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Evaluation of sap flow and trunk diameter sensors for irrigation scheduling in early maturing peach trees

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Summary Five-year-old early maturing peach trees (*Prunus persica* (L.) Batsch cv. Flordastar grafted on GF-677 peach rootstock) were subjected to three irrigation treatments from March 18 to November 10, 2006. Control plants (T0 treatment) which received irrigation in excess of their crop water requirements (1089.7 mm) were compared with plants watered according to sap flow (SF; T1 treatment) or maximum daily trunk shrinkage (MDS; T2 treatment) measurements, so as to maintain SF and MDS signal intensities (control SF/SF in T1 and MDS in T2/control MDS, respectively) close to unity. When SF or MDS signal intensity on at least two of three consecutive days was at or below unity, irrigation was reduced by 10%. When the MDS signal intensity on at least two of three consecutive days exceeded unity, irrigation was increased by10%. During the experiment, estimated crop evapotranspiration was 704.9 mm, and the cumulative amounts of applied water in the T1 and T2 treatments were 463.2 and 654.5 mm, respectively. The MDS-signal-intensity-driven irrigation schedule was more suitable than the SF-signal-intensity-driven irrigation schedule because it was more sensitive and reliable in detecting changes in plant water status, preventing the development of detectable plant water stress. Moreover, it had no effect on fruit size. We conclude that peach tree irrigation scheduling can be based on MDS measurements alone. Changes in the irrigation protocol assayed were proposed to reduce MDS signal intensity deviations above unity, for example, by increasing the irrigation scheduling frequency or the amount of water applied, or both. Irrigation schedules based on maintaining MDS signal intensities close to unity could be applied when local crop factor values are unavailable.

Keywords: stem water potential, trunk diameter fluctuations, water relations.

Introduction

Scarce water supplies necessitate careful management of agricultural crop irrigation in many regions of the world. Irrigation based on plant water status has promise as a technique for optimizing irrigation scheduling because of its dynamic relationship with climatic and soil conditions (Remorini and Massai 2003, Goldhamer et al. 2003, Naor 2006).

To implement this approach to irrigation management, continuous and automatic recording of plant-based water stress indicators, such as sap flow (SF) and maximum daily trunk shrinkage (MDS), is required (Easthman and Gray 1998, Goldhamer et al. 1999, Fernández et al. 2001, Ortuño et al. 2004*a*, 2004*b*, Nicolás et al. 2005 and Ortuño et al. 2006). These techniques are characterized by relatively simple measurement procedures with minimal labor requirements.

Plant water status depends on both the soil water available to the plant and the atmospheric evaporative demand. If absolute MDS or SF values are normalized relative to values under non-limiting soil water conditions, (Ortuño et al. 2005, 2006), values above unity are indicative of water stress (Goldhamer and Fereres 2004).

Numerous studies have proposed the use of SF and MDS for irrigation scheduling (Huguet et al. 1992, Cabibel and Isberie 1997, Easthman and Gray 1998, Goldhamer and Fereres 2001, Cohen et al. 2001); although, field studies to evaluate these irrigation scheduling parameters are scarce (Li et al. 1989, Bussi et al. 1999). To date, only Goldhamer and Fereres (2004) and García-Orellana et al. (2007) have demonstrated the possibility developing an irrigation schedule based only on MDS measurements, but no information exists about irrigation scheduling based on SF measurements.

We carried out a study to test two hypotheses: (1) irrigation scheduling can be based exclusively on plant-based water stress indicators; and (2) when plant-based relative water stress indicators are maintained close to unity, the amount of irrigation water applied provides an estimate of actual crop evapotranspiration if there is no drainage. Specifically, peach trees growing under non-limiting soil water conditions were compared with trees irrigated according to a schedule that maintained MDS or SF signal intensity near unity. The feasibility of irrigation scheduling based exclusively on MDS or SF measurements, and the effects of these irrigation schedules on plant and soil water status and on fruit yield and its components were studied. We also compared the amount of water applied with an estimate of crop evapotranspiration.

Materials and methods

Experimental conditions, plant material and treatments

Experiments were conducted on a farm in Santomera, Murcia, Spain (30°06′ N 1°02′ W, elevation 123 m). The soil is stony and shallow, with a clay-loam texture. Analysis of soil samples showed a high lime content, low organic matter content, low cationic exchange capacity and low available potassium and phosphorus concentrations. Available soil water and bulk density were 200 mm m^{-1} and 1.58 g cm^{-3}, respectively. Volumetric soil water contents (θ_v) at saturation and field capacity were 0.49 and 0.35 m^3 m^{-3}, respectively.

The experiment was performed on 5-year-old early maturing (mid-May) peach trees (*Prunus persica* (L.) Batsch cv. Flordastar) grafted on GF-677 peach rootstock and trained to an open-center canopy. Tree spacing was 5 × 5 m, with a mean ground cover of about 54%. Trees were hand-thinned on day of year (DOY) 70, 30 days after full bloom. Fruitlets were spaced by hand 25 cm apart along the fruit-bearing stems, as for the commercial crop load. The orchard was weeded regularly, and pest control and fertilization practices were those commonly used in commercial orchards.

From January 29 (DOY 29) to November 10 (DOY 314), control treatment (T0) plants were irrigated daily in excess of the estimated crop evapotranspiration (155% ET_c) to ensure non-limiting soil water availability. Crop irrigation requirements were determined according to daily crop reference evapotranspiration (ET_o), calculated with the Penman-Monteith equation (Allen et al. 1998), a crop factor based on the time of the year (FAO 56, Allen et al. 1998) and the percentage of ground area shaded by the tree canopy (Fereres and Goldhamer 1990).

From March 18 (DOY 77), irrigation scheduling began in the two treatments, T1 and T2, to maintain SF and MDS relative signal intensities (control SF/SF in T1 and MDS in T2/control MDS) close to unity, respectively. The irrigation rate was decreased by 10% when SF or MDS signal intensity on at least two of three consecutive days was at or below unity. The irrigation rate was increased by 10% when the MDS signal intensity on at least two of three consecutive days exceeded unity. This irrigation protocol was based on that proposed by Goldhamer and Fereres (2001) for mature trees grown with high frequency irrigation. For all treatments, irrigation was carried out during the night by a drip irrigation system with one lateral pipe per tree row and eight emitters (each delivering 2 l h^{-1}) per plant. Total water amounts applied to each treatment were measured with in-line water meters.

Measurements

Every 30 min, micrometeorological data were collected by an automatic weather station located near the experimental site. Soil volumetric water content (θ_v) of the top 150 mm of the soil profile was measured with a time domain reflectrometer (Model 1502C, Tektronix Inc., OR), as described by Moreno et al. (1996). We measured θ_v at 0.1m intervals between depths of 0.2 m and 0.80 m with a neutron probe (Model 4300, Troxler Electronic Laboratories, NC), in access tubes installed 1.0 m away from the trees and beside the emitters. Measurements (four replications per treatment) were taken in the morning every 5 to 14 days.

Midday (1200 h solar time) stem water potential (Ψ_{stem}) was measured in two mature leaves per plant (four plants per treatment), taken close to the trunk. Leaves were enclosed in a small black plastic bag covered with aluminum foil for at least 2 h before measurements were made with a pressure chamber.

On DOY 87 (phase I of fruit growth), 101 (phase II of fruit growth), 123 (phase III of fruit growth), 160 and 200 (postharvest), leaf conductance (g_l) and net photosynthesis (P_n) were measured at midday in two mature sun-exposed leaves per plant (four plants per treatment), with a portable, closed gas-exchange system (LI-6400, Li-Cor, Lincoln, NE).

Throughout the experiment, micrometric trunk diameter fluctuations were measured in four trees per treatment with a set of linear variable displacement transducers (LVDT) (Model DF ± 2.5 mm, accuracy ± 10 µm, Solartron Metrology, Bognor Regis, UK). The LDVTs were attached to the trunk with a bracket made of Invar, which has a thermal expansion coefficient close to zero (Katerji et al. 1994, and aluminum. Sensors were placed on the north side of the trunk and were covered with aluminized foil. Measurements were taken every 2 s, and the data logger (Model CR10X with AM25T multiplexer, Campbell Scientific, Logan, UT) was programmed to record 15-min means. Maximum daily trunk shrinkage was calculated as the difference between maximum and minimum daily trunk diameter.

Sap flow was measured in T0 and T1 plants by the compensation heat-pulse technique (Swanson and Whitfield 1981), with one set of heat-pulse probes in each of the four trees per treatment. Each set consisted of a heater needle and two 1.8-mm-diameter temperature probes. The temperature probes and the heater needle were installed in parallel holes drilled radially into the trunks, the temperature probes were placed 10 mm downstream and 5 mm upstream of the heater needle. Each heat-pulse probe had four thermocouple sensors (at 6, 12, 22 and 32 mm depth) to monitor the sap velocity profile over radial depth. Sap velocity was measured following the procedure of Green and Clothier (1988), using the theoretical calibrations of Swanson and Whitfield (1981) to account for the probe-induced wounding effects. The temperature signals and the corresponding heat-pulse velocities were recorded at 30-min intervals with heat-pulse instrumentation (MITRA-1, Polytechnic University of Cartagena, Spain).

The effect of the irrigation treatments on fruit size was assessed as the proportion of fruits with a diameter greater or less than a marketable diameter of 56 mm.

Statistical design and analysis

The experimental design was completely randomized with four replications, each replication consisting of three adjacent rows, of 13 trees each. Measurements were taken on the inner tree of the central row of each replicate and the other trees served as border trees. A two-way analysis of variance was performed, and means were separated by the least significant difference range test at the 5% level. Percentage values were arcsine-transformed before statistical analysis. All the measurements were taken on the same tree in each replicate. Values of Ψ_{stem}, g_l and P_n for each day and replicate were averaged before the mean and the standard error of each treatment were calculated.

Results

Daily mean air vapor pressure deficit and ET_o values fluctuated, increasing from the beginning of the measurement period, reaching maximum values in July, and then gradually decreasing (Figure 1). Total ET_o was 1107.4 mm. Total rainfall was low (237.4 mm), falling mainly in spring and autumn (Figure 1). During the experiment, mean daily maximum and minimum temperatures were 30.9 and 7.7 °C, respectively, and mean relative humidity was 61.1 % (data not shown).

In the T0 treatment, θ_v between 0 and 0.80 m in depth was nearly constant, with values close to field capacity (94.1% of θ_v values were at field capacity) (Figure 2A). In T1 and T2, θ_v values were 77.8 and 81.5% of field capacity, respectively, between DOY 89 and 153 and between DOY 215 and 233, being lower in both cases than those of T0 from the beginning of the experiment (Figure 2A). In the T1 and T2 treatments, θ_v was 600 mm below field capacity indicated the absence of drainage (data not shown).

The Ψ_{stem} values in T0, T1 and T2 plants ranged between –0.34 and –0.95, –0.40 and –1.11, and –0.38 and –1.00 MPa, respectively (Figure 2B). No differences in Ψ_{stem} values between T0 and T2 plants were observed, except on DOY 138. However, Ψ_{stem} values of T1 plants were frequently lower than those of T0 plants, mainly from DOY 94 to 216 (phases II and III of fruit growth and three months after harvest). Later, coinciding with a decrease in evaporative demand and the autumn rainfall period (Figure 1), differences between treatments decreased, except on DOY 272 and 297. Non-significant differences in g_l and P_n between treatments were observed during the experiment (data not shown).

Daily SF values in T0 and T1 plants ranged between 11.2 and 105.2 l day^{-1}. Overall, SF values tended to increase until early August (DOY 215) and then decrease (Figure 3A). Daily MDS in T0 and T2 plants varied widely, ranging between 0.02 and 0.43 mm. Overall, MDS values tended to increase from the beginning of the experiment to the end of July (DOY 212), decreasing thereafter (Figure 3B). The differences in SF values between T0 and T1 plants were frequently significant, especially during phase III of fruit growth and after harvest (Figure 3A). In contrast, there were few significant differences in MDS values between T0 and T2, and those that occurred took place mainly at the beginning of phase III of fruit growth (Figure 3B).

The patterns of SF and MDS signal intensity differed (Figures 4A and 4B). After harvest, MDS signal intensity was close to unity (mean MDS signal intensity coefficient of variation (CV) of 0.083), whereas pre-harvest variation in MDS

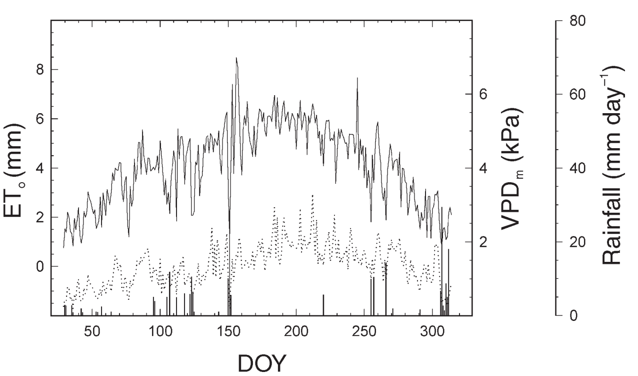

Figure 1. Crop reference evapotranspiration (ET_o, solid line), mean air vapor pressure deficit (VPD_m, dotted line) and rainfall (vertical bars) on days of the year (DOY) during the experimental period.

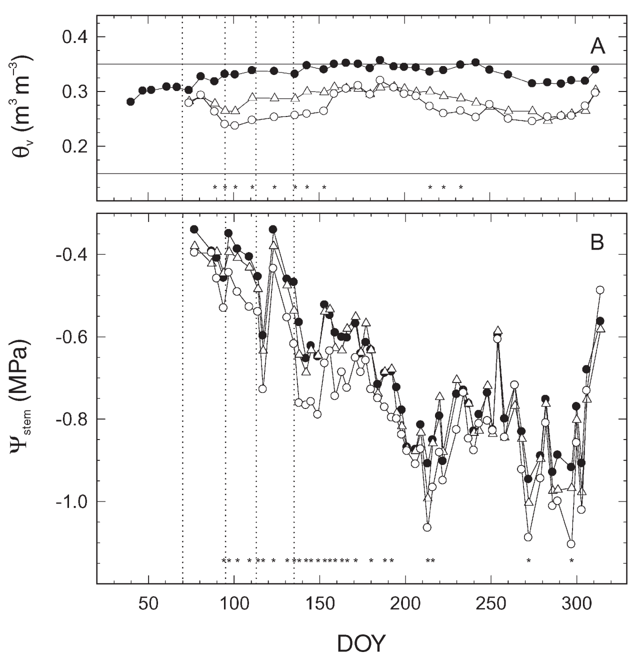

Figure 2. (A) Soil volumetric water content (θ_v) to a depth of 0.80 m in the T0 (●), T1 (○) and T2 (△) irrigation treatments and (B) midday stem water potential (Ψ_{stem}) in T0 (●), T1 (○) and T2 (△) plants on different days of the year (DOY). The interval between vertical dotted lines from left to right represent phases I, II and III of fruit growth. The lower horizontal lines represent θ_v at permanent wilting point and the upper horizontal line represents θ_v at field capacity. The overall mean SE was less than the diameter of the graph symbols. Asterisks indicate statistically significant differences between (A) treatments T1 and T2 and (B) treatments T0 and T1 at the 5% level (least significant difference range test). Each value is the mean of four measurements. Treatments: T0, irrigated daily in excess of estimated crop evapotranspiration; T1 and T2, irrigated to maintain sap flux and maximum daily trunk shrinkage signal intensities near unity, respectively.

signal intensity was greater (CV = 0.168). In contrast, SF signal intensity varied considerably both before and after harvest (CV = 0.182 and 0.188, respectively).

Water applied in the T1 and T2 treatments in each 3-day period reflected the SF and MDS signal intensity for the preceding three days, respectively (Figures 4A and 4B). The cumulative amounts of applied water were 34 and 7% less in the T1 (463.2 mm) and T2 (654.5 mm) treatments, respectively, than calculated ET_c (704.9 mm). The cumulative amount of water applied to the T0 treatment from DOY 77 to 314 was 1089.7 mm. Deviations from the calculated ET_c in the amount of water applied to the T1 treatment were most pronounced between the beginning of the experiment and DOY 152 (the period of fruit growth until 17 days after harvest) and from DOY 170 to 188, whereas deviation from ET_c in the amount of water applied in the T2 treatment were mostly observed between the beginning of the experiment and DOY 106 (phase I and first half of phase II of rapid fruit growth) and from DOY 193 to 268 (Figure 4C).

To compare the degree of water stress in T1 and T2 plants, the time course of changes in the MDS signal intensity ratio between the irrigation treatments (T1/T2) was studied (Figure 5A). The data indicated that during most of the experiment T1 plants experience greater water stress than T2 plants.

On most days, the MDS signal intensity in T1 plants was higher than the corresponding SF signal intensity (Figure 5B).

Although there were no differences between irrigation treatments in fruit number per tree (crop load) and trunk cross-sectional area, T1 plants had a lower yield (kg $tree^{-1}$) due to a lower mean fruit mass that T2 plants (Table 1). The T0 and T2 plants yielded similar proportions of fruits corresponding to the A, B and C extra categories and the non-marketable or non-extra category (categories correspond to diameters of; 73 mm > A ≥ 67 mm, 67 mm > B ≥ 61 mm, 61 mm > C ≥ 56 mm and non-extra < 56 mm (Ministerio de Agricultura)) (Table 2). However, fruits from T1 plants tended to be smaller, with the proportion of fruits in the C and non-extra categories being higher and the proportion of fruits corresponding to the A category lower, than in the other treatments (Table 2).

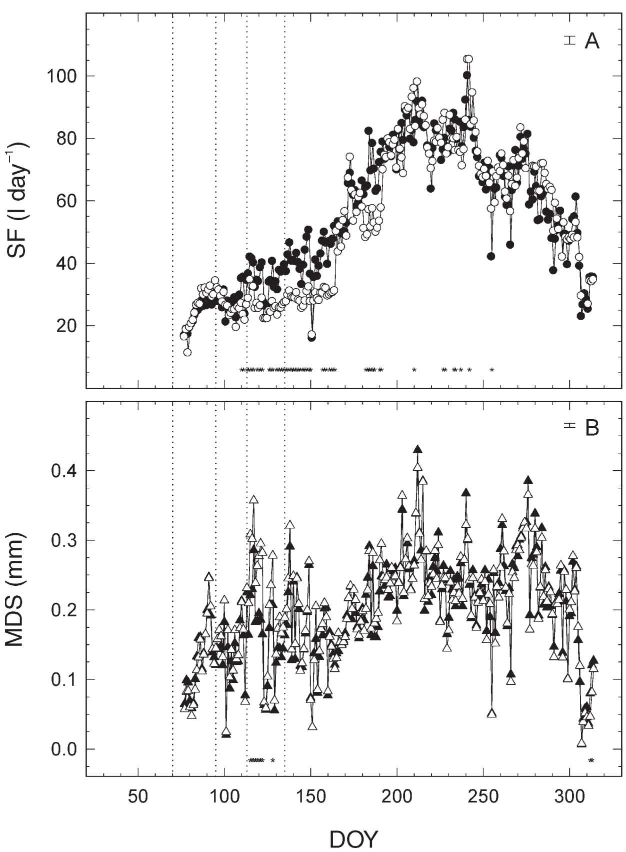

Figure 3. (A) Sap flow (SF) in T0 (●) and T1 (○) plants and (B) maximum trunk shrinkage (MDS) in T0 (▲) and T2 (△) plants on different days of the year (DOY). Asterisks indicate statistically significant differences between treatments at the 5% level (least significant difference range test). Each value is the mean of four measurements. Treatments: T0, irrigated daily in excess of estimated crop evapotranspiration; and T1 and T2, irrigated to maintain SF and MDS signal intensities near unity, respectively.

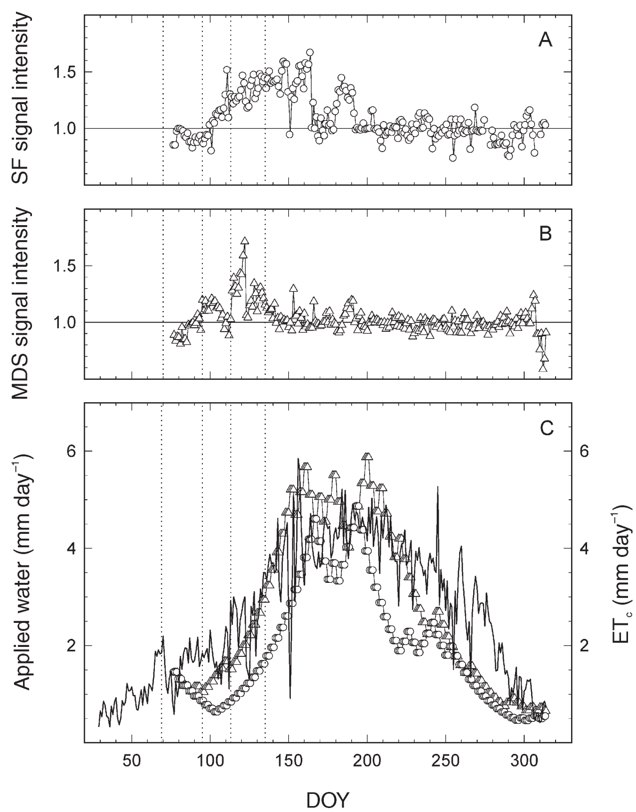

Figure 4. (A) Sap flow (SF) and (B) maximum daily trunk shrinkage (MDS) signal intensity values in T1 and T2 plants, respectively, and (C) amounts of irrigation water applied to the T1 (○) and T2 (△) plants compared with estimated crop evapotranspiration (ET_c, solid line) on different days of the year (DOY) during the measurements period. Each value of SF and MDS is the mean of four measurements. Treatments: T0, irrigated daily in excess of estimated crop evapotranspiration, T1 and T2 irrigated to maintain SF and MDS signal intensities near unity, respectively.

Discussion

The Ψ_{stem}, g_l and P_n values in T0 plants were similar to those in T2 plants, and no symptoms of water logging were evident in the T0 plants even though they were watered in excess of crop water requirement during the observation period. The similarity in the values of g_l and P_n (data not shown), Ψ_{stem} (Figure 3B) and fruit yield and its components (Tables 1 and 2) in T2 and T0 plants indicate that the water status of the T2 plants was unaffected by the irrigation treatment. In contrast, in T1 plants, Ψ_{stem}, fruit yield and fruit size were lower than in T0 plants, demonstrating that the T1 plants were subjected to water stress; although, the effect was mild as the treatment did not result in reduced stomatal conductance (Besset et al. 2001, Centritto et al. 2002, Girona et al. 2005). The observation that the MDS signal intensity in T1 plants was higher than in T2 plants (Figure 5A) during most of the experiment confirmed that T1 plants experienced greater water stress than T2 plants.

The finding that, in T1 plants, the MDS signal intensity was higher than the SF signal intensity on most of days (Figure 5B), indicates that MDS is a more sensitive indicator of water stress in peach trees than SF (Remorini and Massai 2003, Ortuño et al. 2005, 2006, Conejero et al. 2007). Xylem cavitation resulting in reduced hydraulic conductivity, to which peach trees are particularly sensitive (Massai et al. 2000), may have been responsible for the delay in recovery of the SF values.

Crop loads were similar in the different irrigation treatments, indicating that the smaller fruit size of T1 plants (Tables 1 and 2) can be attributed to water stress during fruit growth (Figures 2B and 5A), and confirming that water stress during the period of rapid fruit growth inhibits the attainment of marketable fruit size (Li et al. 1989, Boland et al. 1993, Torrecillas et al. 2000, Girona et al. 2004).

The MDS signal intensity during the post-harvest period displayed low variability and remained close to the selected MDS signal threshold value (Figure 4B), indicating that the amount of irrigation water applied was appropriate, which indicates that irrigation scheduling for peach trees can be based on MDS measurements alone (Goldhamer and Fereres 2004, García-Orellana et al. 2007).

The deviations in SF signal intensity above the threshold value from DOY 102 to 165 and from DOY 180 to 193 (Figure 4A) and the deviations in MDS signal intensity during phase III of fruit growth were greater than expected (Figure 4B). These deviations indicate that the precision of water scheduling decreases during periods of increasing irrigation need (Figure 4C), and that 10% increases in the amount of irrigation water supplied were insufficient, or that irrigation should be scheduled more frequently than every three days.

When plant-based water stress signal intensity approaches unity, tree water status is favorable. In such cases, if there is no drainage, the amount of irrigation water applied provides an estimate of evapotranspiration. By taking into consideration the postharvest period when the CV of the MDS signal inten-

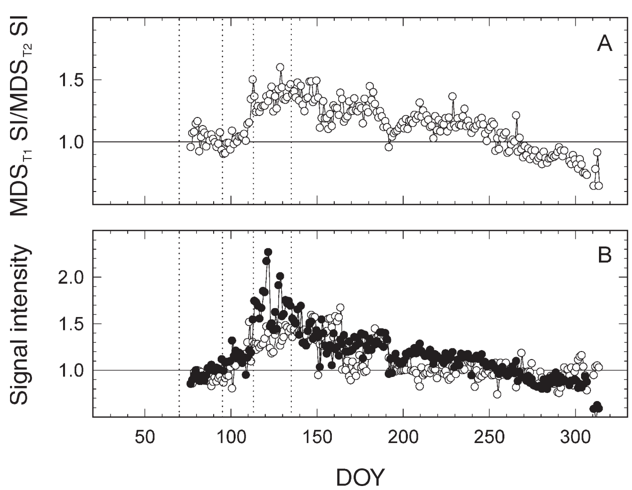

Figure 5. (A) Ratio of maximum daily trunk shrinkage (MDS) signal intensity (SI) in T1 plants to that in T2 plants (MDS_{T1} SI/MDS_{T2} SI) and (B) pattern of development of SF (○) and MDS (●) signal intensities in T1 plants on different days of the year (DOY). Each value is the mean of four measurements. Treatments: T0, irrigated daily in excess of estimated crop evapotranspiration; and T1 and T2, irrigated to maintain SF and MDS signal intensities near unity, respectively.

Table 1. Effects of irrigation treatments on crop load (number of fruits tree^{-1}), fruit load efficiency (number of fruits per tree divided by trunk cross-sectional area (cm^{-2})), mean fruit mass (g) and fruit yield (kg tree^{-1}). Means within a column followed by different letters are significantly different at the 5% level (least significant difference range test). Treatments: T0, irrigated daily in excess of estimated crop evapotranspiration; and T1 and T2, irrigated to maintain sap flux and maximum daily trunk shrinkage signal intensities near unity, respectively.

Treatment	Crop load	Fruit load efficiency	Fruit mass	Yield
T0	221.0 a	2.54 a	125.8 a	26.4 a
T1	192.4 a	2.51 a	117.2 b	21.0 b
T2	212.8 a	2.54 a	122.9 a	24.6 a

Table 2. Effect of irrigation treatments on the distribution of peach fruit categories harvested (%). Based on the EEC directive 3596/90 (Ministerio de Agricultura), fruit extra categories are: A, 73 mm > diameter ≥ 67 mm; B, 67 mm > diameter ≥ 61 mm; C, 61 mm > diameter ≥ 56 mm; and fruit non-extra, diameter < 56 mm. Data were arcsine transformed. Means within a column followed by different letters are significantly different at the 5% level (least significant difference range test). Treatments: T0, irrigated daily in excess of estimated crop evapotranspiration; and T1 and T2, irrigated to maintain sap flux and maximum daily trunk shrinkage signal intensities near unity, respectively.

Treatment	Fruit category			
	A	B	C	Non-extra
T0	22.6 a	53.6 a	20.8 a	3.0 a
T1	10.5 b	43.3 a	34.5 b	11.7 b
T2	20.0 a	47.1 a	25.0 a	7.9 ab

sity in T2 plants was only 0.083 (Figure 4B), the estimated ET_c (584 mm) was only 5% higher than the estimate based on applied water rate (558.1 mm) in the MDS signal intensity-driven schedule (Figure 4C). Thus, bearing in mind the modifications to the irrigation protocol proposed above, the MDS signal intensity-driven irrigation schedule represents a promising procedure for estimating crop irrigation requirements.

We found that an MDS signal intensity-driven irrigation schedule is more suitable than an SF signal intensity-driven schedule because it is more consistent and more sensitive to changes in peach tree water status, it minimizes the development of plant water stress and it has no effect on yield. Nevertheless, the irrigation protocol should be adjusted to minimize MDS signal intensity deviations above the threshold value. This can be achieved by increasing the irrigation scheduling frequency or the amount of water applied, or both.

Acknowledgments

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