

# Evaluation of grapevine water status from trunk diameter variations

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**Abstract** We evaluated the usefulness of short-term trunk diameter variations (TDV) as water stress indicator in field-grown grapevines cv. Tempranillo. Two indices were calculated from TDV, maximum daily trunk shrinkage (MDS), and trunk growth rate (TGR). The seasonal evolution of both indicators was compared with occasional determinations of pre-dawn leaf water potential and stem water potential, measured at early morning ( $\Psi_s^{em}$ ) and at midday ( $\Psi_s^{md}$ ) in irrigated and non-irrigated vines. In the second season, the effect of crop load on the vine water status indicators was also studied. Crop load did not affect either the vine water relations or the TDV. All water potential determinations had much lower variability and were more sensitive than both MDS and TGR to water restrictions. The ability of both indices to detect plant water stress varied largely depending upon the phenological period. In fact, MDS and TGR were only able to detect vine water stress during a short period of time before veraison. During this period, TGR was linearly related to both  $\Psi_s^{em}$  and  $\Psi_s^{md}$ , while for MDS a curvilinear, quadratic equation, better described the relationship with plant water status. After veraison no apparent relation-

ship existed between plant water status and MDS or TGR. Hence, our results question the practical use of both MDS and TGR as variables to automate irrigation scheduling for grapevine.

## Introduction

To evaluate the effects of water deficit on vine water status and performance the most straightforward strategy may be to directly measure the soil water content (SWC) or potential. However, this approach has often been unsuccessful (Naor 2006; Intrigliolo and Castel 2006a) because it is difficult to obtain a precise estimation of the actual bulk soil water availability for the plant (Campbell and Campbell 1982).

Soil water deficit affects different physiological traits that can be used as plant water status indicators. Generally leaf or stem water potential measurements with the pressure chamber are used to determine grapevine water status (Choné et al. 2001). Stomatal closure is among the first responses to drought (Düring 1987) and therefore determinations of stomatal conductance have also been widely used as an indicator of water stress in grapevines (Liu et al. 1978; Jones et al. 2002). However, as these measuring methods cannot be easily automated, it is important to study other techniques able to continuously monitor plant water status and, if successful, to automate irrigation scheduling.

At the present time, monitoring trunk diameter variations (TDV) is widely used to detect plant water status (Goldhamer and Fereres 2001; Naor 2006) Two indices derived from TDV have been employed as possible plant water status indicators: (1) trunk growth rate (TGR) and (2) maximum daily stem shrinkage

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(MDS), or the difference between maximum trunk diameter early in the morning and minimum at early afternoon. This reflects the magnitude of stem contraction along a day.

Trunk growth is a developmental trait affected by plant water stress that can be used as an indirect measurement of plant water status. However, other factors can also affect trunk growth such as the phenological stage (van Zyl 1984) and crop load (Morinaga et al. 2003), mainly because of their effect on carbon partitioning (Wardlaw 1990). Also, during those phenological periods when the trunk is not growing TGR cannot be used as an indicator of plant water status.

Seasonal variations of trunk diameter depend mainly on growth (Kozłowski and Winget 1964). However, there is also a diurnal shrinking and swelling of tissues (Kozłowski 1967). Daily changes of trunk diameter mainly depend on the level of plant tissue hydration (Simonneau et al. 1993). More than 90% of diurnal trunk diameter fluctuations occur on phloem tissues (Irvine and Grace 1997), with only slight elastic deformation of xylem (Molz and Klepper 1973). During the diurnal hours, as the leaf water potential and xylem water potential, concurrently become more negative there is a radial transfer of water from bark tissues into xylem (Parlange et al. 1975). During the late afternoon, plant water uptake exceeds water losses by transpiration, and there is a recovery on xylem water potential. This leads to a reverse in the radial flow of water, from the water conductive elements back to the phloem tissues. Thus, xylem water potential is the driving force of stem shrinkage during the day (Klepper et al. 1971).

In deciduous fruit (Cohen et al. 2001; Marsal et al. 2002; Intrigliolo and Castel 2006b) and citrus (Ortuño et al. 2006) tree species, MDS and TGR were found to be responsive to changes in moisture availability. In all these cases plant water deficit increased trunk shrinkage and decreased trunk growth. However, for at least for *Prunus* species there is not a unique relation valid for the whole season between plant water status and trunk shrinkage (Marsal et al. 2002; Fereres and Goldhamer 2003; Intrigliolo and Castel 2006b). Moreover there is recent evidence that crop load itself might directly affect MDS (Intrigliolo and Castel 2007).

Using trunk growth itself as a water stress indicator in grapevines was explored by Myburg (1996) and Sellés et al. (2004). However, the relationship between MDS, TGR, and leaf or stem water potential had not been explored. Yet in grapevine, this information is of crucial importance to evaluate the feasibility of TDV as water stress indicators during a seasonal course.

Our objective was then, to study the usefulness of MDS and TGR as water stress indicators on Tempranillo grapevines, by (1) comparing the seasonal changes with that of water potential determinations on irrigated and non-irrigated vines with different crop load levels, (2) exploring the relationship between stem water potential and MDS and TGR as a function of the phenological period.

## Materials and methods

### Site description and experimental design

The experiment was carried out during the 2004 and 2005 seasons in a ‘Tempranillo’ vineyard (*Vitis vinifera* L.) planted in 1991 on 161-49 rootstock at a spacing of  $2.45 \times 2.45 \text{ m}^2$  (1,666 vines per ha). The vineyard was located near Requena (39°29'N, 1°13'W, elevation 750 m), Valencia, Spain. Until the year 2000 vines were rain-fed and trained to an open vase system. In 2000, a drip-irrigation system was installed and vines trained to a vertical trellis on a bilateral cordon system oriented in the North–South direction. Canopy management practices, all manually performed, included green pruning, and shoot tip cutting.

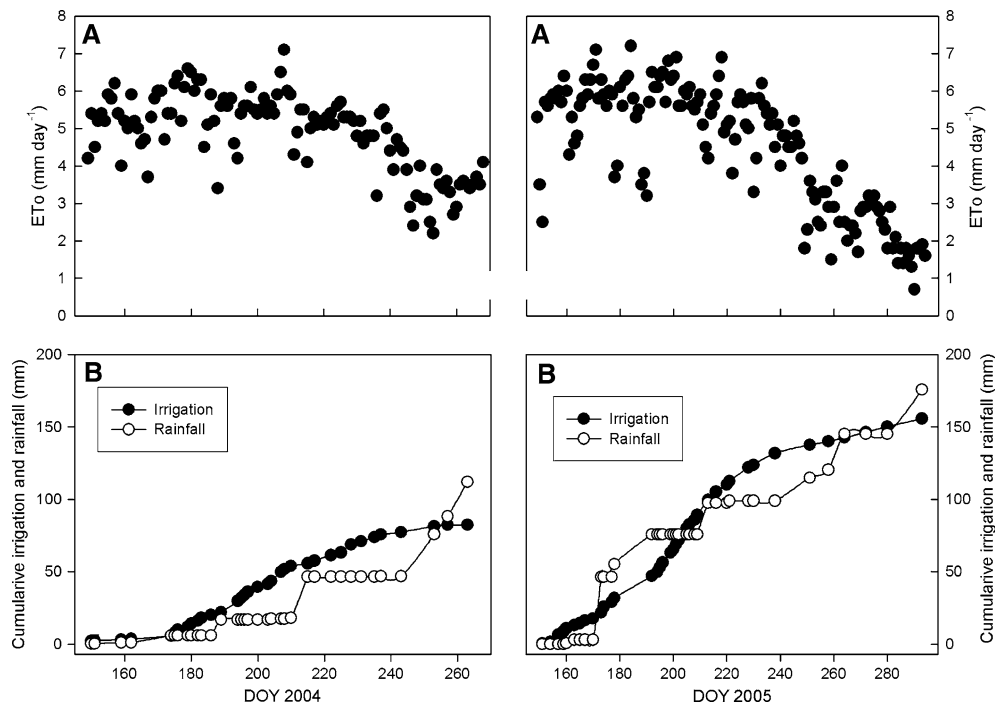
The soil at the site is a Typic Calciorthid, with a clay loam to light clay texture, highly calcareous and of low fertility. It has a deep soil profile (>2 m), available water capacity is about  $200 \text{ mm m}^{-1}$ , and bulk density  $1.43\text{--}1.55 \text{ t m}^{-3}$ . The climate of this area is continental and semiarid with average annual rainfall of 450 mm of which about 65% falls during the dormant period. Weather conditions during the experiment were measured with an automated meteorological station located in the plot and reference evapotranspiration ( $ET_0$ ) was calculated as in Allen et al. (1998).

Drip irrigation was applied with two pressure-compensated emitters of  $2.4 \text{ l h}^{-1}$  located at 60 cm each side of the vine. Irrigation frequency varied from 3 to 5 days per week. Water meters measured the amount applied to each irrigated replicate.

Weather conditions and irrigation application during the two growing seasons are shown in Fig. 1. Rainfall from vintage to vintage was of 520 and 277, in 2004 and 2005, respectively.

### Treatments

The experimental vineyard had seven treatments and six replicates in a randomized complete block design. However, in 2004, sensor performance was studied only in the following treatments: (1) rain fed (non-irrigated),



**Fig. 1** Seasonal variation of **a** daily reference evapotranspiration values ( $ET_o$ ) and **b** cumulative rainfall and irrigation applied

which had not been irrigated since its planting, and (2) irrigated, resulting in a seasonal water application of 82 mm.

In 2005, with the additional objective of exploring the possible effects of crop load on water relations and TDV, sensor performance was tested in four treatments, (1) two non-irrigated treatments, with different cluster levels, 9 and 16 per vine, and (2) other two irrigated treatments, with a seasonal water application of 127 mm, with 8 and 22 clusters per vine. Irrigation normally started in June depending on the SWC measurements and on the rainfall that had occurred during the dormant season. The crop coefficient ( $K_c$ ) employed was estimated according to results obtained in previous irrigation trials in the same vineyard (Intrigliolo and Castel 2006c) and in a close vineyard with cv. Bobal (Salón et al. 2005). Crop coefficient varied according to the phenological period and the expected pattern of leaf area development. Thus, from June to July,  $K_c$  was gradually increased from 0.075 to 0.30. From veraison to harvest  $K_c$  was gradually decreased from 0.30 to 0.20.

#### Water relations determinations

Soil water content was continuously monitored at 20, 40, and 70 cm depths with capacitance probes (EnviroScan, Sentek Pty., Kent Town, SA, Australia). Four access tubes per treatment were placed in the row line

~75 cm from a vine trunk and about 25 cm from a dripper. An in situ calibration against volumetric soil moisture was previously performed by collecting undisturbed soil samples from each depth down to 100 cm in tubes installed for that exclusive purpose. A soil water balance was performed separately, on irrigated and in non-irrigated vines, each year according to the EnviroScan readings. Total vine water consumption was estimated with the irrigation applied and rainfall, plus or minus the average variation in SWC in the soil profile of the four access tubes per treatment. Runoff was considered negligible as the plots were nearly level and there was no visual evidence of it in the few storms that occurred during the study period.

Determinations of water potential were performed with a pressure chamber (Soil Moisture Corp., Santa Barbara, CA, USA) on five representative plants per treatment and two leaves per vine, at early morning (0700–0800 hours solar) and at midday (1130–1230 hours solar) on bag covered (stem water potential,  $\Psi_s$ ) at fortnightly intervals. Determinations at pre-dawn (before 0500 hours,  $\Psi_{pd}$ ) were also carried out on a monthly interval.

In both years TDV were measured with linear variable differential transformers (LVDT, Schlumberger Mod. DF-2.5) on six vines per treatment selected for uniformity and located in one of the blocks. On each plant a sensor was fixed to the main trunk at about 45 cm from the soil surface by a metal frame of Invar

(a metal alloy with minimal thermal expansion). Trunk sensors were installed on the 2-year-old main shoot that supported the bi-lateral cordon system. Average trunk diameter at sensor installation height were 18.8 and 22.3 mm in 2004, and 29.5 and 28.4 mm in 2005, for irrigated and non-irrigated vines respectively.

Data were automatically recorded every 30 s using a data logger (Campbell Scientific, Logan, UT, USA, model CR10X connected to an AM25T multiplexer) programmed to report mean values every 30 min. Other details on sensor characteristics, calibration and data recording were as in Intrigliolo and Castel (2004).

From TDV three different variables were calculated. Maximum daily trunk diameter (MXTD), TGR as the difference between the MXTD of two or more consecutive days, and 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.

#### Sensitivity of the different soil and water status indicators

Sensitivity, in physics, is defined as the signal to noise ratio. Following Naor and Cohen (2003) the signal is calculated as the average relative difference between the non-irrigated vines (stressed) and the irrigated ones (control). The noise is taken as the average coefficient of variation. The sensitivity analysis of the various soil and plant water status indicators was evaluated on data pooled over years separating data according to two phenological periods (before and after veraison). However, this analytical approach was considered to be unsuitable for TGR during the period after veraison. This was because during this period TGR values were close to zero; what resulted in some extremely high ratios despite the very small absolute differences existing in TGR.

## Results

### Soil and vine water status

In 2005, crop load was included in our experiments, in addition to irrigation, as a factor likely affecting the vine water relations. However, the effect of crop load on the water relation parameters evaluated (not-shown) was not significant ( $P < 0.05$ ) in most of the days when they were determined. Therefore, in year 2005, we have combined the data of the two crop load levels for the following sections.

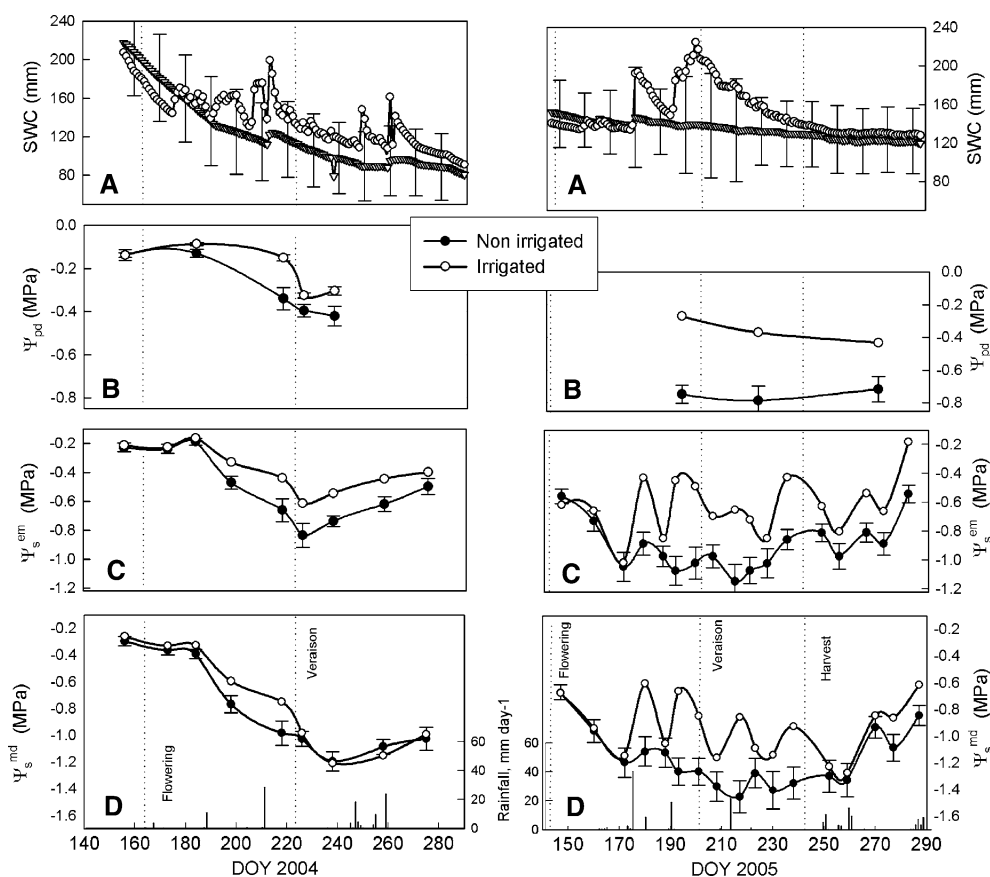
In the non-irrigated vines at the beginning of each season, water content in the 0–90 cm soil profile was of 217 and 140 mm in 2004 and 2005, respectively (Fig. 2a). In 2004, as the season progressed, vines extracted most of the available water in the soil profile, and total vine water consumption during the growing season amounted to  $371 \pm 149$  mm, equivalent to 45% of  $ET_o$ . In year 2005, due to lack of winter rainfall, the soil profile was much drier at the beginning of the season and consequently in the non-irrigated vines total vine water consumption during the growing season was  $225 \pm 79$  mm, equivalent to 19% of  $ET_o$ . As a consequence, water stress experienced by rain-fed vines was much higher in 2005 than in 2004, with the lowest  $\Psi_{pd}$  values reached of  $-0.43$  and  $-0.80$  MPa in 2004 and in 2005, respectively (Fig. 2b). As expected, non-irrigated vines also had lower values of  $\Psi_s^{em}$  and  $\Psi_s^{md}$  than irrigated vines (Fig. 2c, d). In the irrigated vines the calculated water consumption was of  $447 \pm 214$  and  $379 \pm 117$  mm, equivalent to 54 and 32% of  $ET_o$  in 2004 and 2005, respectively.

### Seasonal variation of trunk diameter variation derived indexes

There were large differences in trunk growth between years in both irrigated and non-irrigated vines (Fig. 3a). Total seasonal growth was about 6–7 mm in 2004 versus 1.5–2 mm in 2005. Nonetheless, the growth patterns were similar for both years. In the non-irrigated vines TGR appears to stop 20 before veraison and during the period around veraison it even reached negative values (Fig. 3b). In the irrigated vines this trend was similar but less pronounced. After veraison, independently of vine water status, TGR was more stable to values around 0 and  $10 \mu\text{m day}^{-1}$ . In year 2005, when sensors were installed earlier in the season, trunk growth was also negligible until about 10 days before flowering.

Before veraison, irrigated and rain-fed vines maintained similar TGRs until DOY 185 and DOY 145 in 2004 and 2005, respectively. Later, with the onset of vine water stress (Fig. 2) in the rain-fed plants TGR started to decrease (Fig. 3b). The differences in trunk growth between irrigated and non-irrigated vines were statistically ( $P < 0.05$ ) significant from DOY 195 to 215 in 2004, and from DOY 145 to 195 in 2005.

In both irrigated and rain-fed vines, MDS values at the beginning of the season were very low, around 0–50  $\mu\text{m}$ , and showed a clear increasing tendency until veraison (Fig. 4). After veraison, there is a drop in the MDS values, which remained nearly constant thereafter around 100 and 150  $\mu\text{m}$ . During the periods from



**Fig. 2** Evolution of the different water status indicators in the irrigated and non-irrigated plants. **a** Soil water content (SWC) in the soil profile from 10 to 90 cm depth, and rainfall; **b** pre-dawn leaf water potential ( $\Psi_{pd}$ ), **c** Stem water potential measured at early morning (0700–0800 hours solar)  $\Psi_s^{em}$ , **d** Stem water potential measured at midday,  $\Psi_s^{md}$ , and rainfall. Values are treatment

means of four access tubes for SWC, and 8 and 16 leaves for water potential determinations. DOY, day of the year. Bars indicate 5% minimum significant differences between treatments. Vertical dashed lines indicate the inception of flowering, veraison and harvest

DOY 212 to 226 in 2004, and from DOY 163 to 190 in 2005 non-irrigated vines had MDS values lower, and in most cases statistically significant ( $P < 0.05$ ), than the irrigated ones (Fig. 4).

Similarly to the data previously reported for the water relation variables, crop load did not significantly ( $P < 0.05$ ) affect MDS or TGR, in both irrigated and non-irrigated vines (non-shown).

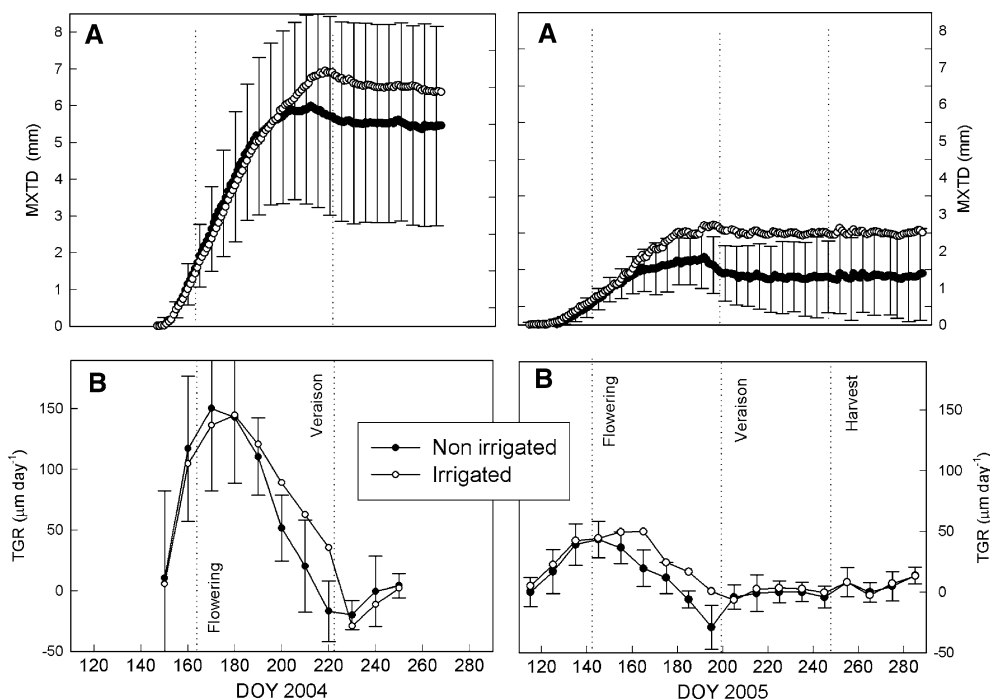
#### Comparison of the sensitivity of the soil and water status indicators

A similar trend of the signal to noise ratio of the different soil and plant water stress indicator was obtained in both years. Therefore, results reported in Table 1 are an average of both years. In both phenological periods, before and after veraison, pre-dawn and stem water potential determinations had the highest signal to noise ratio among all indicators mostly due to their low variability. Before veraison,

TGR had a high signal, but it had the highest variability and as a result lower sensitivity than any of the water potential determinations. Comparing the two indices, MDS was less variable than TGR, but overall its sensitivity was lower because its signal value was much lower.

#### Relationships between TDV-derived indexes and water potential determinations

Combined data from 2 years, both MDS and TGR were significantly ( $P < 0.001$ ) related with  $\Psi_s^{em}$  and  $\Psi_s^{md}$  but only during the pre-veraison periods (Figs. 5, 6). For MDS a curvilinear, quadratic equation better described the relationship with  $\Psi_s^{em}$  or  $\Psi_s^{md}$ . Deviations from linearity were evident from  $\Psi_s^{em}$  values of  $-0.75$  MPa and from  $\Psi_s^{md}$  values of  $-1.0$  MPa (Fig. 5). TGR during the pre-veraison period was, however, linearly related with both stem water potential determinations (Fig. 6). The corresponding values for zero



**Fig. 3** Seasonal variation in the irrigated and non-irrigated vines of: **a** maximum trunk diameter (*MXTD*), **b** average of 10 days trunk growth rate (*TGR*) plotted against the midpoint of the period. Values are treatment mean  $\pm$  standard error of 6 and 12

sensors in 2004 and 2005, respectively. Vertical dashed indicate the inception of flowering, veraison and harvest. DOY, day of the year. Bars indicate 5% minimum significant differences between treatments

TGRs were  $-0.88$  and  $-1.08$  MPa for  $\Psi_s^{\text{em}}$  and  $\Psi_s^{\text{md}}$  respectively.

During the periods from veraison to vintage and also from vintage to the end of the growing season there was no relation between MDS or TGR and plant water status determinations (Figs. 5, 6).

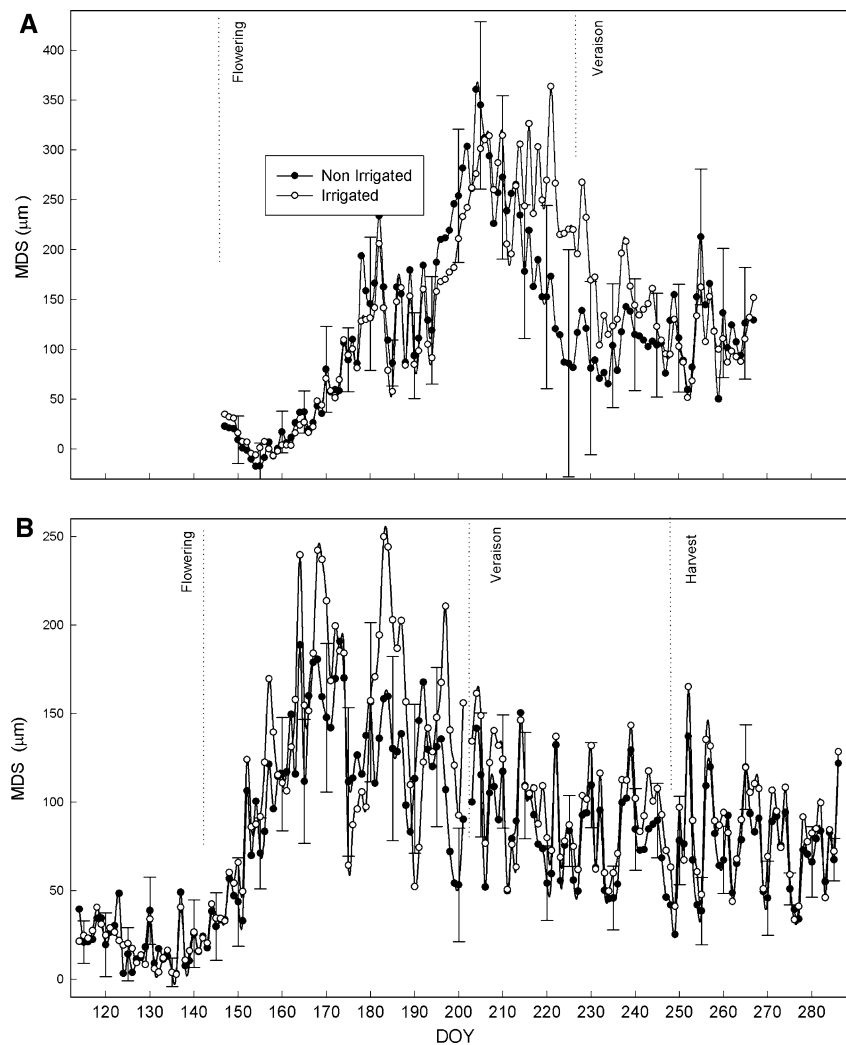
## Discussion

Irrigation increased vine water status and vine evapotranspiration. Considering the leaf area developed by the irrigated vines, 10.4 and 3.7  $\text{m}^2$  in 2004 and 2005, respectively, the estimated  $K_c$  values obtained from the soil water balance budget were 25–39% higher than those predicted for fully irrigated Thompson vines in a lysimeter (Williams and Ayars 2005). Despite the water use data obtained in different conditions not being easily comparable, we might infer that our results appears to overestimate water use probably due to the high spatial variability of the SWC measurements. It seems, in fact, that the absolute values of SWC measurements are not in complete agreement with the pre-dawn water potential measurements. For instance, while in non-irrigated vines at the beginning of year 2005 SWC was higher than at the end of year 2004,  $\Psi_{\text{pd}}$  was lower in early 2005 than at the end of

2004 (Fig. 2). The trend in SWC better reflected the rainfall distribution and irrigation applied. This suggests that capacitance probes are more useful to describe tendencies in the SWC variation, than to give an absolute indication of the water content in the profile.

The rain-fed vines, according to the  $\Psi_{\text{pd}}$  measured, experienced a moderate water stress in 2004, but more severe in 2005. This different development of vine water stress according to years was mainly due to the lack of winter rainfall and consequent lower SWC at the beginning of the 2005 season than in the 2004. In our conditions all  $\Psi$  determinations had low variability, and therefore allowed clear differentiation between treatments along the whole season (Fig. 2, Table 1). Similarly to other reports in fruit tree crops (Naor and Cohen 2003; Intrigliolo and Castel 2004) the sensitivity of MDS and TGR was lower than that of the  $\Psi$  determinations mainly because of the much higher variability for the TDV variables and for MDS also due to lower signal values. In addition, the ability of both MDS and TGR to detect plant water stress is largely dependent on the phenological period (Figs. 3, 4). In contrast Goldhamer and Fereres (2001) in mature almond trees, found that MDS was more sensitive than midday  $\Psi_s$ . They obtained higher signal values for MDS than in this work while variability was similar.

**Fig. 4** Evolution of maximum diurnal trunk shrinkage (*MDS*) in irrigated and non-irrigated vines: **a** in 2004, and **b** in 2005. Values are treatment mean  $\pm$  standard error of 6 and 12 sensors in 2004 and 2005, respectively. Vertical dashed indicate the inception of flowering, veraison and harvest. DOY, day of the year. Bars indicate 5% minimum significant differences between treatments. For clarity bars are only shown each 5 days



**Table 1** Comparison of the sensitivity (Signal to Noise ratio), of the different soil and water status indicators: soil water content in the 10–90 cm profile (*SWC*), pre-dawn leaf water potential ( $\Psi_{pd}$ ), stem water potential measured at early morning (0700–

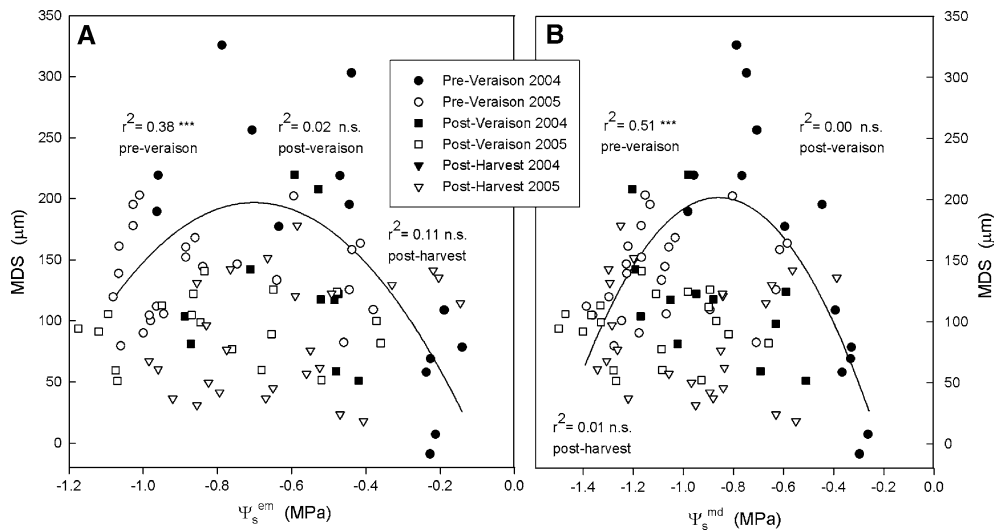
0800 hours solar) ( $\Psi_s^{em}$ ), stem water potential measured at midday ( $\Psi_s^{md}$ ), maximum daily trunk shrinkage (*MDS*), and trunk growth rate (*TGR*)

	SWC	$\Psi_{pd}$	$\Psi_s^{em}$	$\Psi_s^{md}$	MDS	TGR
Before veraison						
Signal (%)	13	127	34	12	9	48
Noise (cv.) (%)	33	14	11	9	26	35
Signal/noise	0.39	9.07	3.09	1.33	0.35	1.37
After veraison						
Signal (%)	17	63	52	29	14	–
Noise (cv.) (%)	40	9	9	9	32	37
Signal/noise	0.42	7.0	5.8	3.2	0.44	–

For all variables signal is calculated as the relative difference between the non-irrigated and irrigated vines and values are reported as percentage of irrigated vines. Signal calculation was not suitable for TGR after veraison (See Materials and Methods)

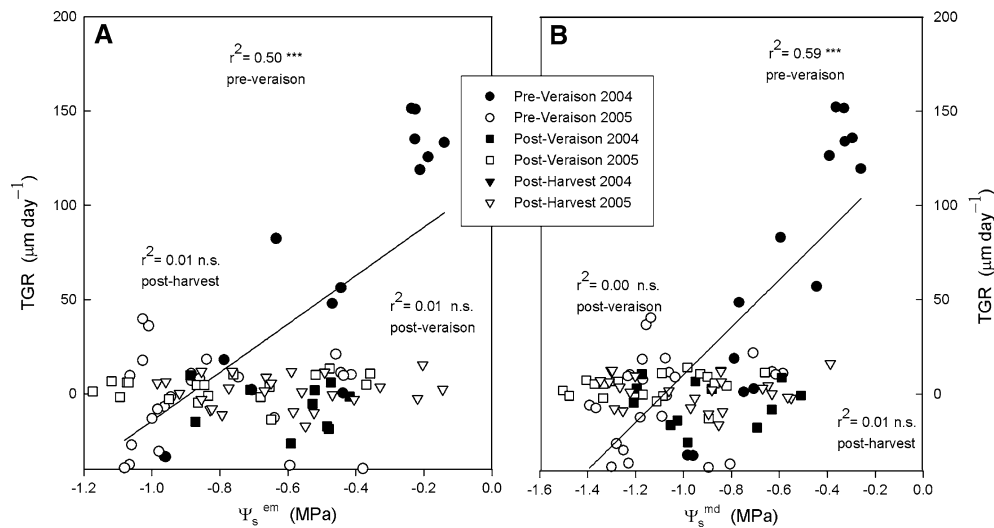
Only during the period from flowering to veraison, when there was a pronounced trunk growth (Fig. 4), vine water stress affected TGR. In fact, during this period trunk growth decreased by  $130 \mu\text{m day}^{-1}$  per each MPa of decrease of  $\Psi_s^{md}$  (Fig. 6). This result confirms that prior to veraison trunk growth in grapevines

is a sensitive parameter to water deficit as previously reported by van Zyl (1984) in Colombar and Sellés et al. (2004) in Crimson seedless. Our results support the general evidence that growth is a process highly sensitive to water restrictions (Hsiao 1973). Reduced plant water status probably decreased the carbohydrate



**Fig. 5** Relationship between maximum daily trunk shrinkage (*MDS*) and: **a** Stem water potential determined early in the morning (0700–0800 hours solar),  $\Psi_s^{em}$  and **b** Stem water potential measured at midday,  $\Psi_s^{md}$ . Data are separated into three phenological periods, before veraison, after veraison and after harvest. Values

are averages of 6 or 12 sensors and eight leaves, respectively. Regression lines, pooling data for seasons and irrigation treatments, are plotted only when there were significant relationships between variables. \*\*\*Significant at  $P < 0.001$ , non-significant (*NS*)



**Fig. 6** Relationship between trunk growth rates (*TGR*) and: **a** Stem water potential determined early in the morning (0700–0800 hours solar),  $\Psi_s^{em}$  and **b** Stem water potential measured at midday,  $\Psi_s^{md}$ . Data are separated into three phenological periods, before veraison, after veraison and after vintage. *TGR* values are

weekly averages of the weeks when  $\Psi_s$  was measured. Values, are average of 6 or 12 sensor and eight leaves, respectively. Regression lines, pooling data for seasons and irrigation treatments, are plotted only when there were significant relationships between variables. \*\*\*Significant at  $P < 0.001$ , non-significant (*NS*)

availability to sustain high *TGR*s and more likely affected cell turgor, which is necessary to maintain cell enlargement.

Even so, in both years, trunk growth showed a seasonal pattern that was in part independent on plant water status. From bloom to 15 days post-bloom *TGR* increased; most likely as a consequence of increasing temperature during this part of the season. After that, *TGR* started to decrease; likely because of increasing

crop sink strength. There is evidence that at the period of fruit set, the berries become an important sink (Hale and Weaver 1962) that might have lead to a reduction in *TGR*. After veraison, trunk growth ceased independently of plant water status. Negligible *TGR*s after veraison were also observed by Myburg (1996) and Sellés et al. (2004). It is well known that after veraison berries are the dominant sink (Williams 1997), and have priority for assimilates in the carbon partitioning among the



different vine organs. During fruit ripening, berries demand high quantity of photo assimilates and they successfully compete with vegetative (Williams 1997) and root (Comas et al. 2005) growth, which are consequently reduced. After harvest there was no recovery in trunk growth, in contrast to mid-season maturing stone fruit trees, where a sudden increase in trunk growth after harvest occurred (Marsal et al. 2002; Intrigliolo and Castel 2004).

Overall our results shown in Fig. 3 indicate that trunk growth largely depends on other factors besides plant water status, a feature that complicates its use as a water stress indicator. The fact that trunk growth behavior changes with the onset of specific berry growth stages suggests that the relationships between vegetative and reproductive growth at veraison are independent of water relations. The phenological changes in the sink-source relations are then a particularly important factor to consider when attempting to use TGR as a water stress indicator. Recently, some reports (Hardie and Martin 2000; Pellegrino et al. 2005) have suggested monitoring shoot growth of de-fruited vines for irrigation scheduling, mainly to avoid the interaction between fruit and vegetative growth. In this sense TGR might behave similarly as shoot growth of a de-fruited vine.

The response of MDS to soil water deficit was less distinct than that of TGR. Differences between irrigated and non-irrigated vines were only clear during a short period of time before veraison, when MDS values of the rain-fed vines became lower than in the irrigated vines (Fig. 2). This was due to the fact that before veraison, as plant water stress progressed, MDS began decreasing (Fig. 3).

Phloem tissues act as capacitors in the whole plant conductive system (Tyree and Ewers 1991), accumulating and storing water during the period of low evaporative demand (e.g., night) and releasing it to the plant flow stream during periods of high evaporative demand (Sevanto et al. 2002). However, if plant water stress surpasses a threshold value, there might be a depletion of the water reservoir of the phloem tissues and then an end of water recruitment (Zweifel et al. 2000). In this case, as reported in Fig. 5, MDS might even decrease with increasing vine water stress. This behavior has been observed in some cases (Cohen et al. 2001; Ortuño et al. 2006) but not in many others (Marsal et al. 2002; Fereres and Goldhamer 2003; Intrigliolo and Castel 2006b). This difference mainly depends on the level of plant water stress reached and also on the tissue ability to retain water against a water potential gradient. In plant tissues with low resistance to water flow and high hydraulic capacitance, as for grapevines

(Zimmerman and Milburn 1982), water can be extracted more easily from the phloem tissues leading to a quicker end of water storage.

Similarly to the features observed for TGR, there was not a unique relation between plant water status and MDS valid for the whole season (Fig. 5), and MDS was not significantly related with  $\Psi_s$  after veraison. Similar to our results in fruited Syrah vines grown in California, MDS was also found less sensitive to water stress after veraison (D.A. Goldhamer, U.C. Davis, personal communication). In other fruit tree species the relationship between MDS and plant water status changed after harvest (Marsal et al. 2002; Intrigliolo and Castel 2006b).

Around veraison, the grapevine the woody tissues start to acclimate for cold hardiness, which includes intracellular cell desiccation and tissue lignification (Goffinet 1997). Both features, together with a decrease in tissue elasticity toward the end of season may lead to the observed drop in MDS after veraison. So, it is generally accepted that tissue elasticity decreases with age, i.e., older tissues having higher resistance to shrinkage (Tyree and Jarvis 1982). It is also well known that before and after veraison the sugar concentration of woody tissues increases (Winkler 1970; Weyand and Schultz 2006). This should lead to a lower water potential gradient between the phloem and xylem and in turn to lower stem contraction for a given stem water potential. It has been shown that the magnitude of stem shrinkage for a given xylem water potential is also affected by differences in osmotic pressure between the bark and xylem (Cochard et al. 2001).

From the relationship presented in Figs. 5 and 6, it might be inferred that a severe water deficit is reached when MDS starts to decrease with declining  $\Psi_s$ , and when null TGRs are reached. The water potential values at which these two events happened were similar ( $-0.75$  and  $-0.88$  MPa for  $\Psi_s^{em}$ , and  $-1.0$  and  $-1.08$  MPa for  $\Psi_s^{md}$ ). According to the relation between  $\Psi_s^{md}$  and midday leaf water potential previously obtained in this same vineyard (Intrigliolo et al. 2005), the above  $\Psi_s^{md}$  values correspond to midday leaf water potential values of  $-1.20$  and  $-1.27$  MPa. These values are very close to the threshold value of  $-1.2$  MPa successfully tested by Girona et al. (2006) for scheduling deficit irrigation in Pinot noir, increasing grape quality with almost no reduction in yield.

Overall we can conclude that in our experimental conditions (normally fruited vines and moderate irrigation rates), particularly after veraison when the control of vine water status might be specially important for fruit quality (Williams and Matthews 1990) TDV

appears not to be a suitable tool for continuously monitoring grapevines water status. This is mainly because their high variability and, particularly for TGR, a strong dependence on years.

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