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ORIGINAL PAPER

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Continuous measurement of plant and soil water status for irrigation scheduling in plum

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Abstract The usefulness of continuous measurement of soil and plant water status for automated irrigation scheduling was studied in a drip-irrigation experiment on plum (*Prunus salicina* Black Gold). Two levels of water restriction were imposed at different phenological periods (from pit-hardening to harvest, post-harvest) and compared with a well irrigated control treatment. Soil matrix water potential (ψ_{soil}) was measured with granular matrix sensors (Watermark); and short-period trunk diameter variation (TDV) was measured with linear variable displacement transformers. The Watermark sensor readings were in reasonable agreement with the irrigation regime and showed a good indication of plant water status across the season ($r^2 = 0.62$), although they were a better predictor of stem water potential (ψ_{stem}) in the dry range of ψ_{soil}. Nonetheless, the most important drawback in their use was the high variability of readings (typical CV of 35–50%). From TDV measurements, maximum daily shrinkage (MDS) and trunk growth rate (TGR) were calculated. Their performance was also compared with ψ_{stem}, which had the lowest variability (CV of 7%). During most of the fruit growth period, when TGR was minimum, MDS was higher in the less-irrigated treatment than in the control and correlated well ($r^2 = 0.89$) with ψ_{stem}. However, after harvest, when TGR was higher, this correlation decreased as the season progressed ($r^2 = 0.73$–0.52), as did the slope between MDS and ψ_{stem}, suggesting tissue elasticity changes. Later in the season, TGR was better related to plant water status. These observations indicate some of the difficulties in obtaining reference values useful for irrigation scheduling based exclusively on plant water status measurements.

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Introduction

To sustain agriculture, it is particularly important to optimize crop yields by minimizing inputs, mainly water and nutrient application.

Many approaches to improve water management have been developed (Fereres and Goldhamer 1990), some of which involve the use of sensors to monitor continuously either the soil water content (Hanson et al. 2000a) or the plant water status (Goldhamer and Fereres 2001).

The granular matrix sensor (GMS) is an option for indirectly estimating soil water content (Leib et al. 2003). It measures soil electrical resistance that can be converted to soil water potential (ψ_{soil}), either using a calibration formula provided in the literature for sandy soils (Irmak and Haman 2001) and silt loam soils (Eldredge et al. 1993), or calibrating them for a specific soil type.

The Watermark (Larson 1985) is a relatively low-cost GMS, which is easy to use and install and can function consistently over a range of soil water tension from −10 kPa to −200 kPa (Leib et al. 2003), which is over a larger range than tensiometers. However, there is evidence of some limitations. For example, the Watermark does not respond to changes at soil water potential higher than −10 kPa and, therefore, may not be a suitable tool in those cases where irrigation practices maintain a low soil tension (Irmak and Haman 2001; Taber et al. 2002). Moreover, the Watermark does not respond properly to rapid drying or partial rewetting of the soil, showing hysteretic behavior (McCann et al. 1992), which consequently may lead to incorrect estimation of the actual soil water status in these situations. Finally, there is also evidence that the Watermark is not suitable for accurate and reproducible measurement of ψ_{soil} or soil water content, as calibration appears to be unique for each individual sensor (Egbert et al. 1992; Hanson et al.

2000b; Leib et al. 2003). In spite of all these limitations, Watermark may be useful when a relative indication of soil wetness is needed, as indicated by reports of their successful use for irrigation scheduling in some herbaceous crops (Shock et al. 1998a, 1998b; Taber et al. 2002) and woody crops (Hanson et al. 2000a).

In contrast, recording trunk diameter variations (TDV) has been proposed in several studies as a tool for continuous estimates of plant water status, particularly stem water potential (ψ_{stem}; Goldhamer et al. 1999; Cohen et al. 2001; Moriana and Fereres 2002). However, recent findings in peach (Marsal et al. 2002) and almond (Fereres and Goldhamer 2003) show that this relationship may change during the season. Therefore, to schedule irrigation based on the information derived from TDV, the robustness of the relationship between TDV and ψ_{stem} must be established.

The objective of our study was, then, to determine the feasibility of using TDV measured with linear variable displacement transformer (LVDT) sensors and ψ_{soil} derived from GMS for irrigation scheduling in a drip-irrigated plum (*Prunus salicina* L. Black Gold) orchard, comparing different water deficits (mild, severe) with well watered plants. The advantages and limits of both techniques are discussed.

Materials and methods

The experiment was carried out during 2002 in a 5-year-old plum orchard (*P. salicina* Black Gold on Marianna GF81) planted at 5×3.5 m spacing and located at Liria (39°45′N, 0°38′W, elevation 300 m), Valencia, Spain. At the beginning of the experiment, the average tree LAI, percentage of shaded area and trunk circumference were 0.73, 29% and 0.29 m, respectively. The soil was a sandy loam with abundant stones (32% by weight) and about 80 cm of effective depth. The irrigation water had an average EC of 1.1 dS m^{-1} (at 25 °C) and an average Cl^- content of 122 g m^{-3}. The fertilization applied through the irrigation system provided N, P_2O_5 and K_2O at 150, 75 and 175 kg ha^{-1} $year^{-1}$, respectively. The agricultural practices followed were those common for the area. The experiment had six 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. To test sensor performance, only the four treatment groups described below were used:

1. Control group irrigated at 100% crop evapotranspiration (ET_c) during the full season
2. Group 33 I irrigated at 33% ET_c from pit-hardening (14 May) to harvest (8 July) and at 100% ET_c during the rest of the season
3. Group 66 I + II irrigated at 66% ET_c from pit-hardening to the end of the season
4. Group 33 II irrigated at 33% ET_c from harvest to the end of the season and irrigated at 100% ET_c until harvest

ET_c was estimated as the product of reference evapotranspiration (ET_o) and crop coefficient (K_c). ET_o was calculated from the Penman–Monteith equation, using hourly data collected by an automated weather station situated near the orchard. K_c values were obtained from Doorenbos and Pruitt (1977) and adjusted for tree size, following Fereres and Goldhamer (1990). On a seasonal basis, the average K_c was 0.2.

Drip-irrigation was applied with six emitters per tree (each delivering 3.85 l h^{-1}) which were located in a double-irrigation line parallel to the tree row. The reductions in the amount of water applied during the deficit periods were achieved by reducing the irrigation duration, while irrigation frequency was the same for all treatments and varied from once per week in early spring and autumn to three times per week during summer. Water meters on each replicate measured the water application.

Soil water potential was measured with eight GMS (Watermark model 200ss, Irrometer Co.) per treatment. They were all located at 30 cm depth and 25 cm distance from the vertical of a dripper situated in the west tree quadrant and at the same distance from the tree. Each of the six experimental trees per treatment had only one Watermark sensor and two trees had an additional sensor. The calibration equations used to convert the soil electrical resistance obtained with GMS (adjusted by soil temperature) to soil water potential were those reported by Allen (2000). Soil temperature was measured with a model 107 temperature probe (Campbell Scientific) installed at the same depth and distance from an emitter as the Watermarks.

TDV were measured with six LVDT (model DF-2.5, Schlumberger) per treatment. On each experimental tree, a sensor was fixed to the main trunk by an Invar frame (Invar being a metal alloy with minimal thermal expansion) located about 20 cm from the ground on the north side. Prior to installation, the transformers were individually calibrated by means of a precision micrometer (Verdtech, Spain). The typical output coefficient was about 85 mV mm^{-1} V^{-1}. The resolution of TDV, including all sources of variation (calibration, non-linearity, excitation, output voltage recording, thermal changes), was about 10 μm. From TDV, we calculated two different indexes, the maximum daily trunk diameter (MXTD) and the maximum daily shrinkage (MDS), the latter obtained as the difference between the maximum diameter reached early in the morning and the minimum reached normally during the afternoon.

All sensor data were automatically recorded every 30 s, using a model CR23X data logger (connected to an AM16/32 multiplexer for soil sensors, connected to an AM25T multiplexer for LVDT sensors) programmed to report mean values every 30 min for LVDT and every 2 h for soil sensors.

ψ_{stem} was measured with a pressure chamber, following the procedures described by Turner (1981), in four leaves per treatment (two leaves per tree on two selected trees that also had soil and plant sensors installed). Mature leaves on the north face near the trunk

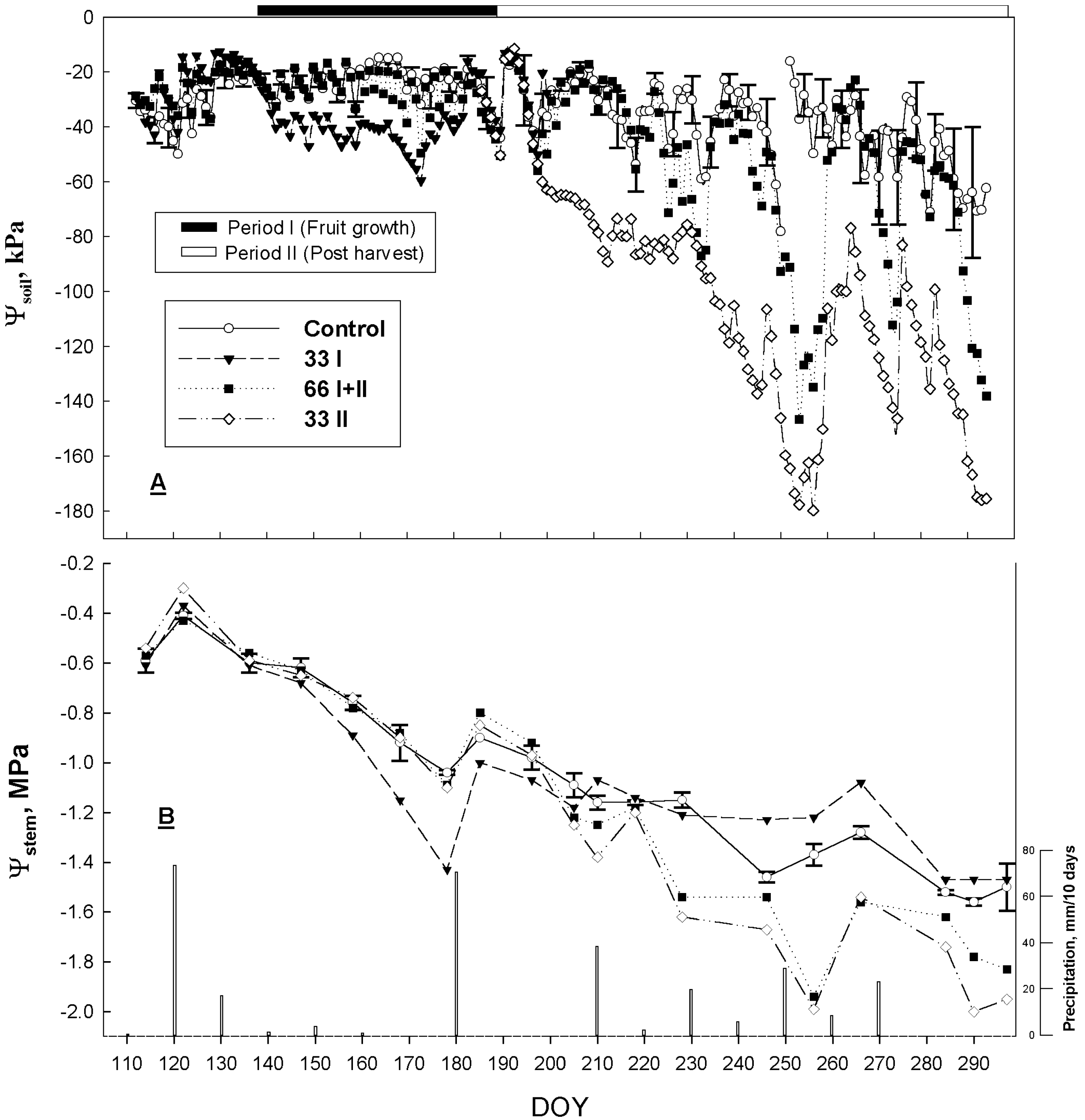

Fig. 1A, B Seasonal patterns of water potentials. **A** Seasonal pattern of soil water potential (ψ_{soil}). For clarity only midday values (averages of eight sensors per treatment) are plotted. The values of the treatment groups 33 I and 33 II during the period when they had no restrictions are not shown. **B** Seasonal pattern of stem water potential (ψ_{stem}). Values given are means of four measurements recorded at midday (1200–1300 GMT). *DOY* Day of the year, *capped bars* standard error

were enclosed in plastic bags covered with silver foil at least 2 h prior to the measurements, which were carried out between 1200 h and 1300 h (solar time) approximately every 10 days from April to November.

Statistical data analysis was performed with Statgraphics Plus ver. 4.1.

Results and discussion

Seasonal dynamics

Soil water potential

During the period from pit-hardening to harvest (period I), ψ_{soil} in the control treatment was nearly stable, with values of −20 kPa to −30 kPa, whereas the two

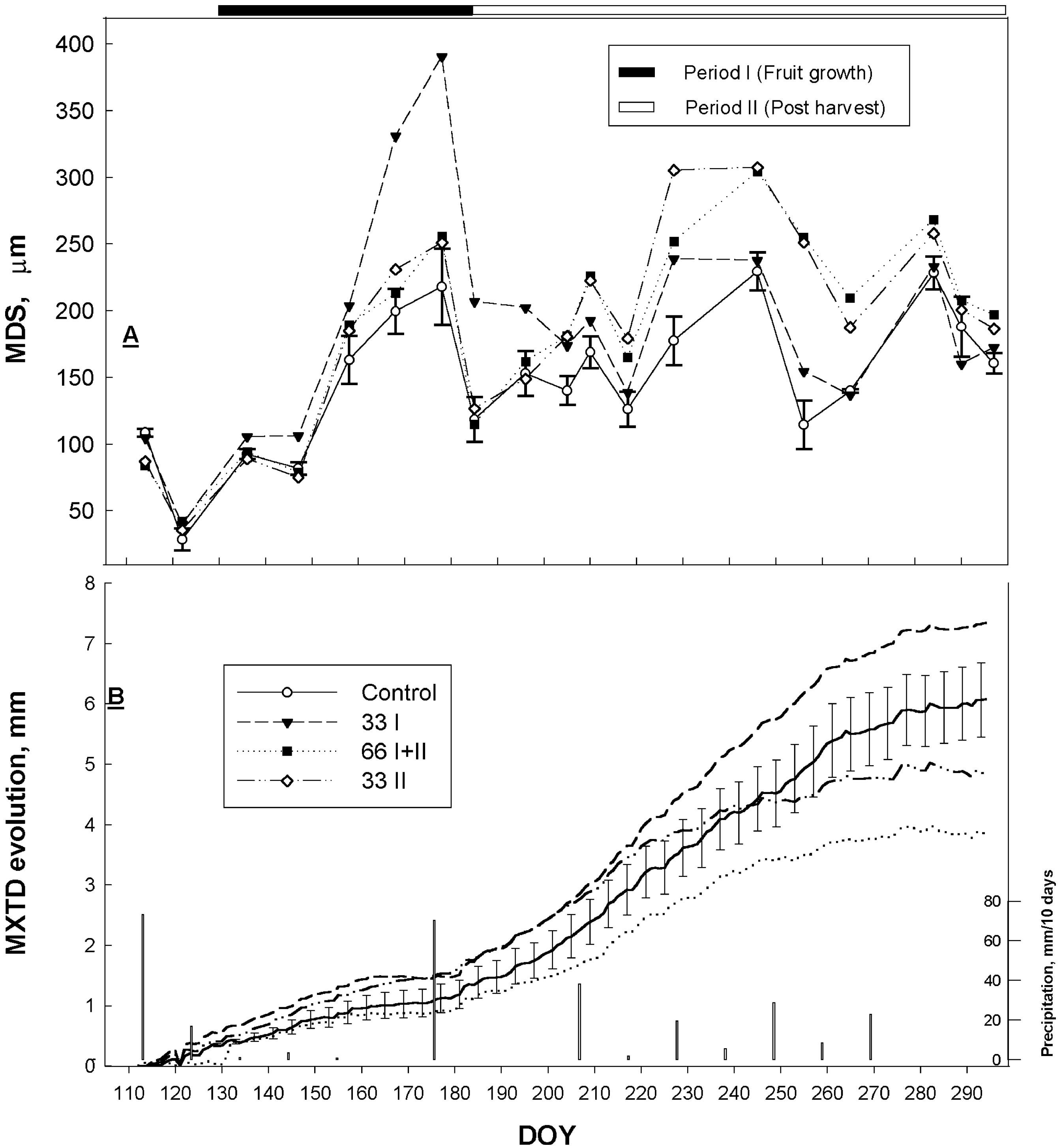

Fig. 2A, B Seasonal patterns of shrinkage and diameter. **A** Maximum diurnal shrinkage (*MDS*). Data on MDS are presented only for those days coinciding with determinations of ψ_{stem}. **B** Maximum daily diameter (*MXTD*). Values given are averages of six linear variable displacement transformer (LVDT) sensors per treatment

restriction levels showed contrasting responses (Fig. 1A). Thus, group 33 I showed a marked tendency to decrease, reaching a minimum value of −60 kPa on day 172. However, group 66 I+II (despite the water restriction) did not show clear differences with respect to the control trees.

During post-harvest (period II), ψ_{soil} in the control trees was less stable than previously, showing a tendency to decrease from −20 kPa just after harvest (day 189) to minimum values around −60 kPa to −70 kPa on day 280 (Fig. 1A). This reflected some underestimation of the K_c employed during this period, as the actual water applied was higher than the esti-

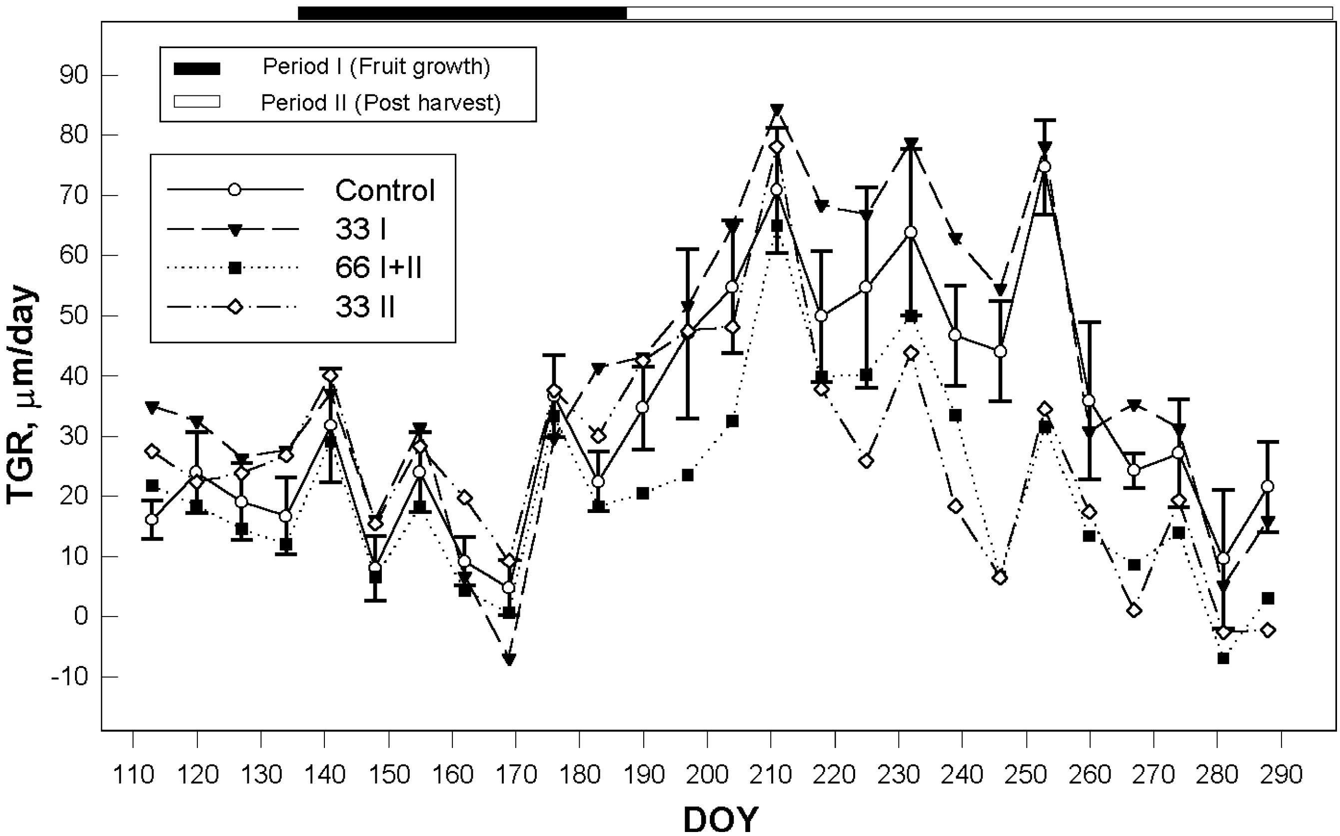

Fig. 3 Trunk growth rate (*TGR*) in the different irrigation treatments. Values given are means of six LVDT sensors per treatment, calculated as averages for 7 days

mated ETc (data not shown). For the deficit-irrigated treatments, the less-irrigated one (group 33 II) showed, as expected, a gradual and steep decline in ψ_{soil}, reaching a minimum value of −180 kPa (after 2 months of restriction) on day 255. In contrast, group 66 I + II did not start to clearly differ from the control trees until day 255 (after 100 days of water restriction) and when its ψ_{stem} (Fig. 1B) was already lower than in the control. This indicated either that the GMS sensor had a low sensitivity to small water restrictions or that the place where the sensor was installed was not representative of the actual soil water content of this treatment.

Over all treatments and seasons, GMS responded throughout the wetting and drying cycles with a time-response to each irrigation event of about 6 h. They functioned consistently over a range of ψ_{soil} of −15 kPa to −180 kPa. A similar working range was previously found (Hanson et al. 2000a; Leib et al. 2003), confirming that GMS operate in a drier range than tensiometers but with a lower resolution at the wet end of soil water potential, as reported by Egbert et al. (1992) and Irmak and Haman (2001). This is an important limitation, especially in sandy soils or in situations where high ψ_{soil} has to be maintained. However, the most important drawback on their use for irrigation scheduling is the high variability of readings, which precludes the detection of small treatment differences, at least under the mild restriction conditions observed here. In fact, despite attempts to minimize spatial variability in soil water content due to the drip irrigation system, by carefully installing all sensors at the same distance from selected emitters, at the same depth and at the same distance with respect to the tree, we obtained typical CV values of 35–50%, increasing at the lower ψ_{soil} range. These values are similar to those obtained in other trials where either Watermark sensors (Taber et al. 2002) or tensiometers (Hendrickx and Wierenga 1990) were employed.

Stem water potential

The evolution of ψ_{stem} (Fig. 1B) showed a decreasing trend along the season in all treatments. In fact, ψ_{stem} values for control trees decreased from an initial value of −0.6 MPa (day 112) to −1.5 MPa (day 295). This was probably due to higher evaporative demand, the increase in leaf area (over days 112–180) and a general gradual reduction in water availability towards the end of the season, even in the more irrigated (control) trees, as previously discussed (Fig. 1A).

When deficit-irrigation was first imposed by pit-hardening, only the more severe level of restriction (group 33 I) showed a marked decrease in ψ_{stem} values, which became noticeable some 15 days after the imposition of water restriction. A minimum value of −1.5 MPa was recorded in this treatment just before

Table 1 Comparison of the sensitivity (signal to noise ratio) of the different variables (see Materials and methods) during the fruit growth and post-harvest periods. *CV* Coefficient of variation

Period	Sensitivity	ψ_{soil}	ψ_{stem}	MDS	TGR
Fruit growth	Signal	1.55	1.18	1.47	1.25
	Noise (CV)	0.43	0.07	0.17	0.25
	Ratio	3.6	16.0	8.4	4.6
Post-harvest	Signal	2.45	1.20	1.36	2.16
	Noise (CV)	0.50	0.08	0.21	0.26
	Ratio	4.9	15.0	6.5	8.3

harvest (after 50 days of restriction). However, group 66 I+II did not show any differences in ψ_{stem} values with respect to the control trees, in agreement with its soil water status as previously discussed. When irrigation returned to full dosage, the group 33 I trees recovered quickly to values similar to those of the control trees.

After harvest, differences in ψ_{stem} were evident in treatment groups 66 I+II and 33 II some 15 days after water restriction started. The differences increased during the season, reaching minimum ψ_{stem} values of −1.9 MPa and −2.0 MPa, respectively, for groups 66 I+II and 33 II by about day 258. Similar ψ_{stem} values achieved during post-harvest did not have a negative impact on the following year's production of an early-maturing plum (Johnson et al. 1994), indicating the possibility of important water savings during this period. Treatment group 33 I, which had no restriction during this period, tended to have slightly higher (i.e. more hydrated) values than the control trees. This was probably a consequence of the reduction in vegetative growth (smaller leaf area; data not shown) which occurred during the previous period of water restriction. The time-course of ψ_{stem} in this treatment was similar to that of the control, decreasing from −1.0 MPa to −1.4 MPa during the period.

Trunk diameter variations

Although the response between species is not unique, MDS values commonly increase with water deficit, especially when water restriction is not severe (Huguet et al. 1992). During period I, treatment group 33 I (before restriction) had similar MDS values to the control trees, but they soon became higher as deficit-irrigation was imposed (Fig. 2A). As the water restriction progressed, differences increased, reaching a maximum difference of about 200 μm by day 178, just before heavy

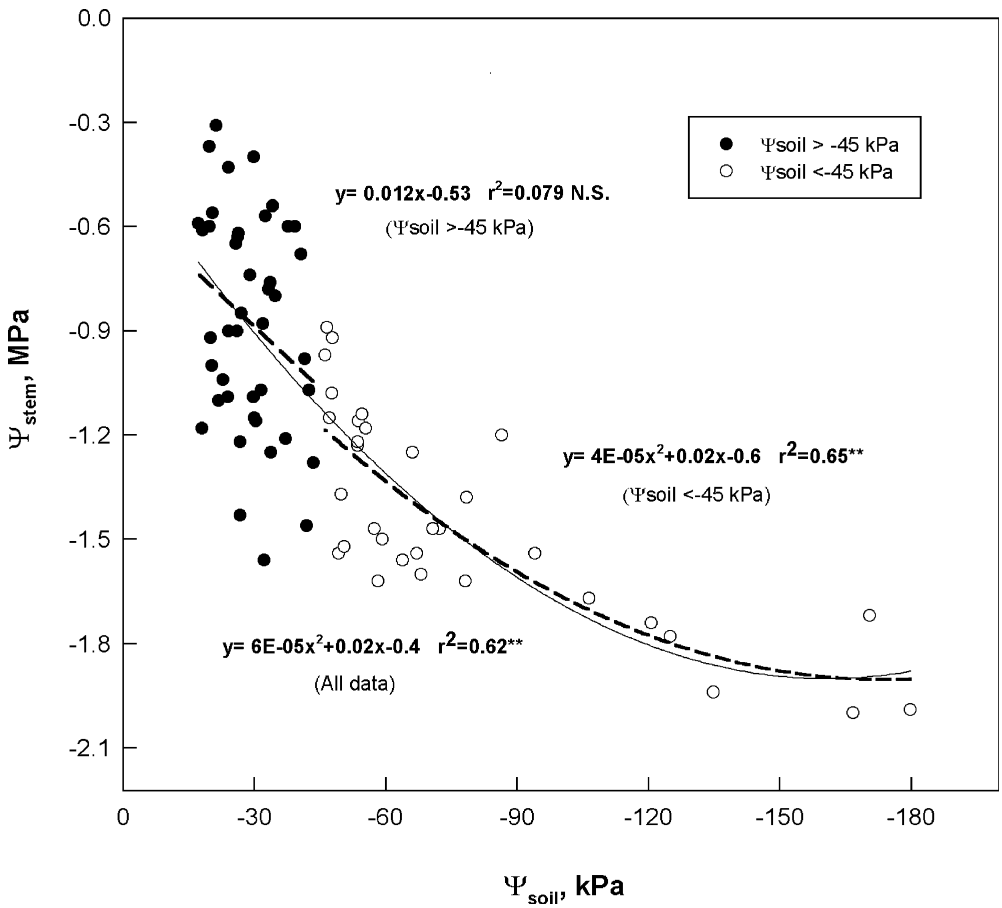

Fig. 4 Relationship between ψ_{soil} and ψ_{stem} for all data, separated for two soil wetness ranges ($\psi_{soil} > -45$ kPa, $\psi_{soil} < -45$ kPa; *dotted lines*). Values are averages for eight sensors and four leaves, respectively. ** Significant at $P < 0.05$

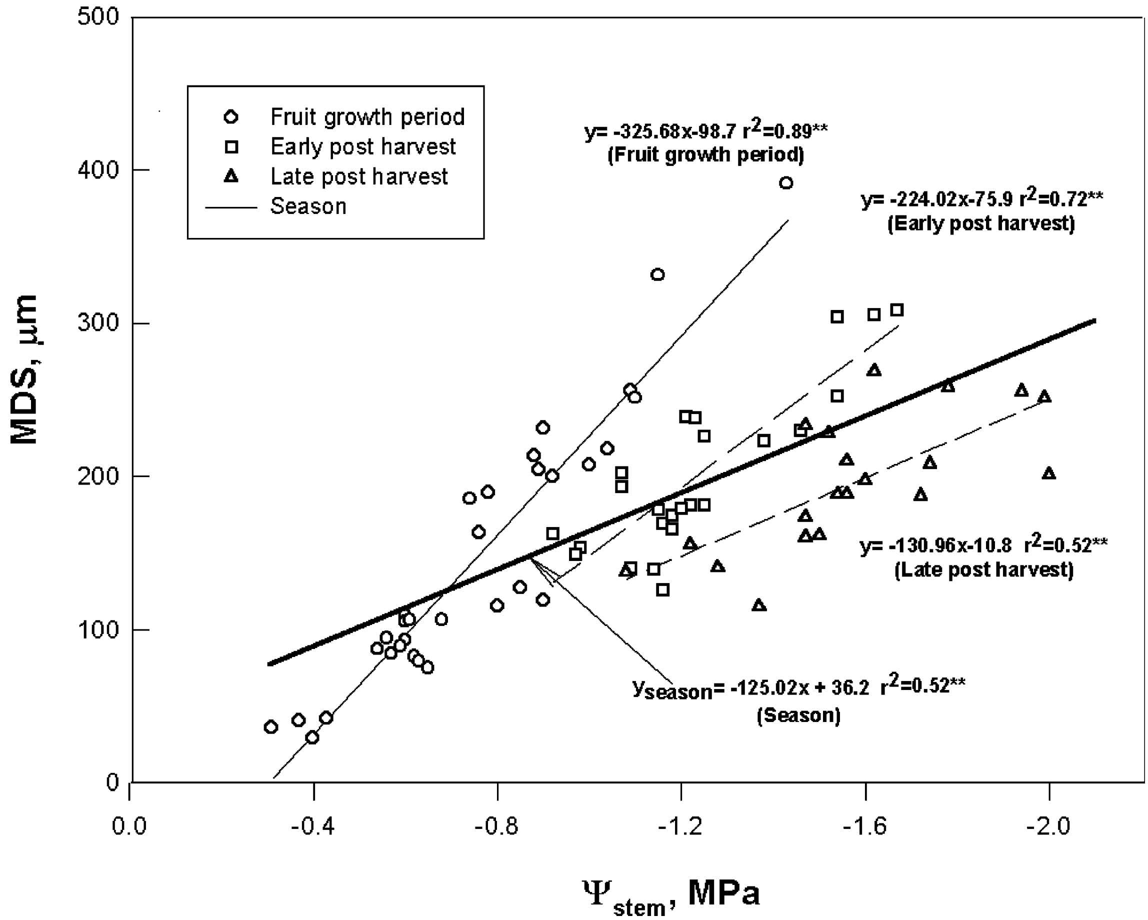

Fig. 5 Relationship between MDS and ψ_{stem} for the whole season and separated according to periods: fruit growth (from day 120 to harvest on day 188), early post-harvest (from harvest to day 215) and late post-harvest (from day 216 to day 297). Values given are averages for six sensors and four leaves, respectively

rain occurred. This was accompanied by a difference of 0.5 MPa in ψ_{stem} between those treatments. In treatment group 66 I + II, MDS values were similar to those of the control trees, in agreement with its soil and plant water status, as previously discussed.

During period II, both restriction levels (groups 66 I + II, 33 II) showed higher MDS than the control trees; and, again, differences became greater as the restriction progressed. Interestingly, treatment group 33 I (irrigated like the control trees during period II) had higher MDS than the control, but ψ_{stem} was similar or even slightly higher during this period (Fig. 1B). This suggests an adaptation of plum trees to water stress. Trees in treatment group 33 I may have a greater tissue elasticity than those in the control treatment, as a turgor maintenance response after the water stress applied during period I (Kozlowski and Pallardy 2002). This feature would lead then to higher shrinkage in this treatment with respect to the control trees for a similar plant water status.

Trunk growth rate (TGR), indicated by the evolution of MXTD, is another variable that can be used as an indicator of plant water status (Goldhamer et al. 1999; Moriana and Fereres 2002). MXTD evolution (Fig. 2B) shows a general tendency towards a very low TGR in all treatments during the fruit growth period (period I), very likely a consequence of fruit-to-vegetative growth competition (Grossman and DeJong 1994) as fruits, especially during stage III of their development, are very strong sinks and have priority for assimilates (Flore and Layne 1997). Therefore, as expected during period I, differences between treatments were small, with only group 33 I having a decreased TGR (Fig. 3) and even reaching negative values as a consequence of the reduction in water application. After harvest (days 210–255) however, TGR in control trees was relatively constant with values around 60–90 µm day^{-1}, which was higher than in the previous period, probably because of less competition for assimilates. In contrast, groups 33 II and 66 I + II had clearly lower TGR. Moreover, in these treatments, trunk growth ended 1 month earlier than in the control trees (Fig. 2B), probably as a consequence of the very low ψ_{soil} and ψ_{stem} reached (Fig. 1A, B).

A seasonal pattern of trunk growth similar to that of our control treatment was recently described for well irrigated peach trees (Marsal et al 2002), indicating the important influence of phenology on trunk growth.

Table 2 Linear regression analysis between MDS (y) and ψ_{stem} (x) and multiple linear regression analysis of MDS (y) and both ψ_{stem} (x_1) and TGR (x_2) during season. ** Statistically significant at $P < 0.05$, * significant at $P < 0.10$. Other values are non-significant

Period	Simple linear regression			Multiple linear regression			
	MDS vs ψ_{stem}			MDS vs both ψ_{stem} and TGR			
	y = mx + b			y = m$_1$x$_1$ + m$_2$x$_2$ + b			
	m	b	r^2	m_1	m_2	b	r_{adj}^2
Fruit growth	−326**	−99**	0.89**	−319**	−0.4**	−85**	0.92**
Early post-harvest	−224**	−76**	0.72**	−206**	−0.34**	−34	0.75**
Late post-harvest	−130**	−11	0.52**	−134**	0.08	−16	0.51**
Fruit growth + early post-harvest	−200**	−23*	0.67**	−210**	−0.76**	−5.5	0.81**
Whole season	−125**	+36**	0.52**	−121**	−0.13	−43.4**	0.50**

Comparison of sensitivity of the different variables

Sensitivity as defined by Fereres and Goldhamer (2003) is the average ratio between the values of a variable for the most stressed treatment and those of the control treatment (the signal) divided by the average coefficient of variation (the noise).

A comparison of the sensitivity during the two main phenological periods (fruit growth, post-harvest) among the different techniques used (Table 1) showed that ψ_{soil} had the highest signal value but the lowest sensitivity, due to its very high variability in both periods. In contrast, ψ_{stem} was the most sensitive, due to its very low CV. Finally, MDS was more sensitive than TGR during the fruit growth period, but the reverse occurred post-harvest.

Contrary to our results, Goldhamer and Fereres (2001) found MDS was more sensitive than ψ_{stem} in mature almond trees. They obtained higher signal values for MDS than in this work, while the variability was similar. This can probably be attributed to differences in the irrigation system, as theirs wetted the whole orchard floor.

Relationships between different indicators

The usefulness of the TDV-derived indexes and GMS sensors was also evaluated by regression analysis between those indexes and ψ_{stem}, commonly used as a standard measurement of plant water status.

Soil water potential was significantly related to ψ_{stem} over the full season ($r^2 = 0.62$, Fig. 4). Multiple regression analysis (including also either daily ET_o or midday air vapor pressure deficit values) only explained an extra 5% of variance (data not shown). Figure 4 indicates that Watermarks are apparently poor predictors of ψ_{stem} when the soil is wet. In fact, when data are separated on two soil wetness ranges ($\psi_{soil} < -45$ kPa, $\psi_{soil} > -45$ kPa), the correlation is clearly higher and only significant in the drier range. Nonetheless, part of the lack of agreement between both variables in the wet range can be attributed to the effects of evaporative demand on ψ_{stem}. Therefore, for irrigation of fruit trees, Watermarks would not be recommended in situations when high ψ_{soil} has to be maintained (for instance phase III of fruit growth), but they can be a useful tool when drier soil conditions are less harmful for fruit growth (e.g. phase II). Finally, we also conducted a regression analysis for the same individual periods used later for the relationship between MDS and ψ_{stem} and found that shorter periods did not improve the correlations (data not shown). This indicates that phenology, apparently, does not influence the relationship between ψ_{stem} and ψ_{soil}.

The regression analysis between MDS and ψ_{stem} (Fig. 5), pooling data across the season, showed that the coefficient of determination was significant, though not very high ($r^2 = 0.52$). However, when broken into three time-periods, the correlation for individual periods clearly improved, except for late post-harvest. Moreover, we observed a general trend towards lower MDS for a given ψ_{stem} and to a reduction in the slope between both variables as the season progressed (Fig. 5). Similar behavior in this relation was also recently reported in peach and almond trees (Marsal et al. 2002; Fereres and Goldhamer 2003), suggesting that this may be a general trend, at least in deciduous fruit trees. The causes are possibly related to TGR and tissue elasticity changes during the season. After harvest, TGR is clearly higher than during the fruit growth period and theoretically (Genard et al. 2001), for a given evaporative demand and soil water potential, the trunk shrinks more when its growth rate is low. In fact, a comparison of the slope of MDS vs ψ_{stem} for the fruit growth period and for the early post-harvest period suggests that changes could be related to differences in TGR between periods. This is supported by the additional 14% of variance explained by regression that included TGR in the model of MDS vs ψ_{stem} (Table 2). However, later in the season, the MDS vs ψ_{stem} slope decreased again; and then the inclusion of TGR in the regression model did not improve the goodness of fit ($r^2_{adj} = 0.50$; Table 2), indicating the likely involvement of factors distinct from growth. It is generally accepted that tissue age affects its elasticity, older tissues being less elastic (higher resistance to shrinkage; Tyree and Jarvis 1982). Therefore, lower MDS for a given ψ_{stem} value late in the season may be due to less elastic, older tissues.

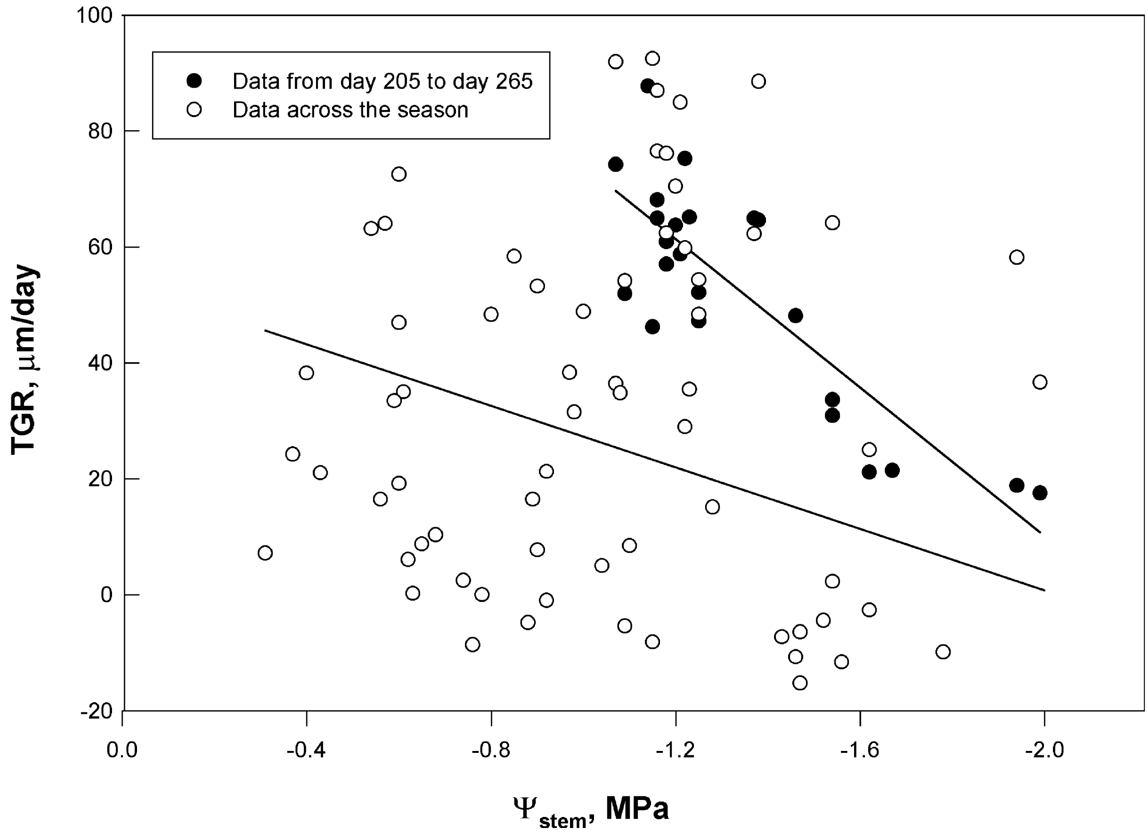

Fig. 6 Relationship between TGR and ψ_{stem}, using data across the full season and for all treatments during a period (days 205–265) of nearly constant TGR rates in the more irrigated trees. TGR values given are averages of the 7 days of the week when ψ_{stem} measurement were collected. Values given are averages of six sensors and four leaves, respectively

Another important issue is to prove the robustness of the relation between MDS and ψ_{stem} for different species. As far as we know, there are no reports of the analysis of TDV in plum or prune trees. However, on 8-year-old peach trees, Cohen et al. (2001) studied the relationship between MDS and ψ_{stem} (although only during phase III of fruit growth) and found values very similar to ours. As an example, for a ψ_{stem} of −1.0 MPa, we obtained 227 μm of contraction, while on peach the same ψ_{stem} corresponded to 230 μm. Nonetheless, more effort is required in order to check the extrapolation of this relationship among different *Prunus* species or cultivars.

Finally, the evolution of MXTD is the other TDV variable related to plant water status. As TGR was not constant during the season independently from water status, it impedes the search for a significant relation between both variables over the full season (Fig. 6). However, for a period when TGR was relatively constant and high in the more irrigated trees (days 205–265), differences were expected to be due mainly to plant water status. This is supported by the high coefficient of determination ($r^2 = 0.71$; Fig. 6) in the regression between both variables, including data from all treatments during this period. However, in peach, Sellés and Berger (1990) found a good correlation over the full season between TGR and ψ_{stem}.

Conclusions

Our results show that ψ_{stem} was the least variable and more sensitive indicator. However, Watermark sensors can be a useful tool especially in the dry range of ψ_{soil}, as they have much higher uncertainty in the wet range. Moreover, their high variability and the reduced zone of influence imply the need for a large number of sensors per orchard. But, MDS is a very good predictor of ψ_{stem} during phases II and III of fruit growth. Therefore, especially during stage III, their use can be extremely important, as it could enable the early detection and prevention of any water stress that could reduce orchard productivity. However, it has to be taken in consideration that the relation between MDS and ψ_{stem} is not unique throughout the season. This is an important feature, as a single MDS value could lead to important deviations when evaluating plant water status, depending on the phenological period. Finally, trunk growth can also be a good plant-based water stress indicator, but the influence of phenology on its evolution impedes establishing absolute threshold values. Therefore, its use is recommended together with a reference obtained on fully irrigated "control" trees.

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