ORIGINAL PAPER

D. A. Goldhamer · E. Fereres

Irrigation scheduling of almond trees with trunk diameter sensors

Abstract The use of plant indicators may be the ideal method for irrigation scheduling but it is hampered by the dynamic nature of plant water status and by the lack of suitable indicators, relative to established scheduling methods based on atmospheric and soil observations. A study was conducted in an almond orchard located in the San Joaquin Valley of California during the 2001 season using trunk diameter variations as the only indicator for determining the amount of irrigation. The ratio of the maximum daily shrinkage (MDS) of tree trunks relative to a reference MDS, calculated from a relationship between MDS of fully irrigated trees and atmospheric vapor pressure deficit, was used as a signal for modifying the amount of applied irrigation water. Applied water was increased by 10% each time the MDS signal exceeded the prescribed threshold. When the MDS signal went below the threshold, applied water was reduced by 10% in an interactive manner. Two schedules were tested with signal thresholds of 1.75 and 2.75, which generated mild and moderate water stress, respectively, as indicated by their stem water potential (SWP) values. The two irrigation treatments had SWP that varied over the season from around −0.7 to −1.1 MPa and −0.8 to −1.7 MPa, respectively. The two schedules resulted in seasonal water applications of 860 mm for the 1.75 and 525 mm for the 2.75 signal threshold treatments. The grower/cooperator, who based his schedule primarily on SWP measurements but also considered the water balance, applied 900 mm. Estimated crop evapotranspiration was 1,030 mm. The mean coefficients of variation for the two irrigation treatments during the monitoring period were 0.115 and 0.031 for the MDS and SWP measurements, respectively. The stress produced by the irrigation treatments hastened fruit maturation, as evidenced by accelerated hull splitting. This resulted in lower fruit hydration just prior to harvest; 17.3% and 8.0% for the two irrigation schedules, respectively, compared with 27.3% for the grower/cooperator. Based on harvesting selected trees with the same nut load, fresh and dry nut weights in the 2.75 threshold treatment were 9.0% and 10.7% less than those of the 1.75 threshold, which were not significantly different from the results for the grower cooperator. Our results demonstrate that it is feasible to develop an irrigation schedule for almond trees based solely on MDS signals, which may be tailored to any desired stress pattern and be operated in full automation with appropriate software development.

D. A. Goldhamer (✉)
Department of Land,
Air, and Water Resources,
Kearney Agricultural Center,
University of California,
9240 S. Riverbend Ave.,
Parlier, CA 93648, USA
E-mail: dagoldhamer@ucdavis.edu
Tel.: +1-559-6466575

E. Fereres
IAS-CSIC and University of Cordoba,
Apdo. 4084, 14080 Cordoba, Spain

Introduction

Water scarcity in many irrigated areas of the world is becoming a fact of life as demand exceeds the sustainable supply. For instance, water currently used in the irrigated lands developed in California over the last five decades is being considered as a possible supply for an expanding municipal sector as well as for environmental preservation. As its population grows and environmental concerns increase, California is likely to be 2.46 billion cubic meters short of water annually in the immediate future for an average rainfall year (State of California Department of Water Resources 1998). For drought years, the difference between supply and demand would be much greater. This gap will likely be met, at least in part, by a number of measures based on agricultural water conservation and reuse. Growers will face increasing pressure to reduce water use,

necessitating the adoption of improved and innovative management practices.

The search for more efficient use of irrigation water has recently focused on increasing water productivity (WP), i.e., the ratio of yield or profit relative to crop evapotranspiration (ET_c; Seckler 1996). At the irrigation district scale, WP varies widely, as shown in a survey of 40 districts around the world (Molden et al. 1998). There many options for increasing WP at the field scale, many of them based on improved management (Howell 2001). Horticultural crops have relatively high WP values and that has resulted in progressive conversion of land from low-value field crops to high-value permanent crops in intensively irrigated areas, such as the San Joaquin Valley of California. Orchard owners seeking improved WP beyond current levels view more precise irrigation scheduling as an important feature of improved irrigation management.

Rational irrigation scheduling procedures are being increasingly adopted, mostly based on carrying a water balance calculation to determine the timing and amount of irrigation (Leib et al. 2002). Required inputs with conventional, low application frequency irrigation systems are ET_c and root-zone water storage capacity. In intensive tree horticulture, high-frequency irrigation systems, such as drip and microsprinklers, require only ET_c information. While the accurate estimation of ET_c is possible in most field crops (Allen et al. 1998), there are uncertainties in determining orchard ET_c, associated primarily with the effects of canopy architecture, degree of canopy cover and soil surface management. Adjusting mature orchard ET_c estimates to young canopies, or to situations with a cover crop or actively growing weeds, creates significant uncertainty in fruit tree irrigation scheduling based on ET_c. Application efficiency is affected by irrigation frequency, soil texture, and system design, maintenance, and operation. The use of soil water monitoring devices for scheduling also requires some knowledge of the distribution and relative density of roots, and the uncertainty increases when the wetted area varies in three dimensions, as in drip irrigation and microsprinklers. Thus, assessing irrigation needs directly from tree measurements could provide an alternative technique for more precise irrigation management.

Shackel et al. (1997) have shown that midday stem water potential (SWP) is the most robust of the different tree water status measurements (predawn and midday leaf water potential, etc.) and thus, is best suited for use in tree-based irrigation scheduling. Lampinen et al. (1995) scheduled a regulated deficit irrigation (RDI) regime in a prune orchard, achieving not only reduced water application but also lower fruit hydration and thus, less drying costs and potentially higher grower profit. However, monitoring SWP requires a significant amount of labor if frequent determinations are required and, in some situations, remote and automated monitoring of tree water status may be a desirable alternative. Continuous records of stem diameter have been correlated with water potential measurements for many years (Klepper et al. 1971) and have been proposed as a management tool for irrigation scheduling (Li et al. 1989). In deficit-irrigated peach trees, Goldhamer et al. (1999a) showed that stem diameter records detected stress earlier than SWP and that the signal strength (magnitude of the measurement relative to that of fully irrigated trees) of trunk maximum daily shrinkage (MDS) for detecting water deficits was greater than that of SWP (Goldhamer et al. 1999b).

Establishing a threshold tree water status measurement that triggers an irrigation is complicated by the fact that tree water status is affected not only by soil moisture but also by evaporative demand. Some reference or baseline number that reflects the water status behavior of a fully irrigated tree is required to interpret SWP measurements for irrigation scheduling (Shackel et al. 1997; Goldhamer and Fereres 2001a). Fereres and Goldhamer (2003) showed that the MDS of fully irrigated almond trees correlated well with VPD and proposed that this relationship could be used to develop reference MDS values. Alternatively, the MDS of a small number of trees specifically irrigated to be "fully" irrigated (applied water around 10% greater than ET_c) could be used as a baseline for irrigation scheduling (Goldhamer and Fereres 2001b). The MDS signal (actual MDS/reference MDS) embodies variation due to a changing evaporative demand and should primarily reflect soil water availability. Thus, MDS signal threshold values indicate how much tree stress is desired—values of 1 reflect no irrigation-related stress while progressively higher values indicate escalating stress levels. Goldhamer and Fereres (2001b) developed irrigation scheduling protocols for young and mature fruit trees with different irrigation systems, based on continuously recorded trunk diameter measurements. In this work, we present a test of those protocols in a commercial almond orchard using MDS measurements as the only indicator for the actual scheduling of irrigation.

Methods

This work took place in a mature almond orchard in western Kern County, California. The trees [*Prunus dulcis* (Mill.) Webb cv. Fritz] were 6 years old and grown in a well drained, clay-loam soil (Typic Torriorthents) with a root zone extending to a depth of about 2 m. Irrigation was done with a buried drip system having 45 cm deep lateral lines located 1.5 m on either side of the tree row (6.40×7.32 m spacing). This resulted in 20, 3.79 l/h emitters per tree and an application rate of 1.5 mm/h. The system was operated 2–3 times per day.

The orchard contained two blocks, each about 4.2 ha, and the irrigation for each block could be operated independently. Data collected during preliminary work at the experimental site in 2000 showed that a MDS signal threshold value of approximately 1.25 resulted in tree water deficits that were virtually undetectable with SWP measurements. Thus, a MDS signal threshold value of 1.75, which we believed would result in mild stress that presumably would have little effect on production, was established for one block while a more severe stress threshold level of 2.75 was set for the other block (hereafter referred to as $T_{1.75}$ and $T_{2.75}$, respectively). Within each block, four trees were instrumented with linear variable differential transformers (LVDTs: Model 2.5 DF;

Solartron Metrology, Bognor Regis, UK) installed on the southwestern primary scaffold. The LVDTs were mounted on holders built of aluminum and INVAR—an alloy comprising 64% Fe and 35% Ni that has minimal thermal expansion (Li et al. 1989)—and covered with silver foil to provide constant shade. Measurements were taken every 30 s and recorded on a datalogger (Model CR 10; Campbell Scientific, Logan, Utah). Data were downloaded every few days and transferred to the laboratory for MDS determination.

We developed a relationship between MDS and mean daily atmospheric vapor pressure deficit (VPD) using MDS values from fully irrigated trees located in the $T_{1.75}$ block collected in April and May 2001, prior to the onset on the irrigation treatments in early June (Fig. 1). Mean daily vapor pressure and relative humidity measurements were taken from a CIMIS (California Irrigation Management Information System) automated weather station located 10 km from the experimental site to calculate VPD. The linear regression between MDS and VPD during this period ($R^2 = 0.77$) was used to determine the reference MDS value required to compute the MDS signal for the two irrigation regimes evaluated.

The irrigation protocols proposed by Goldhamer and Fereres (2001b) involve adjusting the irrigation rates based on the time-course development of the MDS signal strength. If the MDS signal did not reach the MDS signal threshold for three consecutive days, the irrigation rate was decreased by 10%. Similarly, if the MDS signal exceeded the threshold for three consecutive days, the irrigation rate was raised by 10%. Thus, the goal of this experiment was to have the MDS signals oscillate around the 1.75 and 2.75 signal strength thresholds by adjusting the irrigation rates. Applied water was measured on each block with water meters.

Midday shaded leaf water potential (1300–1400 h) was monitored every weekday with a pressure chamber (Model 3005; Soil Moisture Equipment, Santa Barbara, Calif.). Two single leaves in the shade and close to the trunk on each of the four trees per treatment were covered with a moist cloth just prior to excision. The leaf alone was placed in the chamber within 15 s of excision and precautions recommended by Hsiao (1990) were taken to prevent leaf water loss during measurement. Previous work (Goldhamer and Fereres 2001a) has shown that measurements taken in this manner in almond leaves are nearly identical to SWP. Thus, we hereafter refer to our leaf water potential measurements as SWP.

On 30 September, the four instrumented and monitored trees plus six trees of the same size randomly located within each block were mechanically shaken and on 9 October individually harvested to estimate yield. Ten trees in a third 4.2 ha block adjacent to the two experimental blocks and irrigated by the grower/cooperator based on a combination of SWP and water budget measurements were also individually harvested for comparison (hereafter referred to as the Ranch). A 2 kg nut sample was collected from each tree. The number of fully hull split nuts (more than 50% of the suture line split) was determined. The kernels were separated from the shells and hulls to determine the kernel percentages on a fresh and oven dry weight basis. Nut loads were determined by multiplying the fresh nut yields per tree by the percentage of kernels in the corresponding 2 kg sample. Prior to tree shaking, 50 nut samples were randomly collected from the four instrumented trees in $T_{1.75}$ and $T_{2.75}$ on 14, 19, and 27 September. Four Ranch trees were also sampled on these dates. These samples were bulked and analyzed for hull split as outlined above to determine the influence of the irrigation regime on this important yield component.

Results

Tree monitoring

The time courses of MDS, MDS signal, and SWP for both $T_{1.75}$ and $T_{2.75}$ during the period under consideration are shown in Fig. 2. Observed MDS values ranged from 0.1 to 0.9 mm depending on evaporative demand and treatment (Fig. 2a). The $T_{2.75}$ MDS was always greater than that of $T_{1.75}$, except for a few days at the beginning and at the end of the period. The MDS signal evolution (Fig. 2b) shows that the signals for the two treatments went above their respective thresholds between 12 and 15 times during the period and, every time, an adjustment of the irrigation application rate was made 10% upwards. Downward adjustments, which were made following three days of MDS signals below the target threshold, decreased the signal, particularly for the $T_{1.75}$ that approached 1 occasionally, indicating no water stress at that time.

Measurements of SWP showed clear differences between the two irrigation treatments (Fig. 2c). Values ranged from −0.7 to −1.4 MPa in $T_{1.75}$ but oscillated in

Fig. 1 Relationship between maximum daily trunk shrinkage (*MDS*) of fully irrigated trees. Linear regression parameters are shown on the figure
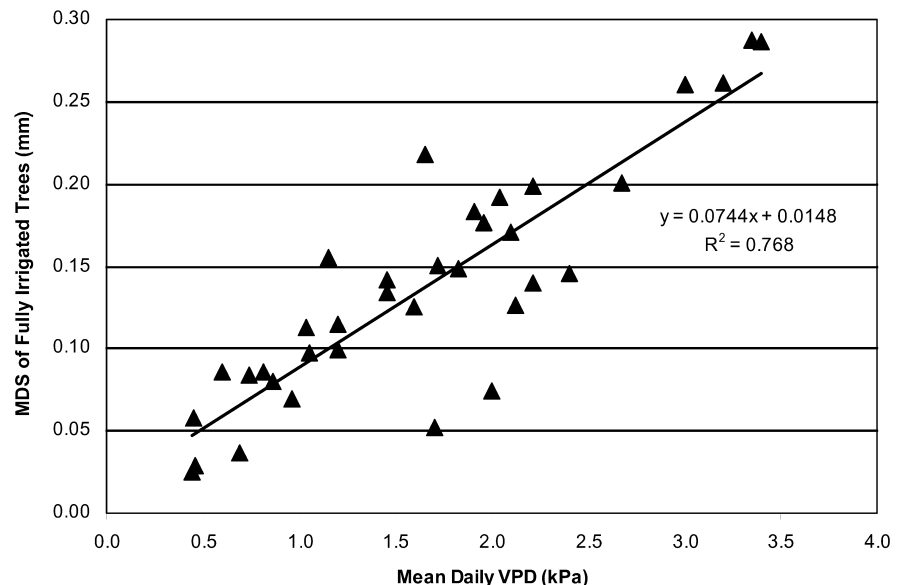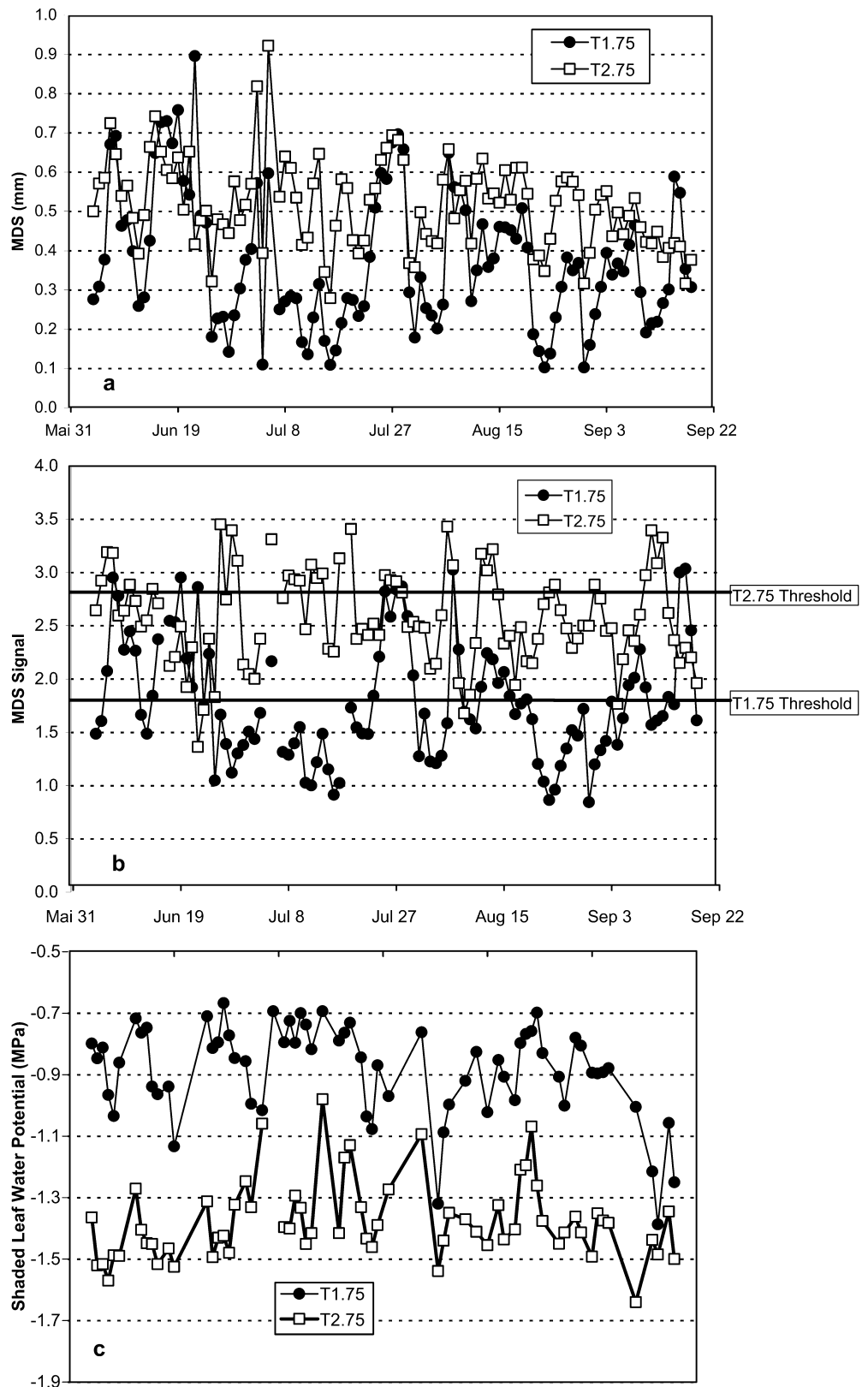

$$y = 0.0744x + 0.0148$$
$$R^2 = 0.768$$

14

a narrower range between −0.8 and −1.1 MPa for most of the summer. In contrast, $T_{2.75}$ had SWP values between −1.3 and −1.5 MPa most days and even reached −1.7 MPa at the end of the period (Fig. 2c).

Variability in either the MDS or SWP measurements among trees of the same treatment could induce uncertainty in determining an irrigation schedule. In this experiment, the average MDS coefficients of variation

(CVs) for the period considered (103 measurements made over 106 days) were 0.124 and 0.105 for $T_{1.75}$ and $T_{2.75}$, respectively (Table 1). These values are significantly different. The SWP CVs for the two irrigation treatments were 0.029 and 0.032, respectively.

Applied water

Rates and cumulative amounts of applied water in both irrigation treatments from the start of the irrigation season, together with the ET_c rate of a mature almond orchard calculated from published crop coefficients (Goldhamer 1989) and CIMIS reference crop water use (ET_o) from the nearby CIMIS weather station, are shown in Fig. 3a, b, respectively. Applied water in both treatments met ET_c through April and was then reduced in anticipation of the start of the experiment in early June (Fig. 3a). Subsequently, the two schedules resulted in substantial differences in applied water rates, particularly at peak demand and prior to harvest. Maximum water application rates were 7.5 mm/day for $T_{1.75}$ in early July and 4.6 mm/day for $T_{2.75}$ in late July. Early in the season, applied water rates in $T_{1.75}$ were well below ET_c but during the experiment (early June–late September), these values were similar, with the exception of late July. At the end of the experiment, 860 and 525 mm of water was applied to $T_{1.75}$ and $T_{2.75}$, respectively; a difference of 335 mm of water. Estimated ET_c was 1,038 mm.

A representative example of how applied water was managed via MDS signals is shown in Fig. 4. Following three days when the MDS signal was below the threshold for $T_{2.75}$, applied water was decreased by 10% on 25 July. This resulted in the MDS signal increasing to 2.91, 2.86, and 2.85 from 26 to 28 July, triggering a 10% increase in the rate of applied water to 4.62 mm/day from 4.20 mm/day (Fig. 4). Applied water was decreased again twice until the signal reached the threshold again by 5 August 5. Oscillations in the MDS signal above and below the threshold continued and adjustments were made in the amounts of applied water.

Table 1 Coefficients of variation determined from mean daily MDS signals and SWP measurements taken from 4 June to 18 September

Stress indicator	MDS signal measurements	MDS signal CV*	SWP measurements	SWP CV
$T_{1.75}$	103	0.124 a**	66	0.029
$T_{2.75}$	103	0.105 b	65	0.032 NSD***

*CV, Coefficient of variation; standard deviation/mean
**Numbers followed by different letters are significantly different using Fisher's least significant difference method ($P = 0.05$)
***NSD indicates no statistically significant differences between irrigation regimes using Fisher's least significant difference method ($P = 0.05$)

Yield and yield components

There was significant variation in the number of nuts among the ten harvested trees of the two irrigation treatments and the Ranch (up to 12%; data not shown). Since fruit load is determined by the stress history of the trees rather than the current year's irrigation treatments (Goldhamer and Viveros 2000; Esparza et al. 2001) and we wanted to minimize the effects of fruit load on fruit component size (kernels, etc.), we chose five trees each in our irrigation treatments and in the Ranch that gave us mean fruit loads that varied by less than 1%. These values and other yield data for these trees are shown in Table 2. Individual fresh and dry nut (hull, shell, and kernel) weights for $T_{2.75}$ were 9.0 and 10.7% lower, respectively, than $T_{1.75}$, which was not significantly different from the Ranch (Table 2). Similarly, individual fresh and dry kernel weights for $T_{2.75}$ were lower than those for $T_{1.75}$ by 9.8 and 11.5%, respectively. Again, $T_{1.75}$ and the Ranch fresh and dry kernel weights were not significantly different. Both irrigation treatments resulted in nuts with a higher fresh and dry kernel percentage than the Ranch nuts (Table 2).

The water stress induced by the scheduling treatments hastened fruit maturation as evidenced by the hull splitting data. At harvest, the percentage of fully hull-split nuts was higher for $T_{2.75}$ than for $T_{1.75}$; 95.2 versus 89.8% (Table 2). The Ranch had significantly lower hull split values at harvest (82.2%) than both irrigation treatments. The 200-nut composite sample taken from four trees per block on 14 September had large differences in hull splitting; 84.5 and 100% of the nuts were fully split in $T_{1.75}$ and $T_{2.75}$, respectively, while only 44.5% had fully split in the Ranch. This resulted in large differences between kernel hydration while the nuts were on the trees between 14 and 27 September (Table 2).

Discussion

Since tree productivity is closely tied to water status, most irrigation researchers recognize that a plant-based stress sensor would provide the most desirable information for use in irrigation scheduling. This fact has driven research and development of a variety of instruments in recent years, including those that monitor sap flow (Cohen et al. 1981; Eastham and Gray 1998) and stem diameter (Li et al. 1989; Link et al. 1998) on a continuous basis in the field. The potential advantages of using stem diameter sensors for scheduling include the fact that stress indicator parameters that can be generated from their data, such as MDS measurements, have a high sensitivity for water stress detection (Goldhamer et al. 1999a; Ueda and Shibata 2001), a good capability for adjusting the schedule in very short time periods as a daily signal is generated, and the potential for complete automation.

Measurement of SWP indicated that both treatments developed water stress (Fig. 2c). The SWP values in $T_{1.75}$ indicated mild water stress while those in $T_{2.75}$ that

Fig. 3 Irrigation water rates
applied in the two sensor-based
scheduling regimes compared
with mature orchard
evapotranspiration (ET_c) rates
with time over the season
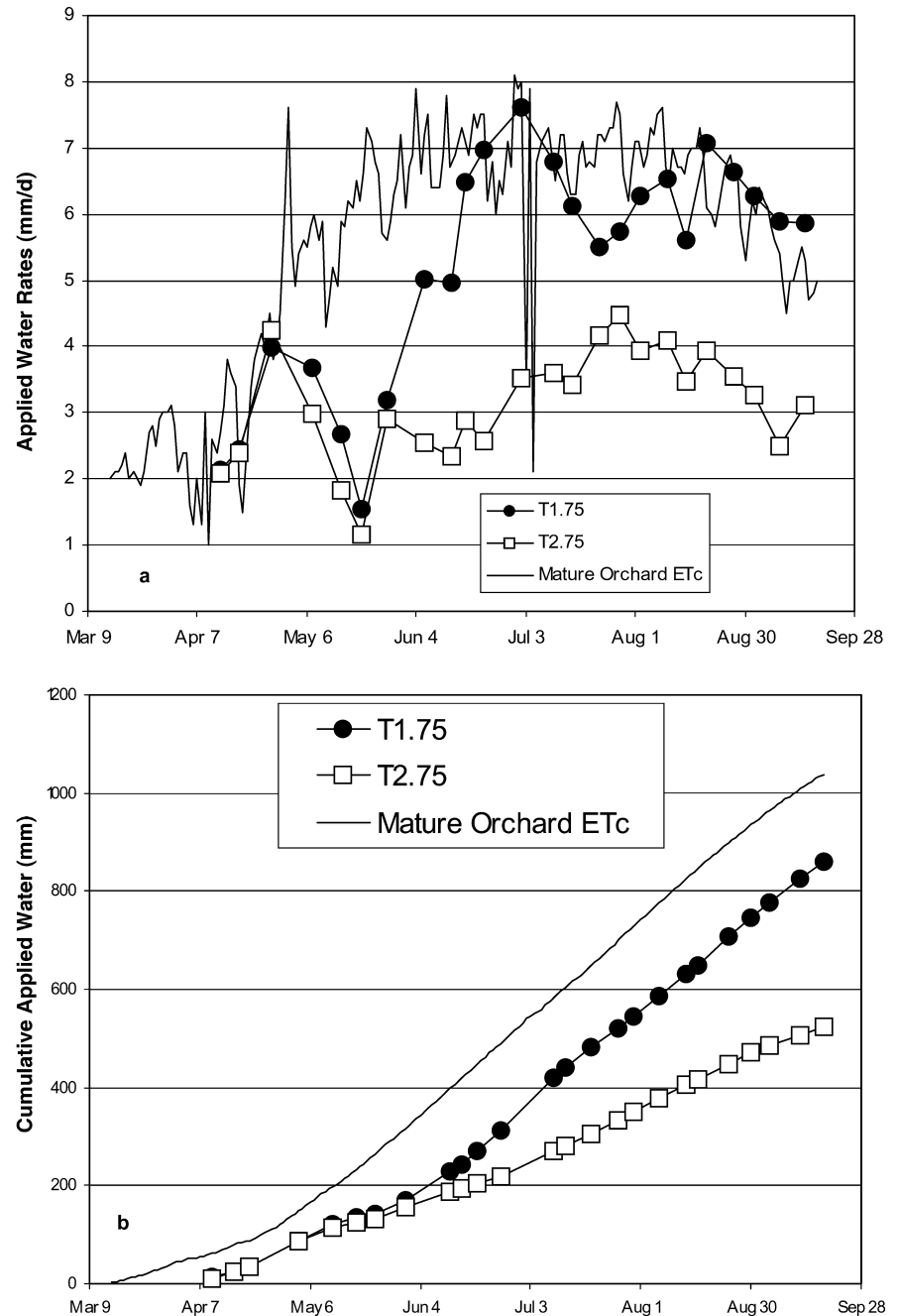
reached values nearly 1.0 MPa lower than the reference SWP baseline reflected moderate to severe stress (Fereres and Goldhamer 1990; Shackel et al. 1997). Our finding that MDS variability is high relative to SWP is consistent with previous reports (Ginestar and Castel 1996; Goldhamer et al. 1999a; A. Naor, personal communication). As stress increased, the MDS coefficient of variation was significantly reduced (0.124 and 0.105 for $T_{1.75}$ and $T_{2.75}$, respectively). This did not occur with SWP. Lower MDS variability with greater stress without concomitant SWP behavior was also reported by Goldhamer et al. (1999b) with deficit-irrigated peach trees that transitioned from mild to severe stress. They suggested that both signal strength and noise are important in assessing the usefulness of both SWP and MDS for irrigation scheduling and proposed using the "signal-to-noise ratio" as an integrating parameter. Using almond baseline values (Goldhamer and Fereres 2001a), the $T_{2.75}$ SWP signal did not exceed 2.0 while the MDS signal approached 3.5 (Fig. 2b). Thus, the higher MDS signal partially mitigates the higher variability and tends to equalize the signal-to-noise ratio for both MDS and SWP. It should also be noted that MDS variability in this study was less than has been reported previously (Goldhamer et al. 1999a, Goldhamer and Fereres 2001b).

The use of MDS as the only indicator for irrigation timing and amount has been proposed by Goldhamer and Fereres (2001b), who suggested that baseline or
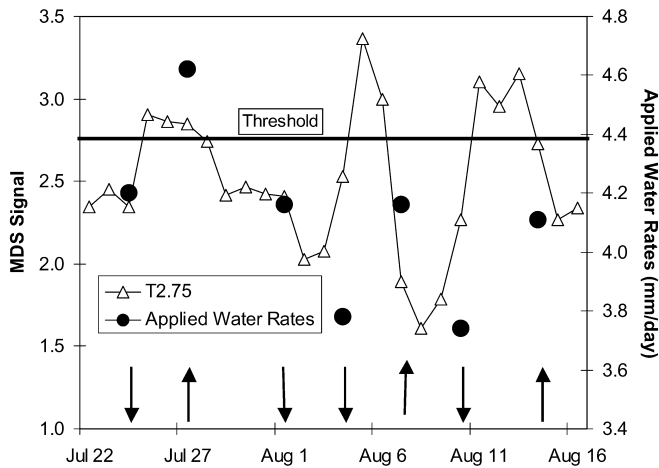
Fig. 4 Example of the interactive nature of the irrigation schedule protocols where MDS signals are consistently above or below the target threshold triggered increases (*upward arrows*) or decreases (*downward arrows*) in the rates of applied water

reference MDS values are required to determine the MDS signal and the need to establish a threshold MDS signal for adjusting the schedule every time the signal consistently deviates from this threshold. In this work, we have shown that it is feasible to schedule irrigations in the field using only sensors that monitor trunk diameter. The baseline was determined by relating MDS to VPD (Fig. 1) and the thresholds for the two treatments were set at the beginning of the season based on previous experience. We do not know if the baseline developed in this study is transferable to other locations, different aged trees, almond varieties, or other *Prunus* species. Our attempts to use the MDS of trees specifically irrigated to create non-limiting soil moisture conditions as the reference were less satisfactory, primarily because of high variability and the possible effects of heavy irrigation on soil salinity and oxygen status.

The use of the protocols based in MDS signals resulted in MDS signal oscillations around the target thresholds for the two irrigation treatments, albeit with deviations both above and below the thresholds that were greater than desired (Fig. 2b). Our protocols were designed to be interactive; changes in the irrigation duration by a constant 10% (the only management variable) to be reflected in MDS signals (Fig. 4).

Scheduling adjustments were made manually here with irrigation duration being the only management variable. We believe that a more detailed, mathematical analysis of the time-course development of the MDS signals should produce algorithms that would allow an electronic controller to better detect the trends in the MDS signals and to react accordingly. This would likely involve changing irrigation timing and durations by a variable percentage. The development of appropriate software should result in MDS signals that oscillate more closely around the target threshold, leading to a more precise management of irrigation.

The use of the two MDS signal-driven schedules resulted in significant differences in applied water rates and seasonal amounts (Fig. 3). Applied water in $T_{2.75}$ was reduced almost 40% from both $T_{1.75}$ and the Ranch (Table 2) and 50% less than mature orchard ET_c (Fig. 3b). Treatment deviations in applied water began in late May and continued through harvest (Fig. 3a). While the Ranch used both SWP readings and ET_c information to develop their irrigation schedule, it is clear that some deficit irrigation occurred, since the Ranch seasonal amount applied was very similar to that of $T_{1.75}$ (Table 2).

When considering the yield and yield component results, note that we report data from trees that had nearly identical mean fruit loads for each irrigation treatment and the Ranch. We found that $T_{2.75}$ trees had lighter nuts and kernels on a fresh and dry weight bases than $T_{1.75}$ and the Ranch, which were similar. Lower kernel weights as the result of preharvest water stress have been well documented in studies by Goldhamer and Smith (1995) and Goldhamer and Viveros (2000), where moderate to severe water stress was imposed. In those studies, water stress reduced hull splitting at harvest. In contrast, our results with mild to moderate stress showed that hull splitting was increased in $T_{2.75}$ relative to $T_{1.75}$ which, in turn, was higher than the Ranch. The magnitude, timing, and duration of tree water deficits clearly influence almond hull split at harvest. Earlier hull splitting, which can also be viewed as accelerated crop maturation, allowed the nuts to dry more on the tree, potentially advancing the harvest date. This can result in price advantages for the grower. Additionally, less ground drying time can reduce ant damage (Zalom and Bentley 1985).

Table 2 Production components of harvested nuts, hull-splitting, and hydration prior to harvest

Irrigation regime	Applied water until 18 September	Fresh nut unit weight	Dry nut unit weight	Fresh kernel weight	Dry kernel weight	Full hull split nuts at 14 September	Kernel hydration**			Full hull split nuts at harvest
							14 Sept	19 Sept	27 Sept	
	(mm)	(gm)				(%)	(% by weight)			
$T_{1.75}$	860	3.57 b*	3.35 b	1.12 b	1.04 b	84.5	26.7	25.2	17.3	89.8 b
$T_{2.75}$	525	3.25 a	2.99 a	1.01 a	0.92 a	100.0	24.1	14.9	8.0	95.2 c
Ranch	898	3.70 b	3.47 b	1.08 ab	1.02 b	44.5	31.2	30.0	27.3	82.2 a

*Numbers followed by different letters are significantly different using Fisher's least significant difference method ($P=0.05$)
**From 200 nut composite sample; 50 nuts per monitored tree, taken prior to 30 September tree shaking

The impact of first year water deficits on almond production may not be indicative of the long-term response of the orchard. Indeed, Goldhamer and Smith (1995) found that after a single season of various deficit irrigation treatments that all applied only 410 mm of water but with different application timings, in addition to a fully irrigated control (1,020 mm), nut loads in the deficit treatments were reduced by up to 63% the following season, even though the orchard was returned to full irrigation. Importantly, the irrigation regime that imposed the majority of the stress preharvest, leaving the most water for postharvest irrigation, had no significant effect on the fruit load in the following season(s).

This study was designed to demonstrate that a single parameter gleaned from trunk diameter monitoring could be used to schedule irrigations in a mature almond orchard. The MDS signal thresholds were chosen to produce different stress levels throughout the season; not to maximize yields. Numerous RDI studies, where stress levels are varied over the season, have shown that seasonal ET_c can be reduced without reducing fruit yield or quality (Goodwin and Jerie 1992; Lampinen et al. 1995; Caspari et al. 1994) and, in some cases, actually improve yield components (Mitchell et al. 1986, 1989). Teviotdale et al. (2001) demonstrated that mild water stress imposed about a month prior to harvest can significantly reduce hull rot, a fungal disease that can cause shoot dieback, but pointed out that monitoring tree stress was burdensome for most growers. On the other hand, the effects of long-term use of RDI on tree longevity and soil salinity have yet to be investigated.

Tree-based (as opposed to soil and atmospheric) RDI triggers have the major advantage of being directly linked to crop productivity. Since the MDS signal has been shown to be a very sensitive stress indicator and has numerous operational advantages over SWP, including lower labor costs and the ability to be directly incorporated into remotely operated, electronic controllers, it may well be a superior tree-based indicator for use where RDI and/or precise irrigation scheduling is needed.

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