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Soil capacitance sensors and stem dendrometers. Useful tools for irrigation scheduling of commercial orchards?

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Abstract

Irrigation scheduling is often performed based on a soil water balance, where orchard evapotranspiration is estimated using the reference evapotranspiration (ETo) times the crop coefficient (Kc). This procedure, despite being widely spread, has some uncertainties. Because of this, plant and soil water status monitoring could be alternatively or complementarily used to schedule irrigation. The usefulness of capacitance probes was evaluated during several seasons in large irrigation districts where irrigation practices were changed over years from the ETo * Kc model to the analysis of soil water status trend. This area corresponds to drip irrigated orchards planted with citrus, peach, nectarine and persimmon. Around 25% less irrigation was applied with no substantial yield penalty when the information provided by capacitance probes was correctly applied for irrigation management. On the other hand, the usefulness of stem dendrometers for continuously monitoring plant water status was evaluated in a young plum experimental orchard. Over two years, irrigation was scheduled using exclusively trunk shrinkage via the signal intensity approach by means of a baseline equation previously obtained in the orchard. Results showed that it was not always possible to schedule irrigation based on the trunk shrinkage signal intensity due to the temporal changes in the reference values that occurred as trees aged. Overall, results obtained are discussed in terms of the possible extrapolation at field level of both capacitance probes and stem dendrometers. Advantages and drawbacks of each technique are analyzed and discussed.

Additional key words*:* citrus; plum; regulated deficit irrigation; trunk diameter variations; water stress.

Resumen

Las sondas de capacitancia y los dendrómetros. ¿Herramientas para la programación del riego en agricultura convencional?

La programación del riego tradicionalmente se ha basado en un balance de agua en el suelo según el modelo propuesto por la FAO que tiene en cuenta la demanda evaporativa de referencia (ETo) y los coeficientes de cultivo (Kc). Esta metodología aún siendo ampliamente empleada tiene ciertas incertidumbres. Por ello es importante contrastar posibles alternativas al modelo de la FAO. A este respecto, hoy en día, se puede recurrir a la medida del estado hídrico del suelo y de la planta mediante el empleo de sondas de capacitancia multisensor y de los dendrómetros, respectivamente. En este trabajo se ha evaluado la eficacia de las sondas de capacitancia en comunidades de regantes donde la programación del riego se cambió a lo largo de los años desde el uso del modelo ETo y Kc hasta el empleo de las sondas, siendo posible de este modo obtener ahorros de agua cercanos al 25%. Por otra parte, en una parcela experimental de ciruelos jóvenes se ha evaluado la eficacia de los dendrómetros y en concreto de la contracción diaria del tronco como único indicador para la programación del riego mediante el concepto de la intensidad de señal. Los resultados han puesto de manifiesto que no fue siempre posible programar de forma satisfactoria el riego mediante el empleo de dicha técnica, posiblemente debido a cambios temporales en las contracciones del tronco de referencia empleadas para calcular la intensidad de señal. En definitiva, se resumen las características principales de las dos técnicas incidiendo sobre su posible empleo a escala comercial, analizando las ventajas e inconvenientes de cada una.

Palabras clave adicionales: estrés hídrico; ciruelo; cítricos; riego deficitario controlado; variaciones del diámetro del tronco.

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Introduction

Irrigation scheduling is often performed based on a soil water balance, where orchard evapotranspiration is estimated using the reference evapotranspiration (ETo) times the crop coefficient (Kc), according to the procedure suggested by FAO (Allen *et al.,* 1998). This protocol, despite being widely spread, has some uncertainties. An important one, particularly in tall tree orchards, is due to the high degree of coupling of trees to the variable air humidity compared to the reference grass that is quite uncoupled from the bulk air and dependent primarily on net radiation (Annandale and Stöckle, 1994). In addition, in woody crops, water use might change as function of several orchard and tree characteristics affecting the amount of light intercepted by a tree (Consoli *et al.,* 2006), soil orchard management (Allen *et al*., 1998) or tree crop level (Naor, 2006).

The irrigation scheduling based on a soil water balance only provides information on the amount of water to apply to an orchard during a certain period. The irrigation frequency to schedule is then left to the grower practical experience. Indeed, the optimum frequency of irrigation depends upon several orchard and irrigation system design characteristics very difficult to take into account in simple models. However, the frequency of irrigation is a crucial aspect of irrigation scheduling that strongly determines the overall orchard irrigation efficiency.

In this sense, irrigation scheduling could be performed using complementarily plant and soil water status determinations that might provide more specific, real-time, information of the orchard water needs. Because of its inherent nature, soil water status information is clearly more readily and easily used by growers as its variation along the season can be easily interpreted. Despite it has been shown that plant response to a given soil water status might be dependent on the evaporative demand (Sadras *et al.,* 1993); at a grower scale, it can be assumed that soil water status alone could be a good indicator of plant performance. Analyzing trends in soil water content (SWC) or potential might be simply used for irrigation scheduling.

Determination of soil water status has been long explored and used for irrigation scheduling. Several tools are nowadays available for this purpose (Leib *et al.,* 2003). Single sensors tools such as the granular matrix sensors, tensiometers or small capacitance, impedance or time domain transmission probes might provide for a relatively low-cost information of soil water status in a single spot of the root zone (Intrigliolo and Castel, 2004). However, for a better control of soil water trends at different depths, with the additional aim of controlling the percolation of water below the root zone, multi-sensor probes with nearly continuous readings of soil water content at different depths are preferred (Starr and Paltineanu, 1998a,b). Capacitance probes are nowadays the most widespread tools used for this purpose, particularly thanks to the availability of easy-to-use friendly software allowing users to easily visualize and analyze soil water content trends by customized graphs.

The use of soil capacitance probes has been the subject of previous research where it was shown that they are not reliable for precise determinations of the soil water balance (Evett, 2000; Vera *et al.,* 2009; Evett and Schwartz, 2010). Indeed, for research purposes, where accurate readings of SWC are needed, neutron probes are certainly still a more useful tool (Evett *et al.,* 2006, 2009). However, the use of capacitance probes as an indicator of SWC trend at different depths could be potentially useful to growers, in order to clearly identify trends in soil water changes and as an aid for optimizing the irrigation scheduling.

On the other hand, measurements of plant water status integrate both soil water available to the plants and the climatic conditions, and might therefore provide for a better prediction of tree responses to water supply (Intrigliolo and Castel, 2006a). In this sense, stem water potential is the more commonly used parameter to estimate plant water status (Shackel *et al.,* 1997). However, since its measurement cannot be easily automated the use of trunk diameter variations as water stress indicators has also been evaluated in the last years (Naor, 2006). In this respect, the maximum diurnal trunk shrinkage (MDS) has been proposed as a reliable water stress indicators in woody crops (see revisions by Fernández and Cuevas, 2010; and Ortuño *et al.,* 2010). In a number of studies it has been shown that MDS in well irrigated trees depends largely on the climatic conditions (Fereres and Goldhamer, 2003; Intrigliolo and Castel, 2006b; Ortuño *et al.,* 2006). This

Abbreviations used: ETc (crop evapotranspiration), ETo (reference evapotranspiration), FDR (frequency domain reflectometry), Kc (crop coefficient), LAI (leaf area index), LVDT (linear variable differential transformers), MDS (maximum diurnal trunk shrinkage), RDI (regulated deficit irrigation), SI (signal intensity), SWC (soil water content), VPD (air vapour pressure deficit), Ψstem (midday stem water potential).

complicates the use of MDS in absolute terms to schedule irrigation as proposed by Bussi *et al.* (1999). To counteract the effects of the climatic conditions it is required a previous knowledge of the effects of the evaporative demand on MDS and latter use this relationship or «baseline» as a reference to correct the actual MDS values obtained. The ratio actual MDS/well irrigated MDS, named as signal intensity (SI, Goldhamer and Fereres, 2001), can then be the used as an indication of the water status of the trees to schedule irrigation.

The research reported here summarizes results obtained in experimental and in commercial orchards where the feasibility of using capacitance probes and stem dendrometers for scheduling either full or deficit irrigation was studied. Overall, results obtained are discussed in terms of the possible extrapolation at field level of both techniques. Advantages and drawbacks of each technique are analyzed.

Material and methods

Soil water capacitance sensors experiment

Experiments reported correspond to the commercial applications of frequency domain reflectometry (FDR) soil probes in an irrigation district of 2000 ha located in the Marquesat region, Valencia (39° 15'N, 0° 36'W, elevation 114 m). This area, depicted in Figure 1, corresponds to drip irrigated orchards planted with citrus, stone fruit trees and persimmon, where water for irrigation is supplied by growers via several small water authorities (companies that provide growers with water for irrigation).

Historically, irrigation scheduling in the area was based on the use of reference evapotranspiration, crop coefficients and precipitation values reported by the «Instituto Valenciano de Investigaciones Agrarias» Irrigation Technology Transfer Service (IVIA-STR, http://estaciones.ivia.es/). During winter and early spring of 2005, 32 soil capacitance probes were installed in different orchards (Fig. 1 and Table 1) located within the limits of the irrigation districts in locations representative of the whole range of crops and soil conditions of the area.

Multi-depth capacitance probes installed were C-Probe (Agrilink Inc., C-probe, series I, Adelaide, Australia) with 4 sensors located at depths of 10, 30, 50 and 70 or 80 cm. Access tubes were installed in the north side of a tree at a distance of around 15 cm from an irrigation emitter. Water content was determined at each depth every 5 min, and 15 min averages were stored in the probe datalogger and transmitted via radio. A single probe was installed on each of the 32 selected orchards (Table 1). Therefore, within the entire area, there was approximately a single probe per each 62 ha. Hence, from 2005 onwards, irrigation was scheduled

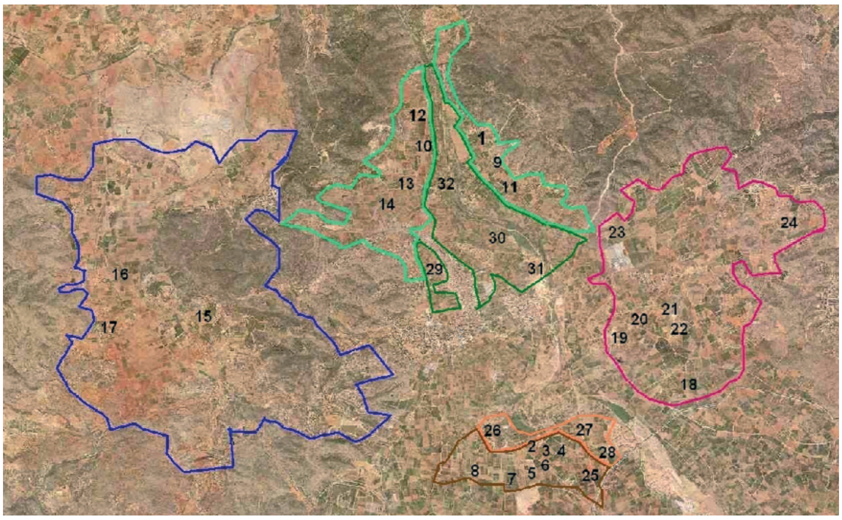

Figure 1. Aerial photograph for the area where the irrigation scheduling procedure based on the soil capacitance probes was applied. The colored lines delimit the different water authorities. Numbers shown correspond to the location of the different plots where soil capacitance probes were installed. Additional information on each specific location is available in Table 1.

Table 1. List of soil capacitance probes installed in different orchards with their location within the Valencia province, area and soil texture. It is shown those plots where Ψstem was measured during 2008. Soil texture data were not available for all orchards

Probe number	Crop	Ψstem	Place	Area (ha)	Soil texture
1	Mandarine	Yes	Llombai	0.37	Sandy loam
2	Persimmon	No	Catadau	0.33	Clay loam
3	Peach	Yes	Catadau	0.66	Clay loam
4	Plum	No	Catadau	0.54	Sandy clay loam
5	Mandarine	Yes	Catadau	1.52	
6	Nectarine	Yes	Catadau	0.47	Clay loam
7	Mandarine	No	Catadau	1.16	
8	Orange	No	Catadau	0.54	
9	Peach	Yes	Llombai	0.65	Sandy loam
10	Mandarine	No	Llombai	4.58	Sandy clay loam
11	Peach	Yes	Llombai	1.87	Sandy loam
12	Orange	No	Llombai	0.44	
13	Mandarine	Yes	Llombai	0.47	
14	Mandarine	No	Llombai	0.68	Loam
15	Mandarine	Yes	Llombai	0.84	Loam
16	Mandarine	No	Llombai	0.03	
17	Peach	Yes	Llombai	0.90	Clay loam
18	Mandarine	No	Alfarp	0.71	Loam
19	Orange	No	Alfarp	3.91	
20	Peach	Yes	Alfarp	0.50	Sandy loam
21	Mandarine	No	Alfarp	0.49	Sandy loam
22	Mandarine	Yes	Alfarp	0.62	Sandy loam
23	Peach	Yes	Alfarp	0.38	
24	Mandarine	Yes	Alfarp	3.58	Sandy clay loam
25	Persimmon	No	Carlet	0.20	Loam
26	Mandarine	No	Catadau	1.25	
27	Mandarine	No	Catadau	0.85	
28	Persimmon	No	Carlet	0.74	
29	Orange	No	Llombai	1.03	
30	Orange	No	Llombai	0.62	
31	Mandarine	No	Llombai	0.47	
32	Mandarine	No	Llombai	0.37	

on the base of SWC trends provided by the capacitance probes and analyzed with the C-Probe Software.

The irrigation scheduling approach with the capacitance probes was based on the following two main points: 1) the maintenance of SWC in the 10-50 cm depth in an optimum range between field capacity and an allowable soil water depletion that depends on the farmer strategy, crop species and phenological periods for each species, and 2) avoiding water percolation down to 70-80 cm in order to minimize water lost by drainage. This is based on the evidence that for drip irrigated woody crops, very often, the more active root water uptake zone is located in the first 60 cm of the soil profile (Andreu *et al.,* 1997; Abrisqueta *et al.,* 2008). For these purposes sensors were normally located at 10, 30, 50 and 80 cm. In order to have a clear data visualization and interpretation, the manufacturer software graphs are set to give the SWC sums of the three sensors located at 10, 30 and 50 cm, and another graph shows the SWC trend at 70-80 cm.

The «water authorities» technicians were responsible for recording and analyzing the data from the capacitance probes. The information was indeed used to adjust the volumes of water applied. However, on each water authority, there were orchards where the final irrigation scheduling was carried out exclusively by the technicians (technician irrigation type), but there were other orchards where growers had on-demand water, which means that the grower would finally decide their irrigation regime and frequency regardless of the technicians recommendations (grower irrigation type). This is a common feature for many irrigation districts of south-east Spain.

Water applied by all the water authorities over the entire irrigation district were recorded starting from season 2004, before the new irrigation protocols, based on soil water sensors, were initiated, up to year 2008. Year 2004 was then used as the reference season and in the rest of the years, annual water application, corrected for seasonal rainfall, was compared to that of the reference year.

In order to check if the irrigation scheduling protocols based on the soil capacitance probes were detrimentally affecting plant water status, in the last experimental season midday stem water potential (Ψstem) was determined in some of the citrus and peach plots (Table 1) where irrigation was scheduled with the soil capacitance sensors. Stem water potential, was measured periodically with a pressure chamber, following the procedures described by Turner (1981), in four leaves per orchard and occasion. Mature leaves, from the north face near the trunk, were enclosed in plastic bags covered with silver foil at least two hours prior to the measurements, which were carried out between 12:00 and 13:00 h solar time.

In addition, in order to asses if the irrigation scheduling procedure affected tree performance, the yield values of selected citrus and peach orchards were recorded during the course of the experiment (from season 2004, the reference year, till year 2008).

Stem dendrometers experiment

The usefulness of stem dendrometers as the only variable to schedule irrigation was studied in an experiment carried out during 2005 and 2006 in a 6-year old plum experimental orchard (*Prunus salicina*. 'Black Gold' on Marianna GF81) planted at 5 × 3.5 m spacing and located at Liria, Valencia (39° 45'N, 0° 38'W, elevation 300 m), Valencia, Spain. At the beginning of the experiment average tree leaf area index (LAI) and percentage of shaded area were 1.5 and 30%, respectively. The soil is a sandy loam with abundant (32% by weight) stones and about 80 cm of effective depth. The irrigation water had an average EC of 1.1 dS m^{-1} and an average Cl concentration of 122 mg L^{-1}.

The experiment had three treatments and three replicates in a randomized complete block design. Each experimental plot comprised three adjacent rows of eight trees per row, with the two center trees of the central row being used for measurement. Irrigation treatments were:

1) Control, fully irrigated trees where irrigation scheduling was based on the standard FAO approach replacing crop evapotranspiration (ETc), that was estimated as the product of reference evapotranspiration (ETo) and crop coefficient (Kc). The reference evapotranspiration was calculated from the Penman-Monteith equation using hourly data collected by an automated weather station situated near the orchard. Crop coefficients were obtained from Allen *et al.* (1998) and adjusted for tree size following Fereres and Goldhamer (1990). On a seasonal basis, average Kc was 0.5.

2) Standard regulated deficit irrigation (RDI) where water was applied at 25% of ETc during May (phase II of fruit growth) and at 50% of ETc during post-harvest (mid-July to the end of October). During the rest of the season (phase I and III of fruit growth) water was applied at 100% of ETc.

3) Regulated deficit irrigation scheduling based on stem dendrometers (MDS_{RDI}). Irrigation was scheduled in order to maintain the signal intensity, SI (*i.e.* the actual maximum diurnal trunk shrinkage (MDS) of this treatment divided by the MDS reference value), around certain threshold values, similar to the methodology used by Goldhamer and Fereres (2004). The MDS reference values were calculated using: i) the reference baselines equations previously obtained during 2002 to 2004 in the well watered trees of the same orchard, as reported in detail in Intrigliolo and Castel (2006b) and ii) the actual average midday air vapor pressure deficit (VPD) values recorded in the orchard. The threshold values for SI were 1.0 (*i.e.* absence of plant water stress) during phases I and III of fruit growth and 1.5 and 1.7 for phase II of fruit growth and for post-harvest, respectively. Irrigation was scheduled on a weekly basis, and the irrigation dose modified accordingly to the SI value, that is decreased or increased when the SI value was below or above the threshold value, respectively. The SI target values chosen were based on previous experiments (Intrigliolo and Castel 2005, 2006b) in the same orchard.

Trunk diameter variations were measured in MDS_{RDI} treatment with six linear variable differential transformers (LVDT, Schlumberger Mod. DF-2.5). On each experimental tree a sensor was fixed to the main trunk by a metal frame of Invar (a metal alloy with a minimal

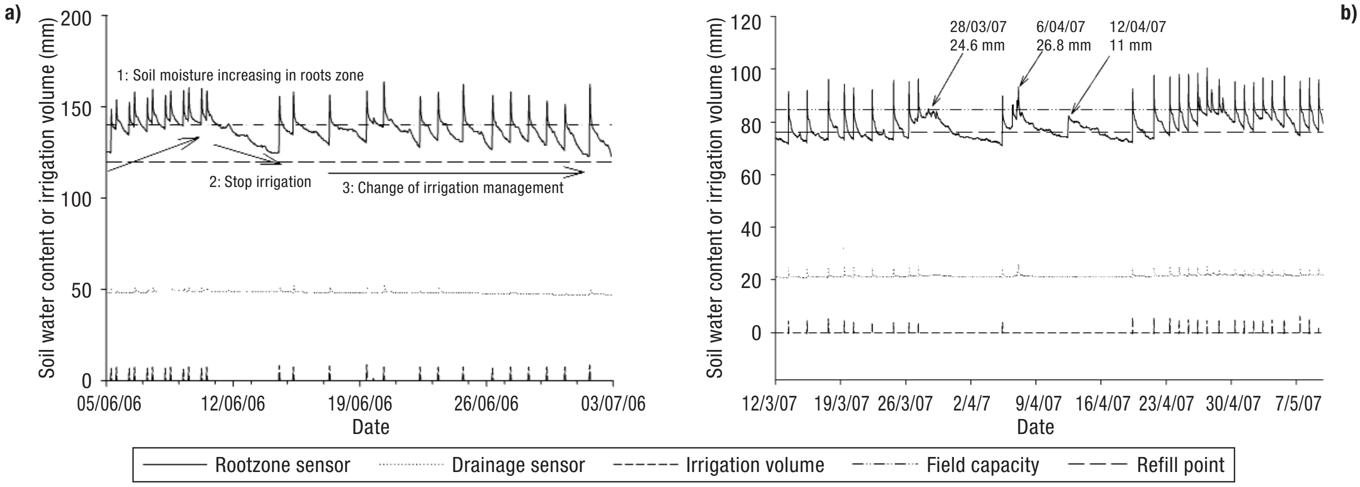

Figure 2. a) Examples of soil water content evolution for irrigation scheduling during a period of absence of rainfall. Irrigation frequency was changed in order to avoid an increase of the soil water content below the root zone. b) Example of use of soil capacitance sensor for irrigation scheduling after rainfall events.

thermal expansion) located about 20 cm from the ground on the north side. Other details on their installation, calibration and data recording were given in Intrigliolo and Castel (2004). Maximum daily shrinkage was obtained as the difference between the maximum diameter reached early in the morning and the minimum reached normally during the afternoon.

Ψstem was also measured following the same procedures described for the soil capacitance sensors experiment in three trees per treatment and 2 leaves per tree.

Results and discussion

Soil water content capacitance sensors

An example of SWC trends for citrus trees cv. Marisol (Fig. 2) shows that irrigation management was changed decreasing the frequency of irrigation in order to optimize water applications (Fig. 2a). The decrease in the irrigation frequency allowed maintaining the water content in the root zone (10-50 cm depth) at near optimum levels (*i.e.* 80-90% of field capacity), thereby reducing the total water application.

Another practical application of the soil sensors is to provide information on when to re-start irrigation after rainfall events (Fig. 2b). In these circumstances it is difficult for growers to quantify the amount of effective precipitation, which is a very difficult parameter to estimate correctly, since it depends on several variables difficult to model. Analyzing the evolution of the SWC trend after the rainfall event can be used to decide when to start irrigation allowing for a certain depletion of SWC. In the case of the results reported in Figure 2b, after the rainfall events of March and April 2007, irrigation was only re-started when the SWC in the root zone went below the allowable depletion of 16% of field capacity.

The seasonal variation of the SWC in a typical probe (one out of the 32 probes installed), shows that SWC in the root zone was reasonably constant over the years (Fig. 3). Although in all the seasons there was some increase in the SWC in the deeper sensor, suggesting that there was some water going deeper than 80 cm,

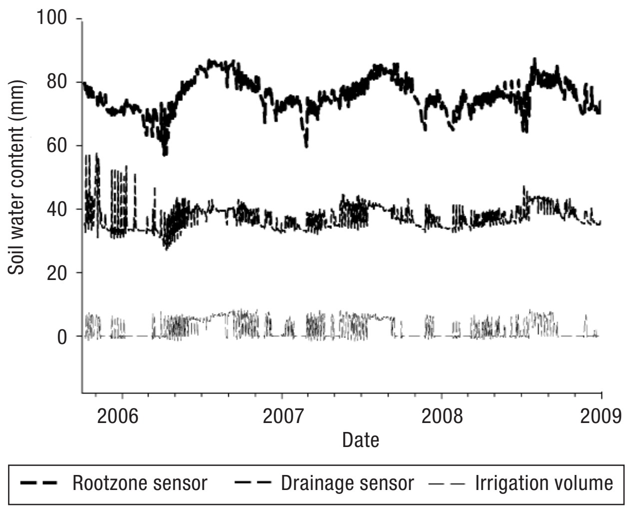

Figure 3. Example of soil water content trend over several seasons registered in one capacitance probe tube. Soil water content in the root zone (10-60 cm) and at 80 cm (deeper sensor) and irrigation volumes applied are separately shown.

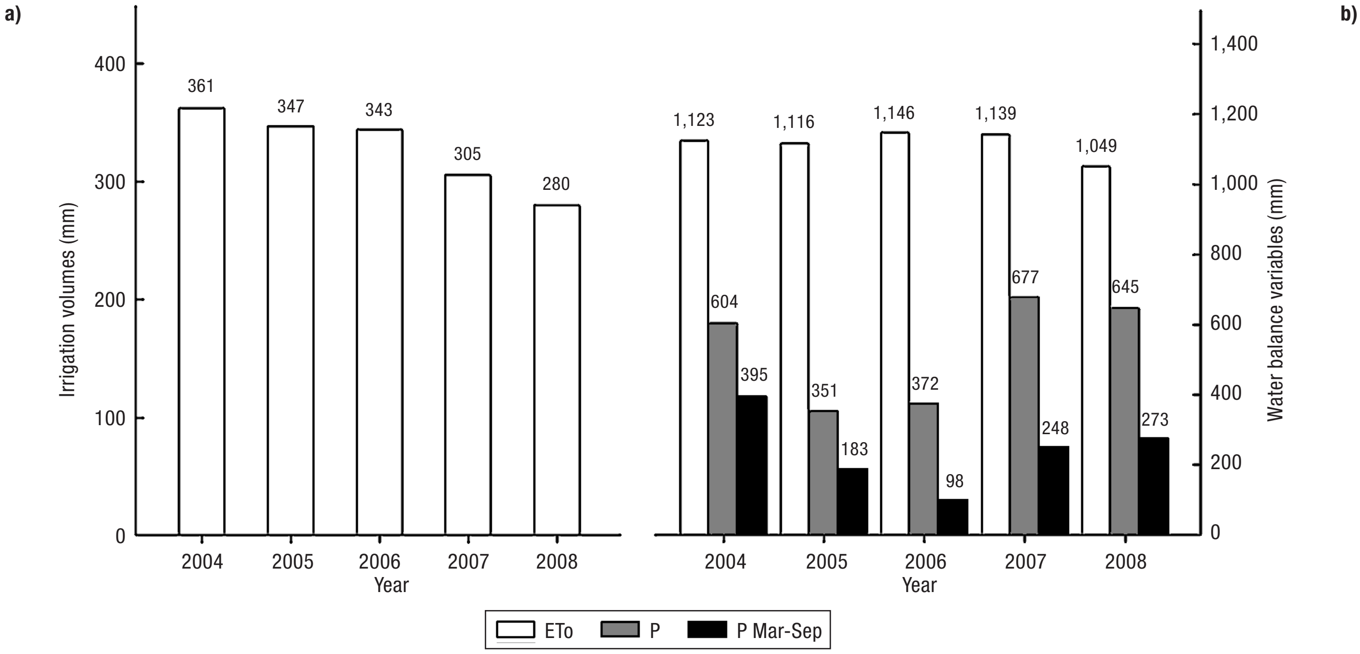

Figure 4. a Average irrigation volumes applied for an entire irrigation districts. b) Climatic conditions during the experimental years. Annual reference evapotranspiration (ETo) and rainfall and irrigation rates from March to September are shown.

the intensity of this phenomenon diminished along the seasons (Fig. 3).

The analysis of water application for the whole irrigation district where plots were irrigated based on a mix of both the technician and the grower final decision, shows that there was a clear decreasing trend of water applications after year 2005 once the capacitance probes where installed and irrigation was scheduled using the SWC trend information (Fig. 4a). In fact, in year 2008, there was a water saving of 23% compared to year 2004, before irrigation scheduling with the capacitance probe started. Reference evapotranspiration was only 7% lower in 2008 than in 2004 and yearly rainfall was 6% higher in 2008, but the precipitation during the main irrigation season (March to September) was 31% lower in 2008 than in 2004 (Fig. 4b).

The seasonal variation of Ψstem of several citrus and peach orchards, where irrigation was scheduled with the capacitance probes, reveals that the irrigation scheduling procedure did not detrimentally affect plant water status (Fig. 5). In fact, in almost all citrus orchards Ψstem was above –1.1 MPa, which is considered a value representative of well watered trees under Mediterranean conditions (Intrigliolo *et al.,* 2008). Only in one plot, in a few occasions, Ψstem went down to –1.5 MPa, suggesting that only that particular orchard

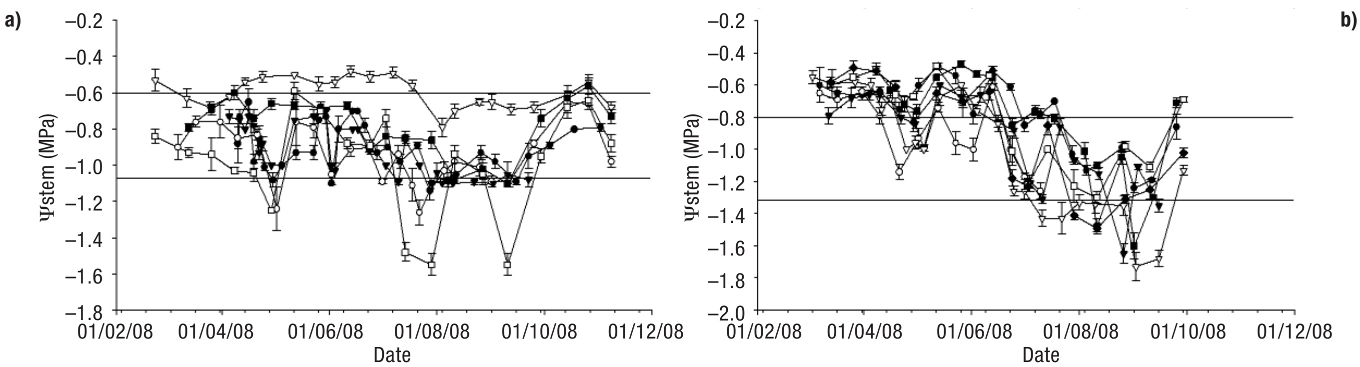

Figure 5. Seasonal variation of midday stem water potential (Ψstem) during 2008 in a) citrus and b) peach orchards where irrigation was scheduled using the soil capacitance sensors information. Horizontal solid lines enclose the range of Ψstem values for well irrigated trees. Different symbols are used to differentiate between orchards.

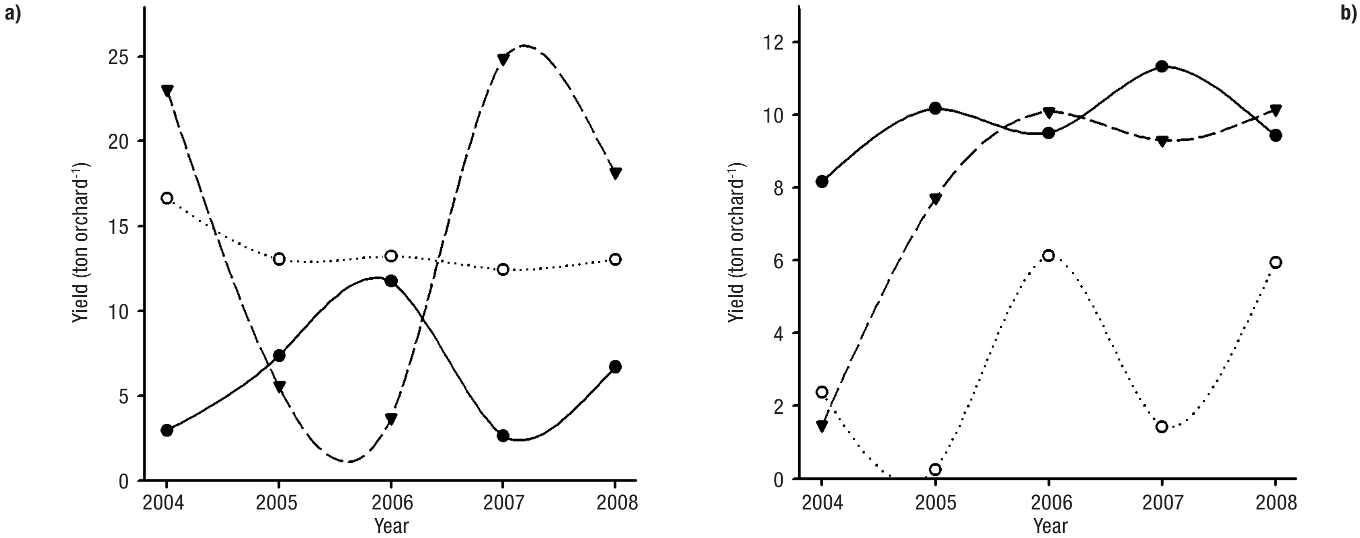

Figure 6. Variation over years in the yield value of selected a) citrus and b) peach orchards where irrigation was scheduled using the soil capacitance sensors. Different symbols are used to differentiate between orchards.

might have suffered some circumstantial water stress. In the peach plots, at the beginning of the season (*i.e.* fruit growth period) Ψstem was always above –1.0 MPa (threshold for well watered stone fruit trees; Naor, 2006), and from July onwards, plant water status decreased, which coincides with the post-harvest period when growers deliberately reduce water applications, as some water stress during post-harvest is often applied to control tree vigor (Johnson and Handley, 2000).

In addition to the plant water status, the analysis of year-to-year variations in yield reveals that there was not a decreasing trend in the fruit produced for the plots where irrigation scheduling was changed from the ETo * Kc model (season 2004) to the SWC trend analysis (seasons 2005 to 2008, Fig. 6). Slopes of the regression lines of yield *versus* seasons, were for all plots not statistically different ($p < 0.05$) than zero.

An analysis of water application was conducted separating data according to the actor involved in taking the final irrigation scheduling decision, either the technician that has direct access to the SWC information, or the grower himself, that despite potentially has access to the same information, he may schedule his own irrigation based on other information or feeling. In the case of technician-scheduled plots, the volumes of water applied clearly decreased from year 2004 to year 2008, with a reduction in the last season of 37% of total water application (Fig. 7). In the case of grower-scheduled plots, the irrigation regimes did not change much over the years and only in the final year 2008 was there a decrease of 13% in water application with respect to 2004 (Fig. 7). It is crucial then that an adequate transference of the information obtained with the probes effectively reaches the grower, who is the final user, in order to take advantage of the full potential that this type of devices might offer for irrigation scheduling.

Stem dendrometers experiment

In the first experimental season in treatment MDS_{RDI} irrigation scheduling was able to maintain the SI values

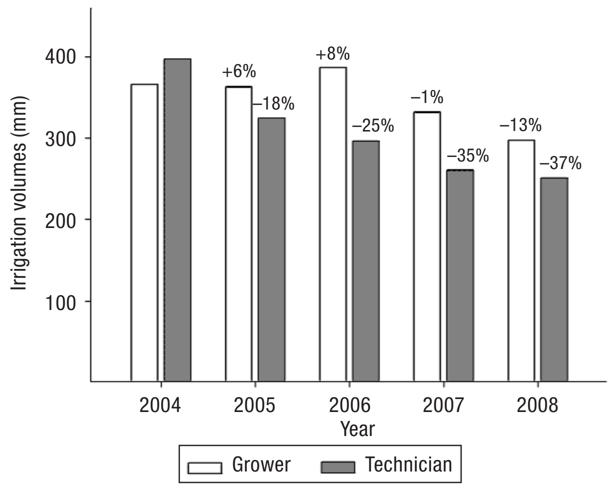

Figure 7. Average irrigation volumes applied for entire irrigation districts. Plots are separated according to the actor involved in taking the final irrigation scheduling decision, the water authority technician or the grower.

(*i.e.* MDS_{RDI}:MDS_{REF}) around the previously established target values (Fig. 8b). At the beginning of the season, when the first water applications were scheduled according to the ETo * Kc procedure, SI was below 1.0, indicating that MDS was below the reference, probably because trees had not yet fully completed their canopy

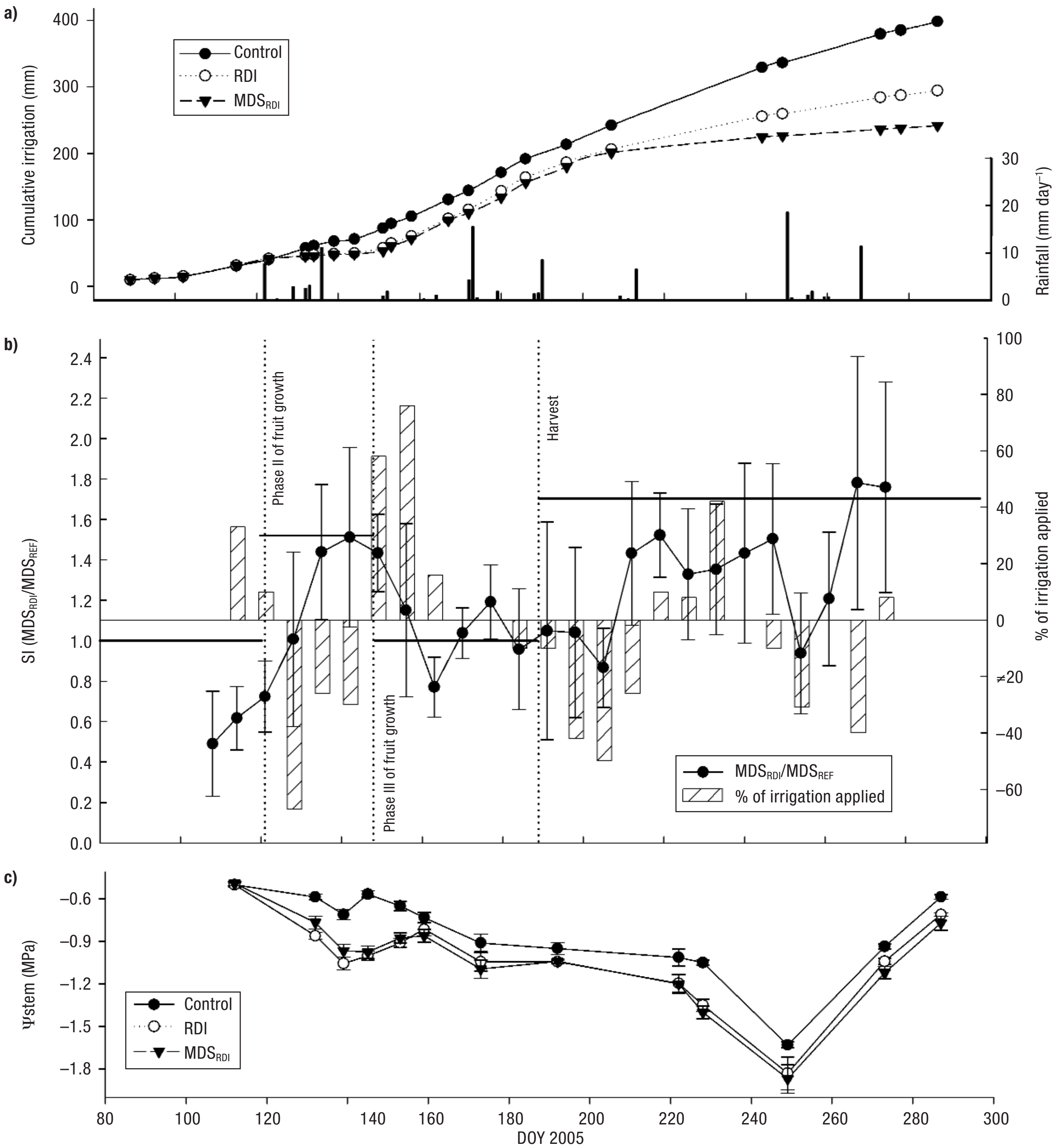

Figure 8. Seasonal variation during 2005 of a) irrigation volumes applied in the different treatments, b) average weekly values of the signal intensity for the MDS_{RDI} treatment and the relative percentage of variation in the irrigation volumes applied with respect to the previous week. Values of signal intensity shown are average of six sensors and error bars are the standard error, c) midday stem water potential (Ψstem) for the different treatments. Values are average of six determinations per treatment and error bars are the standard error. DOY: day of the year.

growth. With the onset of phase II of fruit growth (*i.e.* pit hardening) when water application started to diminish, SI increased to reach the target value of 1.5 by the end of this phase. During the final stage III of fruit growth, when it is known that water restrictions can be harmful for final fruit size (Naor, 2006), the target values of SI were 1.0, in order to ensure absence of water stress. During this period irrigation volumes were increased and SI went down to 1.0. After harvest, water restrictions were initiated, and despite some rainfall events that disrupted the watering regime, SI increased during the post-harvest period up to 1.7.

At the beginning of the season the irrigation volumes applied in treatment RDI and MDS_{RDI} were similar and only by the end of the post-harvest period they started to diverge as consequence of the scant water application to MDS_{RDI} in attempting to increase the SI. By the end of the season, RDI and MDS_{RDI} allowed for water saving with respect to the control treatment of 27% and 39%, respectively.

Water restrictions applied both in RDI and in MDS_{RDI}, showed the expected decrease in plant water status (Fig. 8c), but the Ψstem values recorded where in both cases higher than the limits of plant water stress producing detrimental effects on tree performance obtained in previous experiments (–1.5 MPa during fruit growth and –2.0 MPa during post-harvest; Intrigliolo and Castel 2005, 2006a). This occurred, in both treatments, in the RDI one where plant water status was just the result of the water restrictions deliberately imposed and in treatment MDS_{RDI} where the irrigation regime was modulated according to the tree water status (*i.e.* the SI value).

Despite the considerable water savings achieved there were not significant differences in tree yield nor fruit weight between deficit irrigated treatments and the control, nor between the two deficit irrigated strategies (Table 2). However, treatment MDS_{RDI} allowed for higher water savings.

Unfortunately, in the second season in treatment MDS_{RDI} it was not always possible to maintain the SI close to the target value during each specific phenological period (Fig. 9b). During fruit growth it seems that there was a delay between the actual water stress suffered by the trees and the target level. Trees did not reached the threshold SI of 1.5 by the end of phase II, as it was planned, but this threshold was reached later, well in the middle of the rapid fruit growth period. This feature was not attributable to stem dendrometers malfunctioning but to the fact that in field conditions the timing when a certain plant water stress is reached depends not only on the onset of irrigation restrictions but also on the weather conditions. During post-harvest, there was always an increasing trend of SI that reached the target value only by the end of the deficit irrigation period.

During most of the 2006 season the SI tended to be lower than 1.0, a fact which suggests that the calculated reference MDS values (given by the reference equations based on previous years data) where probably overestimating MDS for this particular year. Recent findings have shown that MDS can also be affected by other factors, independently of environmental conditions, such as tree age, tree size, the phenological period and the crop load (see revision by Ortuño *et al.,* 2010). The use of a reference equation could be then more complex than previously thought when a single season irrigation scheduling with a reference equation was evaluated as in almond trees in California (Goldhamer and Fereres, 2004).

An alternative approach to avoid this problem is to relate the actual MDS values of a given treatment to the reference MDS values concurrently obtained in well irrigated trees in the same plot. This method implies

Table 2. Yield components results for the stem dendrometers experiment carried out in plum trees. Water was applied to match ETc (control) or water was applied at 25% of ETc during phase II of fruit growth and at 50% of ETc during post-harvest (RDI) or according to certain signal intensity values based on maximum diurnal trunk shrinkage (MDS_{RDI})

	2005			2006		
	Control	**RDI**	**MDS_{RDI}**	**Control**	**RDI**	**MDS_{RDI}**
Irrigation (mm)	398	294	241	380	289	214
Yield (kg tree^{-1})	36.4	31.4	31.2	37.1	31.1	30.6
Average fruit weight (g)	103	104	99	85	88	83
# fruit tree^{-1}	354	301	338	441	355*	378

* denotes statistically significant differences at $p < 0.05$ with respect to the control.

higher management complexity (*e.g.*, at least two different irrigation schedules within the same orchard) than when reference lines are used, as well as an increase in investment costs (*e.g.*, higher number of sensors), but results reported in the literature have always showed good performance for this strategy even

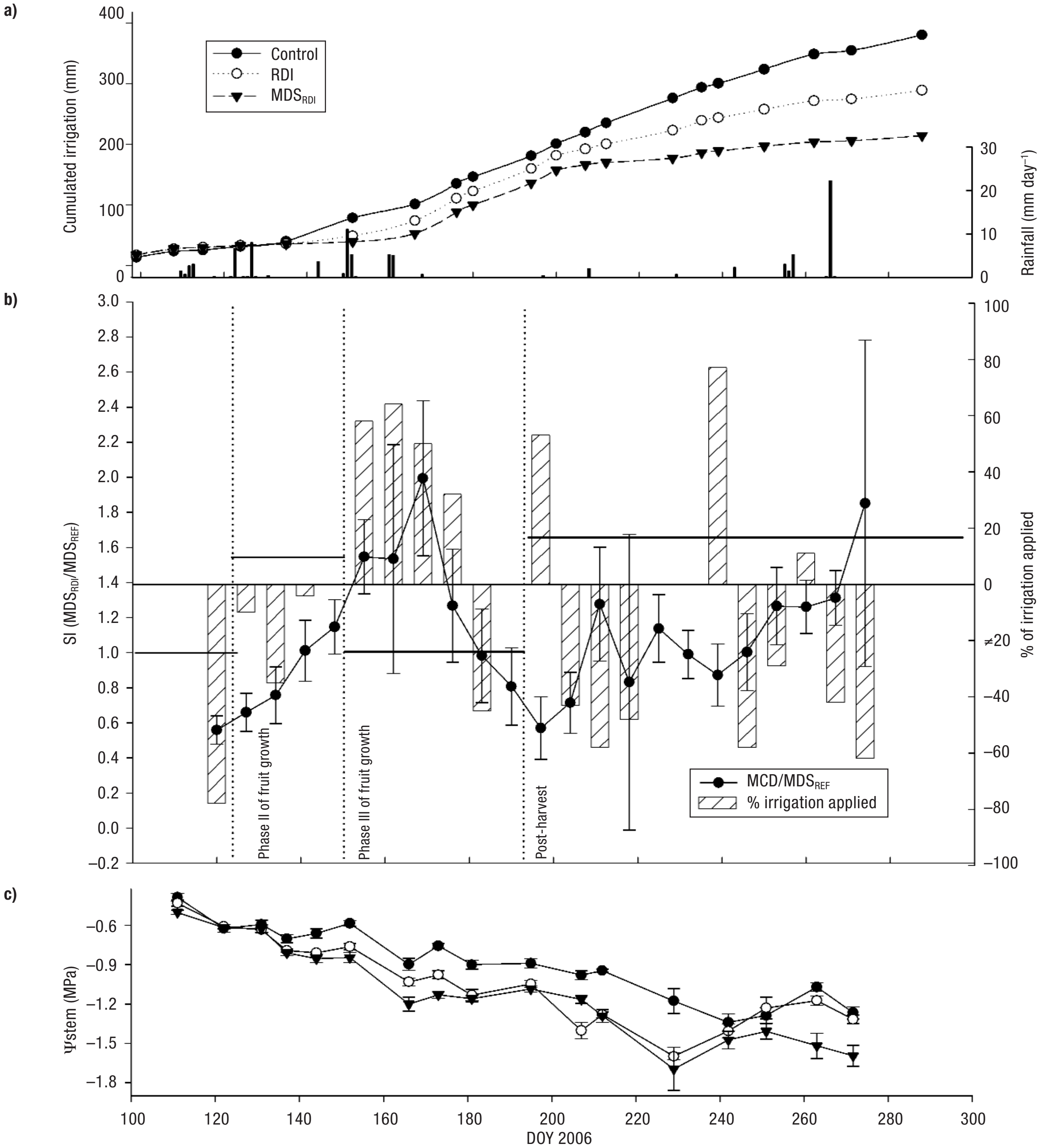

Figure 9. Seasonal variation during 2006 of a) irrigation volumes applied in the different treatments, b) average weekly values of the signal intensity for the MDS_{RDI} treatment and the relative percentage of variation in the irrigation volumes applied with respect to the previous week. Values of signal intensity shown are average of six sensors and error bars are the standard error, c) midday stem water potential (Ψstem) for the different treatments. Values are average of six determinations per treatment and error bars are the standard error. DOY: day of the year.

over more than one season (Conejero *et al.,* 2007; García-Orellana *et al.,* 2007; Vélez *et al.,* 2007).

The water restrictions during 2006 again decreased plant water status (Fig. 9c). Both deficit irrigated treatments had similar seasonal variation of Ψstem except during post-harvest, when MDS_{RDI} trees were more stressed than the RDI ones due to the small amount of water applied to the MDS_{RDI} treatment in order to reach the SI target value. Similarly to the first season, Ψstem did not reach harmful levels in any of the two deficit irrigated strategies.

In RDI programs a main issue is always how water restrictions will affect tree water status, which does not only depend on the relative restriction in relation to potential ETc but also on several orchard and weather characteristics difficult to predict. The MDS_{RDI} treatment was designed in order to avoid harmful water restrictions for tree performance. Although in the RDI trees water stress was also never too severe, water savings in the MDS_{RDI} treatment were higher than in the RDI, with similar tree performance. In fact, in 2006, and similarly to the first season, water restrictions did not decrease fruit weight at harvest, and there were no significant differences in tree yield (Table 2). This suggests that the deficit irrigation regime evaluated was effective on saving water without any yield penalty.

General remarks

Overall results reported suggest that both, the soil capacitance probes and stem dendrometers can be a useful tool for improving irrigation management, both in cases of full irrigation regime or in order to schedule deficit irrigation avoiding that water restrictions would lead to plant water stress too severe and detrimental to tree performance. Following exclusively the ETo * Kc irrigation scheduling procedure growers do not have direct information on the effects of their irrigation regime on the orchard (*i.e.* soil and plant) water status.

The important advantage of capacitance probes is that the data interpretation is more straightforward, mainly due to the manufacturer's user-friendly software for data management. In the case of stem dendrometers, to the best of our knowledge, there are not yet hardware and software packages available that could offer the possibility to growers to easily use and understand these sensors data variation along the season. This is also because the information derived from trunk diameter variation is much more complex to interpret. In addition, despite the LVDT sensors are nowadays quite robust, adequate field maintenance is still required for proper data recording and interpretation.

Though both stem dendrometers and capacitance sensors are readily available in the market, there are still no new irrigation controllers capable of reading, processing and interpreting the data obtained from the sensors for automatically scheduling deficit irrigation. This is a major drawback for successful transfer of these technologies to the final users.

In addition, our experience suggests that the use of soils and plant water status information should never be considered as an excluding tool with regards to the FAO approach, but contrarily as a complementary approach to follow. Water scheduling decisions should be based on a step-by-step procedure where the first step should be to estimate irrigation requirements with the ETo * Kc approach. This is because this procedure is simple, easily and cheaply available for growers thanks to the irrigation technology transfer services existing in many of the main irrigation districts of Europe, US and other developed countries. Only after having estimated tree water needs with the ETo * Kc procedure, can growers adjust and optimise the water applications with the additional aid of either soil and/or plant water status information. In this sense it should be taken into account that a weather station measures the ETo representative of large irrigated areas (*i.e.* entire irrigation districts) while both stem dendrometers and, particularly the soil capacitance probes give a measurement of a single spot within an entire orchard. In the case of the soil probes this is even more important given the large heterogeneity of soil properties and the three-dimensional gradients of soil water distribution originated by drip irrigation. In addition the capacitance probes only have a very small sensing volume (around 5 cm radius; Vera *et al.,* 2009). For dendrometers, data presented also showed that there was a large sensor-to-sensor variability in the MDS readings, indicating the need to install several (6-8) sensors in a single orchard.

Finally there are however some other non-technical limitations for the wide-spread use of any type of sensors. A main problem in south-east Spain is the high minifundism (small orchard surface) with more than 60% of the orchards smaller than 2 ha. Hence these growers cannot pay the high cost of equipment (each soil probe costs around € 2500 and a set of 6 stem dendrometers about € 3200), a fact aggravated by current low market prices of fruit.

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