 55, plant water status was recovered in both treatments, and specially since DOY 73 when pruning was made in the entire plot. During phase II of fruit growth (DOY 218, 232, 239 and 244)., Ψ_{Stem} significantly decreased in the SB strategy, compared with control treatment. The plant water status values reached are probably consequence of the high evaporative demand during these periods. However, the threshold of -1.3 to -1.5 MPa established by Ballester et al. (2011and 2014) and González-Altozano and Castel (1999) to avoid negative consequences in quality and yield was not exceeded. During phase III of fruit growth (DOY 266 and 279) both treatments had an inadequate plant water status with the lowest values of Ψ_{Stem} recorded in the SB strategy. The θ_{crit}^{Val} used for this period was 24% vol. according to the low VPD registered in phase III of fruit growth (Table 5). However, final fruit growth and ripening took place and, even if the evaporative demand was low, the fruit sink demand for photoassimilates was elevated being the irrigation volumes applied probably insufficient. It would be desirable to increase the θ_{crit}^{Val} for this stage, maintaining the levels of the phase II of fruit growth (29% vol.) until harvest. This fact underlines the importance of an appropriate determination and timing of the moisture thresholds.

Notwithstanding the water savings obtained in the SB strategy, no significant differences were found between treatments in terms of yield reaching 73.3 ± 23.2 kg tree^{-1} and 72.1 ± 19.8 kg tree^{-1} in control and SB strategy, respectively. These yield levels are well in line with the expected tree performance for mandarin trees in the area as reported in previous research (Ballester et al. 2014; Nicolas et al. 2016). The highest CWP was obtained in the SB strategy, 7.2 kg m^{-3}, compared to the control treatment, 5.4 kg m^{-3} demonstrating that, the irrigation scheduling developed can optimize irrigation efficiency by better adjusting the watering regime to the actual orchard water consumption. Although there are other models for scheduling irrigation in citrus trees (Alba et al., 2003; Bonet et al. 2010), they do not consider the limits of moisture and its adaptation to other soils, two elements that are the basis of the model proposed. This work demonstrates that an irrigation schedule adjusted to the soil water content dynamics can improve the water use efficiency. However, irrigation time calculated by the proposed strategy should be monitored to avoid errors associated with FDR probe management. The small volume of soil sampled by FDR probes, the influence of air gaps or the lack of contact between sensors and soil may cause problems (Evett and Parkin, 2005; Evett et al., 2006). The crop coefficient method for estimating water needs is too general and empiric, but it could be considered as a reference to compare results and reveal errors. Indeed, occasional determinations of plant water status could be also included in order to check if the irrigation scheduling regime is detrimentally affecting crop production.

Similar water savings with no yield reductions as observed in the present work were obtained in previous studies also in citrus trees using other irrigation strategies such as regulated deficit irrigation (RDI) (Ballester et al., 2014) and subsurface drip irrigation (Martínez-Gimeno et al., 2018). The SB strategy coupled with RDI strategies could be used to improve water productivity, reduce tree growth and improve fruit composition, enhancing thus economical profit (Pérez-Pérez et al., 2010). However, the SB strategy provide a θ_{crit} considering an adequate Ψ_{Stem}, then future studies will be necessary to expand the scheduling range for conditions of greater stress in controlled deficit irrigation strategies. Moreover, the use of more paired θ_{FDR} and Ψ_{Stem} measurements, not only restricted to the stress cycles tested, would substantially improve the determination of the critical soil water content thresholds.

4. Conclusions

The determination and use of the θ_{crit} is a useful tool for optimizing irrigation scheduling. The SB strategy computes the water doses considering the θ_{FDR} and avoiding excessive depletions which may result in a too severe tree water stress. The strategy includes two steps for scheduling irrigation with FDR probes across mandarin orchards under similar climatic conditions. On the one hand, a standardization methodology minimizes sensor-to-sensor variations allowing to use absolute values of θ_{crit} for estimating irrigation needs. On the other hand, an extrapolation methodology adapts θ_{crit} to any soil physical condition. The irrigation strategy was implemented in a commercial orchard, and water savings reached 26% without limiting yield, thus increasing crop water productivity. Future work will be necessary for assessing the suitability of the proposed strategy in a multi-season study for different citrus varieties or species and under different crop conditions.

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Table 1. Summary of the soil physical properties and crop data as inputs for the LEACHM model.

Component	Parameter	Units	Value
Soil profile data	Soil bulk density	kg dm^{-3}	See table 2
	Clay	%	See table 2
	Silt	%	See table 2
	Organic carbon	%	See table 2
	Particle density (clay. silt and sand)	kg dm^{-3}	See table 2
	Exponent for Campbell's equation	-	See table 2
	Hydraulic conductivity	mm d^{-1}	See table 2
	Particle density (clay. silt and sand)	kg dm^{-3}	2.65
	Particle density (organic matter)	kg dm^{-3}	1.10
	Wilting point	kPa	-1500
Crop data	Maximum ratio of actual to potential T	-	1.1
	Minimum root water potential	kPa	-3000
	Root resistance	-	1
	Crop cover fraction	-	1
	Pan factor	-	1.50
Weather data	Rain	mm	Daily data
	Potential evapotranspiration	mm	Weekly totals
	Temperature	ºC	Mean weekly
	Thermal amplitude	ºC	Mean weekly

Table 2. Soil physical and chemical properties for the different soils where FDR probes were installed.

	Reference				Scheduling	
Parameter	**1**	**2**	**3**	**4**	**1**	**2**
Soil bulk density (kg dm^{-3})	1.53	1.54	1.56	1.49	1.55	1.58
Clay (%)	28.0	29.0	26.0	24.0	25.4	24.7
Silt (%)	35.5	35.5	36.0	39.0	39.9	39.8
Organic carbon (%)	0.48	0.52	0.44	0.62	0.54	0.54
Air entry value (kPa)	-0.33	-0.72	-0.75	-0.66	-2.51	-2.23
Exponent for Campbell's equation (-)	12.00	12.00	11.31	11.59	7.49	11.15
Hydraulic conductivity (mm d^{-1})	99.48	37.20	59.04	111.72	118.68	95.52

Table 3. (A) Critical soil water content measured by FDR probes ($\theta^{Def}_{crit-FRD}$), and (B) standardized critical soil water content (θ^{Def}_{crit}) for probes noted as Definition 1 to 4 obtained from solving linear regressions from Figure 1. Average vapour deficit pressure (VPD) is indicated for each period.

	Period A1 - A2 **VPD = 0.9 - 1.1 kPa**	**Period B1 - B2** **VPD = 1.1 - 1.3 kPa**	**Period C1 - C2** **VPD = 0.2 - 0.4 kPa**
A) Critical soil water content measured by FDR probes, $\theta^{Def}_{crit-FRD}$ (% vol.)			
Definition 1	34.1	36.2	33.6
Definition 2	31.7	33.2	30.3
Definition 3	33.6	35.3	30.5
Definition 4	31.3	33.6	28.2
B) Standardized critical soil water content, θ^{Def}_{crit} (% vol.)			
Definition 1	26.6	28.9	26.0
Definition 2	28.2	29.6	26.8
Definition 3	24.9	26.8	21.4
Definition 4	27.3	30.3	23.4
μ	26.8	28.9	24.4
σ	1.4	1.5	2.5

Table 4. Fitting linear regression equations between volumetric soil water content measured by means FDR probes (θ_{FDR}) and simulated with LEACHM model (θ_{SIM}) for Definition (1 to 4) and Validation (1 to 2) FDR probes. Constants a and b are the fitting parameters and Rsqr is the coefficient of determination.

	$\boldsymbol{\theta_{FDR}}$ **= a** $\boldsymbol{\theta_{SIM}}$ **+ b**		
	a	**b**	**Rsqr**
Definition 1	0.89	10.45	0.90
Definition 2	1.03	2.68	0.93
Definition 3	0.91	11.00	0.82
Definition 4	0.78	9.97	0.90
Validation 1	0.69	15.63	0.72
Validation 2	0.67	14.62	0.84

Table 5. (A) Critical soil water content for scheduling irrigation by FDR probes ($\theta_{crit-FRD}^{Val}$) and (B) standardized critical soil water content for scheduling irrigation (θ_{crit}^{Val}) for probes noted as Validation 1 and 2 for post-harvest, bloom and fruit-set and phases I II and III of fruit growth. Average vapour deficit pressure (VPD) is indicated for each phase.

	Post-harvest	**Bloom and fruit set**	**Phase I**	**Phase II**	**Phase III**
	VPD = 0.6kPa	**VPD = 0.6 kPa**	**VPD = 0.9 kPa**	**VPD = 1.1 kPa**	**VPD = 0.5 kPa**
A) Critical soil water content measured by FDR probes, $\theta_{crit-FRD}^{Val}$ (% vol.)					
Validation 1	32.2	32.2	33.9	35.5	32.2
Validation 2	30.3	30.3	31.9	33.5	30.3
B) Standardized critical soil water content, θ_{crit}^{Val} (% vol.)					
Validation 1	24.0	24.0	26.5	28.8	24.0
Validation 2	23.4	23.4	25.8	28.1	23.4
μ	23.7	23.7	26.2	28.5	23.7
σ	0.4	0.4	0.5	0.5	0.4

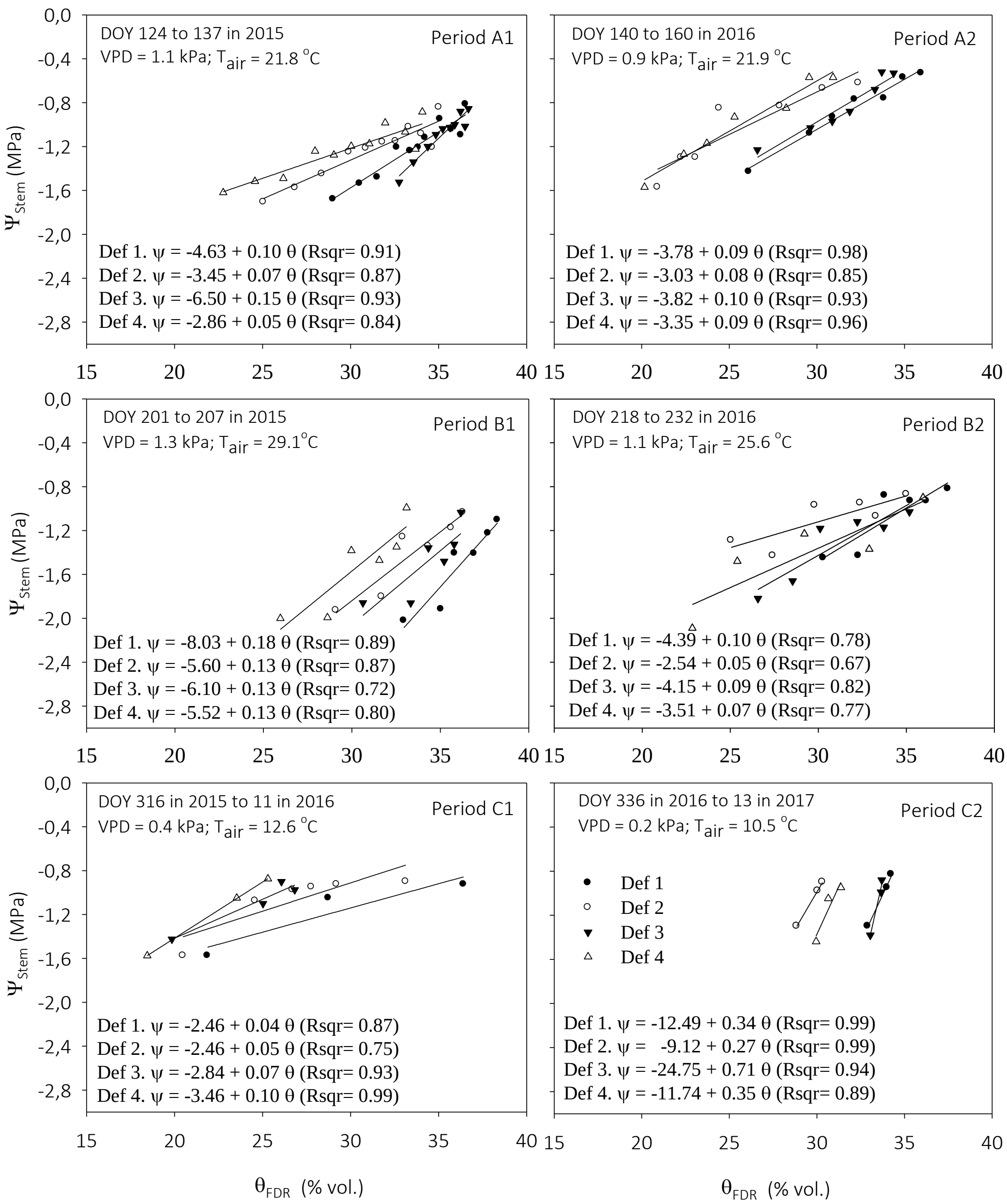

Fig. 1. Experimental values of midday stem water potential (Ψ_{Stem}) and its corresponding soil water content measured with FDR probes (θ_{FDR}) in the layer 0.2 – 0.5 m obtained from the drought cycles made in 2015 and 2016. Def. refers to the four FDR probes used for measuring soil water content. Linear regression and coefficient of determination (Rsqr) for each repetition are represented. Day of the year (DOY), average air temperature (T_{air}) and average air vapour pressure deficit (VPD) is indicated for each graph.

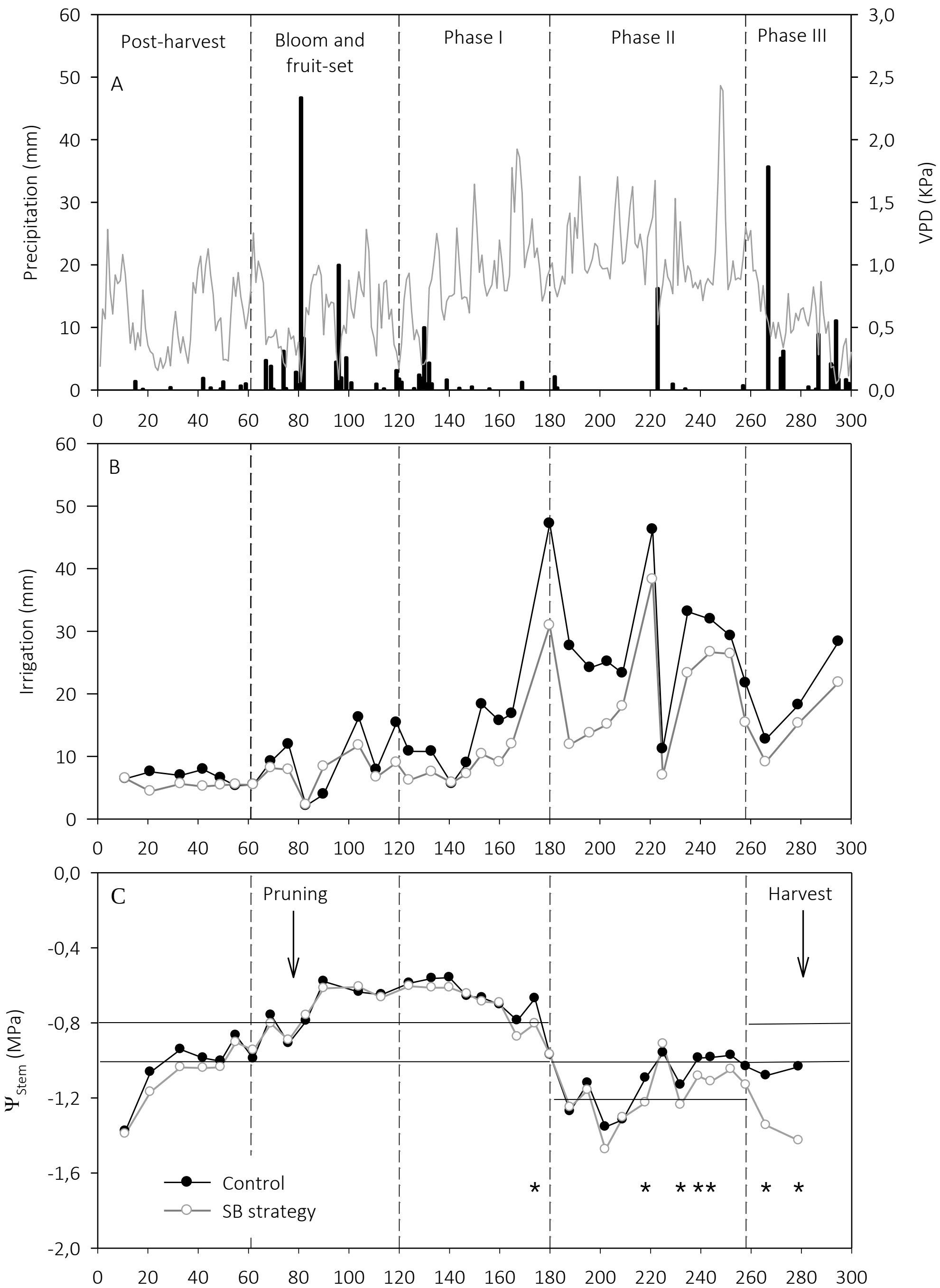

Fig. 2. Seasonal patterns of (A) mean daily air vapour deficit pressure (VPD; solid line) and precipitation (vertical bars); and (B and C) irrigation depths and midday stem water potential (Ψ_{Stem}) in each treatment [control and sensor-based (SB) strategy] during 2016. Control treatment was irrigated during the whole season at 100% ET_c and the SB strategy was irrigated following soil water content measured with FDR probes. In C, horizontal lines show the thresholds of ψ_{stem} used to evaluate plant water status; and asterisks represent statistically significant differences in ψ_{stem} at P<0.05 between treatments. Vertical dotted lines show post-harvest, bloom and fruit-set and fruit growth phases (I, II and III). Arrows in figure (C) indicate the pruning and harvest date.