Identification of the water stress level in olive trees during pit hardening using the trunk growth rate indicator.

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ABSTRACT

Water scarcity is generating an increasing interest in deficit irrigation scheduling. The trunk diameter fluctuations are daily cycles that have been suggested as tools for irrigation scheduling. The trunk growth rate (TGR) was suggested as the best indicator for olive trees during pit hardening. The aim of this work is to clarify how the TGR could be used to identify water stress levels. The experiment was performed during the 2017 season, in a commercial, super-high-density orchard in Carmona (Seville, Spain). Four different irrigation treatments were performed according to midday stem water potential values and TGR. The data obtained were very variable and both indicators presented a wide range of water status throughout the season. The maximum trunk diameter data clearly showed the pattern of the trees water status but the comparison between treatments and the identification of the water stress level was not possible. The average TGR was linked to the midday stem water potential, but with a minimum amount of data. Irrigation scheduling based on the average TGR was difficult because of the great increases in some daily TGR values. For clarity, the pool of data was grouped by midday stem water potential. These water stress levels were characterized using the weekly frequency of TGR values. The increase of water stress reduced the frequency of values between -0.1 and 0.3mm day^{-1} from 60% to less than 25%. Moderate water stress levels increased the percentage of values lower than -0.3mm day^{-1} from 7% to 37%. The most severe water stress conditions increased the TGR values between -0.3 and -0.1mm day^{-1} from 16% up to 22%.

Keywords: Regulated deficit irrigation, trunk diameter fluctuation, water relations.

INTRODUCTION

Deficit irrigation has been traditionally scheduled using a percentage of the crop evapotranspiration (Behobudian and Mills, 1997). For most fruit trees, this approach allowed knowing the yield effect of water stress based on the moment when this restriction is applied (Behobudian and Mills, 1997). However, the trees response to irrigation restrictions depends on the phenological stage (when), water stress level (how), and duration (how long) of the water stress (Hsiao, 1990). When these three factors are considered, regulated deficit irrigation (RDI) is actually performed and discrepancies between works can be explained (i.e. peaches, Girona, 2002). In the last years, several irrigation works have focused on the different water stress indicators reported and even suggested specific irrigation scheduling in fruit trees considering these tools (Steduto et al 2012, García-Tejero and Durán-Zuazo, 2018). But the environmental effect on most of these indicators limits their suitability for application in commercial orchards.

Irrigation restrictions during pit hardening in olive trees have no yield effect under moderate water stress conditions (Goldhamer, 1999). The fruit development is affected by a midday stem water potential (SWP) lower than -2MPa during this period, although the fruit size is recovered after adequate rehydration (Girón et al 2015). Severe water stress levels, with midday water potential values lower than -4MPa, had a limiting yield effect (Moriana et al 2003; Iniesta et al 2009; Fernández et al 2013, among others). Therefore, there are SWP data suggesting suitable water stress levels for this fruit tree. However, the SWP is not an automatic continuous tool and its usefulness is limited in the smart agriculture. Trunk diameter fluctuations are daily cycles of swelling and shrinkage that provide several indicators, reported as early signals of water stress in olive trees (Moriana and Fereres, 2002). The trunk growth rate (TGR), the difference between two consecutive daily peaks (Goldhamer et al, 1999), has been reported as the only indicator really useful in olive irrigation scheduling (Moriana and Fereres, 2002, Moriana et al 2010, Fernández et al 2011). The typical seasonal pattern of maximum diameter in fully-irrigated mature olive trees is an increase before pit hardening and an almost constant value thereafter (Moriana et al 2003). This is reflected in positive TGR values before pit hardening and almost null thereafter. Daily TGR values, however, even in fully-irrigated conditions, are extremely changeable and difficult to understand. Several works reported the average TGR during pit hardening as an indicator of water stress (Moriana et al 2013; Girón et al 2015). But the average TGR does not benefit from the main advantage of this measure, the continuous monitoring. Girón et al (2016) suggested that part of this great variation in daily TGR is related to large variations of the daily vapour pressure deficit (VPD), and this relationship could be inversely proportional. A large reduction in VPD between days increases the TGR value. Recently, Corell et al (2017) reported that only daily TGR data lower than -0.1mm day^{-1} were related to water stress conditions. In that work, authors suggested that the maximum diameter picture indicates the water stress pattern but the average TGR for a period and the daily TGR would be the indicators to consider for irrigation scheduling (Corell et al 2017). Using these results, the aim of this work was to schedule regulated deficit irrigation based on average and daily TGR values. The daily TGR would show the moment when the water stress starts, while the average TGR would be the target value to establish different levels of water stress.

MATERIAL AND METHODS

Site description and experimental design

The experiment was conducted during 2017 at the commercial farm "Morillo" located in Carmona (37.49ºN, -5.67ºW, Seville, Spain). The olive (*Olea europaea* L cv Arbequina) orchard is a super-high density (4*1.5m) plantation, with 11 years of age at the beginning of the experiment. Trees were irrigated each other day with one line of drips (3.4l h^{-1})

separated 0.4m. The effective depth of the soil is very variable between plots and went from 0.4 to more than 1m. The soil texture is sand-loam, with a high percentage of carbonate (higher than 25%) and pH around 8.4. The organic matter at 0-40cm is around 1.8%, with an adequate level of P_2O_5 and K_2O.

The statistical design included randomized complete blocks with 4 repetitions and 4 irrigation treatments. The experimental plot included 3 rows of around 20 trees each, and the measurements were obtained from the central row. The amount of water applied was measured with a water meter in each plot. The irrigation treatments were defined based on the pit hardening period. The beginning of the pit hardening period was estimated according to Rapoport et al (2013) around day of the year (DOY) 160. To summarise, this date was defined as the moment when a change in the slope of the longitudinal fruit growth was measured. The end of pit hardening period was on DOY 245. This date was selected considering the possible harvest day (early November). The irrigation treatments were:

- **Control.** Trees were irrigated to obtain an optimum water status throughout the season with around 100% ETc (crop evapotranspiration). Irrigation problems reduced the amount of water applied in some plots from day of the year (DOY) 199 to 208, with a reduction in midday stem water potential.
- **Sustained deficit irrigation (SDI).** Irrigation was scheduled to distribute 150mm throughout the season. During pit hardening the amount of water supplied was almost constant and, after this period, it was reduced slightly.
- **Regulated deficit irrigation 1 (RDI-1).** Irrigation was scheduled using the midday stem water potential (SWP) and the trunk growth rate (TGR). Before pit hardening, water was applied only when SWP values lower than

-1.2MPa were measured. During pit hardening, this threshold of SWP was lowered to -2MPa. In this period, the TGR values were considered following the Corell et al (2017) and Girón et al (2015) recommendations. Thus, two indicators were considered: daily TGR and average TGR. The average TGR was calculated using all the data available for each tree during pit hardening. Water was applied when the daily TGR was lower than -0.1mm day^{-1} (according to Corell et al 2017) and the average TGR was lower than -0.031mm day^{-1} (double the value suggested by Girón et al 2015). From pit hardening, trees were irrigated when the TGR average was lower than -0.016mm day^{-1} (according to Girón et al 2015). The TGR average was calculated with all the data from pit hardening.

- **Regulated deficit irrigation 2 (RDI-2).** Irrigation scheduling as RDI-1 but with a higher level of water stress during pit hardening and limited seasonal amount of water (150 mm). During pit hardening, the SWP threshold was -3MPa and the average TGR was -0.062mm day^{-1}.

The amount of water applied was estimated taking into account the difference between the threshold considered and the value measured. The trees were not irrigated if the difference was lower than 10%. The maximum irrigation rate was 4mm day^{-1}, which was the maximum crop evapotranspiration estimated for the average season. This value was applied when differences were higher than 30%. When they were between 20-30%, the irrigation was 2mm day^{-1} and just 1mm day^{-1} for the interval 10-20%.

Meteorological conditions throughout the experiment

Weather data during the season were obtained from the "Villanueva de Rio y Minas" station in the Andalusian Weather Stations Network (Fig. 1). This station is located approximately 25km away from the experimental orchard. Data during 2017 were typical of Mediterranean zones, with null rainfall during the summer period and warm winters. Maximum potential evapotranspiration values (ETo), higher than 6mm day^{-1}, were measured from the end of Spring until mid-August. The average ETo during the pit hardening period (DOY 160-245) was 6.18mm day^{-1} with null rainfall. During phase I, extending from shoot sprouting until pit hardening (DOY 46-160), the average ETo was 4mm day^{-1} and the total rainfall was 136.5mm. However, during the recovery period, from pit hardening until the 1st of November, rainfall was very scarce, 25.6mm, while the ETo was still high with an average of 3.7mm day^{-1}. The total rainfall this year was very low, 277.9mm, considering the seasonal average (539mm, AEMET, 2018).

Measurements

The water relations of the trees were studied in combination with the soil moisture, leaf gas exchange and midday stem water potential measurements. The soil moisture was measured with FDR sensors (Echo20 HS10, Decagon Device, USA). Measurements were made in four plots per treatment. The FDR probes were placed in the irrigation line, about 30cm from an emitter (Fernández et al., 1991). Data were obtained at 0.2m and 0.4m depth. The leaf gas exchange was measured with the midday leaf net photosynthesis using an infrared gas analyser (CI-340, CID BioScience, USA) in one fully expanded sunny leaf per tree. The water potential was measured at midday in one leaf per tree, using the pressure chamber technique (Scholander et al., 1965). The leaves near the main trunk were covered with aluminium bags at least one hour before measurements were taken and a pressure pump was used (PMS model 1000).

Trunk diameter fluctuations are a daily cycle of shrinkage and swelling in which different indicators can be estimated. The most common ones are the maximum daily shrinkage (MDS) and the trunk growth rate (TGR) (Ortuño et al., 2010). The MDS values are not an early indicator of water stress (Moriana and Fereres, 2002) and only the TGR values were considered. The TGR is the difference between two consecutive daily maximums (Goldhamer et al. 1999), the TGR on day “n” is the difference between the maximum daily diameter for day “n+1” and for day “n”.

The trunk diameter fluctuations were measured in one tree per repetition using a band dendrometer (5μm accuracy, D6, UMS, Germany) attached to the main trunk. The band dendrometer works like a beam when bending. The trunks were measured using the nodes of a wireless sensor with a network topology for easy installation and maintenance. The band rested on a part of the trunk surface. The ends of the band were joined with Invar steel, an alloy of Ni and Fe with a thermal expansion coefficient close to zero (Katerji et al., 1994), the band circled the trunk. A Teflon net below the steel prevented friction with the bark surface. Each band dendrometer was plugged into a node (Widhoc smart solution SL, Spain) near the sensor. These nodes were integrated by two different parts. One being the measurement interface, and the other the processing, recording and communication system. The nodes generated a stabilized power supply of 10Vdc to the band dendrometer. The data from each sensor node were sent wirelessly to cloud. Ten measurements of each band dendrometer were taken every hour.

Data analyses were performed with ANOVA and the mean separation was made using a Tukey’s test with the Statistix (SX) program (8.0). Significant differences were considered when p-level<0.05 in both tests. Calculations of the p-level were performed considering the F-test of variance equality. When conditions of variance equality could not be obtained, a decrease in the degree of freedom and, therefore, a more restrictive p-value was calculated. The number of samples measured is specified in the text and figures.

RESULTS AND DISCUSSION

The pattern of water applied and the crop evapotranspiration (ETc) are shown in Fig. 2. The amount of water applied in the Control treatment was clearly different from the rest of treatments in the experiment. In Control trees, slightly lower values than the calculated ETc were applied from DOY 160 to 220. However, such reductions were lower than 20% when maximum differences occurred (between DOY 199 to 208). From DOY 220, the Control irrigation was higher than 100% ETc and reached a maximum value of approximately 500mm. The water applied in deficit treatments was very similar and the main differences occurred from the mid-pit hardening period. From DOY 200, until the end of this period, the water applied to RDI 2 was slightly lower than RDI 1 and SDI. After pit hardening, both RDI 1 and 2 received a higher amount of water, at similar rates; while SDI received a clearly lower amount in comparison. Overall, the water applied in RDI 2 and SDI was almost the same, around 150mm, while RDI 1 received a slightly higher amount with 185mm.

The soil moisture at 0.2 (Fig. 3a) and 0.4m (Fig. 3b) was very changeable throughout the experiment and it presented very high variability within treatments. No significant differences were found throughout the experiment at any of the depths. The trends of the treatments were very erratic and there were no clear patterns in any of the depths considered. The data varied from 0.25 to 0.4m^3 m^{-3}. The Control data were the most constant with typical maximum values from DOY 230. In this treatment, there was a clear reduction of soil humidity in the period DOY 200-230. For the rest of treatments, only RDI 1 at 0.4m depth presented data generally lower than Control until the end of the experiment from DOY 160.

The pattern of midday stem water potential (SWP) is showed in Figure 4. Before pit hardening (DOY 160), the SWP values were very similar and higher than -1.5MPa. In the period of pit hardening (from DOY 160 until 243), the maximum level of water stress was reached in all treatments. There were several problems with the irrigation of Control trees and during the period from DOY 199-222, the SWP values decreased drastically with minimum values lower than -3MPa. After that, the trees completely recovered with values higher than -1.5MPa. The SWP patterns for RDI 1 and RDI 2 showed a continuous decrease until the end of this period. In these treatments, average minimum values, even below -4MPa, were measured at the end of the period with significant differences with Control. The pattern of SDI was slightly different, as there was a continuous decrease until the end of August but with moderate level of water stress around -3MPa. The SWP differences between Control and the rest were reduced from DOY 243. However, there was no effective recovery of any of the deficit treatments until DOY 293 with the rainfall (approximately 24mm in two days).

The midday net photosynthesis (Pn) was also affected by the irrigation scheduling (Fig. 5). Before pit hardening, the Pn was very similar between treatments and approximately 10μmol m^{-2} s^{-1}. In the period of pit hardening, the irrigation problems of the Control trees reduced drastically the Pn values on days 166, 190, 207. On the rest of dates, Control tended to higher values than the rest of treatments and significant differences were found at the end of this period (DOY 237 and 242). The Pn patterns in RDI 1 and RDI 2 were similar, with minimum Pn values below 5μmol m^{-2} s^{-1}, from DOY 190. This severe gas exchange restriction was longer in RDI 2 (until DOY 257) than in RDI 1 (until DOY 243), though the recovery was delayed until the end of the experiment. Finally, the SDI pattern was slightly different from previous treatments. There were oscillations of the Pn values in SDI, with a clear decrease at the end of pit hardening. In this treatment, the period of minimum Pn values was shorter than in RDI 1 and RDI 2, from DOY 242 to 265.

The daily course of trunk diameter was only available from DOY 167 and just partially. All the sensors were working from DOY 195. Figure 6 shows the Maximum Diameter data. The Control trees presented a cycle of increase and decrease of the Maximum diameter from DOY 185 to 222. From this date on, maximum diameters were almost constant with a slight decrease on DOY 240 and a continuous increase from this last date. RDI 1 presented a continuous decrease until DOY 240. From this date, the Maximum Diameter showed a great cycle of increase and decrease in which the daily trunk growth rate (TGR) was significantly lower than in Control. The seasonal pattern of RDI 2 was very similar to RDI 1, with slightly lower values before DOY 240 but with similar great cycles from this date on. Finally, the SDI treatment presented a continuous decrease until DOY 212 and, after this date, a great cycle of increase and decrease, similar to the ones obtained in RDI 1 and RDI 2. Most of the significant differences in TGR (the slope of the maximum Fig 6) occurred from DOY 240 between Control and the rest of treatments. However, such differences did not always follow the same pattern because of the cycles of increase and decrease. Sometimes the TGR was even higher than Control, when TGR values were significantly lower on the previous or the next day.

The average TGR for two different periods and for the whole season is presented in Table 1. There were no significant differences between treatments because of the high variability within them. However, there were clear trends. The Control data presented an almost constant TGR during pit hardening and oil accumulation. The average TGR in RDI 1 and 2 during pit hardening was higher than the target (-0.032 and -0.064mmday^{-1}), such variations were likely related to the great increases in deficit treatments when they were irrigated. The lowest average TGR was obtained in RDI 2, while RDI 1 and SDI showed similar values. The average TGR increased in the deficit treatments during the period of oil accumulation, especially in SDI trees. Such recovery allowed obtaining an average TGR for the whole season close to or higher than -0.016mm day^{-1}, the initial water stress target level. The average TGR data for each plot in the two periods considered presented a significantly good fit with the midday stem water potential at the end of each period (Fig 7a). Three plots were not included in this regression due to the volume of data; two of them are not represented in Fig 7 (there were no data), and the third is represented by the circled white square (approximately 50% of TGR data were lost). There was also a significant relationship between the average TGR and the average and minimum midday stem water potential at the end of both periods, but the fit was poorer than the ones in Fig 7a (R^2= 0.42 and 0.20). The average seasonal midday stem water potential also presented a good fit with the average seasonal TGR for each plot (Fig. 7b). There was a significant but poorer relationship with the last data of water potential (R^2=0.59 vs 0.64 in Fig. 7b). Finally, a trend could be found in the relationship between the weekly average TGR and the midday stem water potential (Fig. 7c). In this case, although the relationship was significant, the fit was very poor when the number of data was considered (n=189; R^2=0.42). Corell et al (2017) suggested that the average TGR was related to the water stress level. However, the data in Table 1clearly shows that it is difficult to work with the seasonal average TGR, mainly because of the resulting very high increase in some treatments when they are irrigated. The average TGR then had two main limitations: the data lost and the great increase after irrigation on some dates. In addition, the average TGR is not very suitable as an irrigation scheduling tool in comparison to the water potential. Moreover, it is not clear if the relationships in Fig 7 were unique, and they would probably change in different orchards or seasons, despite this, the average TGR could be useful as a water stress indicator.

Fig. 6 and Table 1 clearly show that, in all the treatments, positive and negative values of TGR are possible, even though the water stress levels of the trees were very severe and different. These values are probably the main issue to manage the average TGR and to compare treatments. As an example, the daily TRG and midday stem water potential values for individual plots from DOY 222 to 236 is presented in Fig. 8. The most stressed plot, with SWP between -3 and -4MPa, shows daily TGR values varying between almost 1 and -1mm day^{-1}. This plot presented a pattern of daily TGR similar to the SWP at the bottom of Fig. 8. On the other hand, the less stressed plot, with SWP from -2MPa until about -1MPa, presented also positive and negative values, but the daily TGR oscillated in a narrower interval than the previous one, and the cycles of both plots did not coincide. Finally, the intermediate plot presented data similar to that from the less water stressed, but the pattern changed throughout the period. At the beginning, the daily TGR was similar to the second treatment, but progressively changed towards lower values and negative values became more frequent. Part of this variation of daily TGR could be related to the vapor pressure deficit (VPD). Girón et al (2016) suggested that, for olive trees, part of the daily TGR variations are related to increase and decrease of VPD between different days. The increment of VPD from one day to the next was partially related to a reduction in the daily TGR (Girón et al, 2015). Corell et al (2017) suggested that only daily TGR values below -0.1mm day^{-1} were associated with water stress conditions and the more stressed trees presented a higher frequency of values lower than -0.1mm day^{-1}. Additionally, Archer et al (1997) suggested a model to estimate the water potential from the daily curves of trunk dimeter fluctuations. In this sense, the daily TGR values would vary according to the pattern of water potential without a direct relationship with the water stress level. According to the model of Archer et al (1997), the same midday stem water potential could be associated to positive values, for instance the most stressed plot on DOY 230, and negative values, for instance the intermediate plot on DOY 236. Therefore, the daily TGR values would be a relative indicator with little or no relation to the midday stem water potential. However, Girón et al (2016) presented a good agreement between the average TGR during pit hardening and fruit drop or fruit size. In theory, the daily TGR values could be associated with the water stress level, but such levels of water stress would be better described by the frequency than by the absolute value. Corell et al (2017) reported that the water stress increased the frequency of daily TGR below -0.1mm day^{-1}.

Figs 6 and 8 clearly show that severe water stress conditions are associated to high positive daily TGR values when the trees were irrigated. Such response of great recovery with rain and/or irrigation is commonly described in the literature (i.e. in olives trees Moriana et al 2003, Moriana et al 2013, Girón et al 2015). In order to clarify this response, the complete pool of average weekly TGR data was classified according to the water potential on each date. Only data lower than -3MPa and higher than -2MPa were considered. Fig. 9 presents the relationship of the average weekly positive TGR between two measurements of midday stem water potential based on the water potential measured before irrigation. Only plots that were irrigated between two consecutive measurements of midday stem water potential were considered. Fig. 9 shows a great dispersion in the values of average TGR, but all of them were higher than 0.3mm day^{-1} when the SWP before irrigation was lower than -3MPa. Conversely, almost all the average TGR were lower than this value when the SWP was below -2MPa. Therefore, daily values of TGR higher than 0.3mm day^{-1} could be related to conditions of severe water stress level.

The influence of daily TGR frequency was also studied with all the data measured. Midday stem water potential data from all treatments were grouped in four different levels of water stress. Level 1 up to values of -1.4MPa (according to the threshold suggested by Moriana et al 2012), level 2 from -1.4MPa to -2.5MPa (according to the threshold suggested by Diaz et al, 2018), level 3 from -2.5 MPa to -4MPa (according to the threshold suggested by Diaz et al, 2018), and level 4 below -4MPa. In order to estimate the pattern of daily TGR, weekly frequencies for different value ranges were calculated. The values of daily TGR considered were below -0.3, between -0.3 and -0.2, between -0.2 and -0.1, between -0.1 and 0.3 and higher than 0.3mm day^{-1}. Fig. 10 shows the average weekly frequency of these daily TGR for each water stress level considered above. In all the water stress levels, there were daily TGR values positive and negative, but there were clear changes in frequency. The frequency of daily TGR values between -0.1 and 0.3mm day^{-1} decreased significantly with an increase of the water stress level from 60% at level 1 until 26-22% at levels 3 and 4, respectively. Conversely, daily TGR values lower than -0.1mm day^{-1} were always measured at all water stress levels but increased with the water stress. The lowest daily TGR values, below -0.3mm day^{-1}, were minimum at stress level 1 (7%) and maximum and significantly different at level 3 (36%) and 4 (38%). Differences between water stress level 3 and 4 were related to the frequency of values between -0.3 and -0.1mm day^{-1} which were higher, although not significantly, at level 4 than 3. Such increase meant that more than 60% of daily TGR values at level 4 were below -0.1mm day^{-1}, while at level 3 they were approximately 50%.

These results suggest that the pattern of TGR is complex and related to various factors. The evaporative demand, the level of water stress and the response to irrigation events are combined into the daily TGR measured under field conditions. In this way, the daily TGR vs water potential relationship is difficult and probably changeable during the season or for different orchards, but this lack of results does not invalidate the usefulness of this indicator as an irrigation scheduling tool. In mature olive trees, during the pit hardening phase, a great percentage of values between -0.1 and 0.3mm day^{-1} were related to conditions with no water stress. These variations and the less common values out of this range could be related to adjustments of the tree water relation to the evaporative demand (Girón et al 2016). The olive tree physiology is closely related to the evaporative demand. The daily evolution of leaf conductance is linked to the daily pattern of VPD (Angelopoulos et al., 1996). These variations on the trunk diameter could be related to general modifications of the tree water. Díaz-Espejo et al (2018) suggest that under no water stress conditions, olive trees regulate the water status in order to minimize the leaf dehydration using an isohydric response. In this way, the water in the trunk reservoir could be involved in part of this regulation. The trunk diameter variations are produced mainly by changes in the water content and growth of the bark (Brough et al., 1986) and they are considered a water reservoir in the tree (Simonneau et al., 1993). On the other hand, water stress conditions could be identified with negative values below -0.1mm day^{-1} of daily TGR as Corell et al (2017) reported. However, the greatest negative daily TGR were measured under moderate water stress level (level 2 and 3) instead of severe conditions. These high rates of dehydration in the tree are in agreement with the high capacity of dehydration reported in the literature for this species (among others, Angelopoulos et al., 1993, Moriana et al. 2003, Iniesta et al., 2009, Díaz-Espejo et al 2018). According to Díaz-Espejo et al (2018), at these moderate water stress level (from -1.4 to -4MPa) the hydraulic conductivity of the tree is almost unaffected, and the stomatal closure and osmotic adjustment are the more intensive physiological responses. This partial embolism resistance of olive trees has been partially related to extraxylematic components (Díaz-Espejo et al 2018) which could be associated to the TGR variation.

CONCLUSIONS

The trunk growth rate (TGR) provided information about the moment when the water stress occurs and the level of the water stress. The different parameters used did not always present clear or complete information. The maximum trunk diameter presented clear information about the pattern of the irrigation treatments and it help identify conditions of water stress, but not the level of water stress. The comparison between treatments was not possible only with the maximum diameter data. The average TGR was related to the midday stem water potential but this indicator alone is not a useful irrigation scheduling tool because a minimum number of data is needed (i.e. weekly in the present work). The average TGR evaluates a period of irrigation but it is difficult to use for daily irrigation scheduling as the water stress target level. Daily TGR values were very changeable and the same midday water potential measurement was associated to very different daily TGRs. However, all these changes can help explain the water status of the trees. Frequency and absolute values of daily TGR are tools for continuous irrigation scheduling.

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Figure captions

Fig. 1. Seasonal pattern of potential evapotranspiration (ETo) and rainfall during 2017 season. Vertical lines limit the period of pit hardening. Source: Villanueva Rio y Minas station. Andalusian Climatic Network.

Fig. 2. Seasonal pattern of rain, estimated crop evapotranspiration and water applied in each treatment. Each point is the average of 4 values. Vertical bars represent the standard error. Vertical lines limit the pit hardening period.

Fig.3. Seasonal pattern of soil moisture at 20 and 40cm depth. Each point is the average of 4 values. Vertical bars represent the standard error. Vertical lines limit the pit hardening period.

Fig. 4. Seasonal pattern of midday stem water potential. Each point is the average of 4 values. Vertical bars represent the standard error. Vertical lines limit the pit hardening period. Asterisks indicate significant differences ($p<0.05$, Tukey Test).

Fig. 5. Seasonal pattern of midday net photosynthesis rate. Each point is the average of 4 values. Vertical bars represent the standard error. Vertical lines limit the pit hardening period. Asterisks indicate significant differences ($p<0.05$, Tukey Test).

Fig. 6. Seasonal pattern of maximum diameter. Each point is the average of 4 values. Vertical lines indicate the end of the pit hardening period. Asterisks significant differences in trunk growth rate ($p<0.05$, Tukey Test).

Fig. 7. Relationship between (a) average trunk growth rate in two different periods vs midday stem water potential at the end of each period (Y=0.060+0.027X; R^2=0.61***; Error=0.024; n=29; circled data not included); (b) seasonal average trunk growth rate vs seasonal average midday stem water potential (Y=0.070+0.033X; R"=0.64***; Error=0.016; n=14; circled data not included) (c) weekly average trunk growth rate vs midday stem water potential at the end of that week. Each point is an individual plot value. Circle points indicate plots where more than 50% of data were lost.

Fig. 8. Pattern of daily trunk growth rate (TGR) and midday stem water potential (SWP) during two weeks in three individual plots.

Fig. 9. Relationship between midday stem water potential (SWP) before irrigation and weekly average of trunk growth rate (TGR) after irrigation. Solid triangles are data for

individual plots with SWP lower than -3MPa. Empty triangles are data for individual plots greater than -2MPa. The empty and solid circle is the average of all the values in each group. Horizontal and vertical bars are the standard error of TGR and SWP in each data group.

Fig. 10. Weekly frequency of daily TGR values at various levels of water stress. Water stress conditions have been described with midday stem water potential values (Ψ)greater than -1.4MPa, between -1.4 and -2.5MPa, between -2.5 and -4MPa and lower than -4MPa. Daily TGR were grouped in higher than 0.3mm day^{-1}, between -0.1 and 0.3mm day^{-1}, between -0.1 and -0.2mm day^{-1} and lower than -0.3mm day^{-1}. All data for individual plots were considered and grouped according to Ψ values. Different letters in each range of daily TGR indicate significant differences between the water stress level for the same range of daily TGR values ($p<0.05$, Tukey Test).

Table 1. Average trunk growth rate (TGR, mm day^{-1}) and standard error during the pit hardening period, oil accumulation and whole season. Each point is an average of 4 values. There were no significant differences between treatments. (Tukey Test $p<0.05$)

	Pit Hardening	**Oil accumulation**	**Whole season**
Control	0.024±0.011	0.033±0.010	0.027±0.011
RDI 1	-0.006±0.014	-0.003±0.031	-0.006±0.015
RDI 2	-0.032±0.011	0.009±0.011	-0.015±0.008
SDI	-0.007±0.054	0.051±0.055	0.002±0.017