Limitations and usefulness of Maximum Daily Shrinkage (MDS) and trunk growth rate (TGR) indicators in the irrigation scheduling of table olive trees.

I.F. Girón[a,b] M. Corell[c, b], A. Galindo[d], A. Torrecillas[d], F. Moreno[a,b], A. Moriana[c,b*]

[a] Instituto de Recursos Naturales y Agrobiología (CSIC), P.O. Box 1052, E-41080 Sevilla, Spain.

[b] Unidad Asociada al CSIC de Uso sostenible del suelo y el agua en la agricultura (US-IRNAS). Crta de Utrera Km 1, 41013, Sevilla, Spain.

[c] Departamento de Ciencias Agroforestales, ETSIA, Universidad de Sevilla, Crta de Utrera Km 1. 41013 Sevilla, Spain.

[d] Dpto. Riego. Centro de Edafología y Biología Aplicada del Segura (CSIC). P.O. Box 164. E-301000 Espinardo, Murcia, Spain

*Corresponding author: amorianal@us.es Phone: (+34)954486456; Fax: (+34)954486436

Abstract

Maximum daily trunk shrinkage (MDS) is the most popular indicator derived from trunk diameter fluctuations in most fruit trees and has been reported to be one of the earliest signs in the detection of water stress. However, in some species such as olive trees (*Olea europaea* L), MDS does not usually change in water stress conditions and trunk growth rate (TGR) has been suggested as better indicator. Most of this lack of sensitivity to drought conditions has been related to the relationship between the MDS and the water potential. This curvilinear relationship produces an uncertain zone were great variations of water potential do not imply any changes of MDS. The MDS signal, the ratio between measured MDS and estimated MDS with full irrigation, has been thought to be a better indicator than MDS, as it reduces the effect of the environment. New methodologies for estimation of the MDS signal in olive trees have been recently suggested. On the other hand, though literature results suggest an effect of environment in TGR values, there are not clear relationship between this indicator and meteorological data. The aims of this work are, on one hand, to study the improvements of the baseline approach in the MDS signal and on the other study the influence of several meteorological variables in TGR. Three years' data from an irrigation experiment were used in to carry out the MDS analysis and six years' data for full irrigated trees were used for TGR study. The comparison between MDS vs water potential and MDS signal vs water potential presented a great scattering in both relationships. However, in the interval of water potential between -1.4 and -2MPa, the MDS signal presented a clear increase, which was not identified in the relationship of MDS vs. water potential. It is likely that the seasonal estimation of the baseline would provide a better adjustment of the MDS signal in relation to the water potential and could be useful at the beginning of the water stress period. On the other hand, TGR was

affected significantly for the increment of the daily average vapour pressure deficit (VPD) of the previous day and this relationship was affected for the fruit load level.

Keywords: Olea europaea, trunk diameter fluctuations, water potential, water relations.

Introduction

Trunk diameter fluctuations (TDF) are a daily cycle of shrinking and swelling of the trunk that have been reported since the 60’s (Ortuño et al., 2010). The development of sensors and dataloggers during the 90’s allowed a re-discovery of the usefulness of these indicators in irrigation scheduling. Research works about drought response of TDF indicators in fruit trees and even automatic irrigation scheduling based on these indicators have been reported (i.e. “Pepista”, Huguet et al., 1992).

Several types of indicators can be obtained from the daily TDF curves. The most common and early sign of water stress in most fruit trees is the maximum daily shrinkage (MDS) (Ortuño et al. 2010). The increase of MDS compared to fully irrigated trees was reported, from the first works, as an indicator of water stress conditions (Klepper et al, 1971). However, the increase in MDS is also related to the evaporative demand (Herzog et al., 1995). Thus, evaporative demand is an interference of this indicator that reduces its usefulness in commercial orchards. In order to reduce this limitation, Goldhamer and Fereres (2001) suggested the MDS signal: the ratio between measured MDS and MDS with full irrigation. Fully irrigated conditions could be estimated from baseline equations, where MDS is related to a meteorological variable, such as reference evapotranspiration (ETo), vapour pressure deficit (VPD) or temperature (Ortuño et al, 2010; Fernández and Cuevas. 2010).

The usefulness of MDS, however, is not the same in all fruit species. In young olive trees, MDS was not affected by water stress, even when gas exchange was reduced (Moriana and Fereres, 2002). This lack of response has been reported in mature olive trees and in different cultivars and conditions (Moriana et al., 2003; Moriana et al., 2010; Fernández et al., 2011). Moriana et al (2010) suggested that the absence of response to water stress in MDS is related to the pattern of this indicator during a drought cycle. The relationship between MDS and water potential is curvilinear in all fruit trees, showing an initial increase of MDS with the reduction of the water potential until reaching a maximum value, and then MDS values decrease as the severity of water stress continues to increase (Ortuño et al, 2010). This relationship presented the highest MDS values in olive trees (maximum around 0.8-1mm) (Moriana et al., 2000) and the first linear phase, until the maximum MSD values, has been considered to be caused by variations in the conditions of the evaporative demand (Pérez-López et al., 2013). Since the MDS values during summer in fully irrigated olive trees were around the maximum, moderate water stress conditions would be in the uncertain zone were clear differences of water potential (between -1.4MPa and -2MPa) presented similar MDS values. In addition, Moriana et al (2013) reported greater values of MDS in fully irrigated conditions for trees which were deficit irrigated in the previous season than in trees with full irrigation. The MDS baseline is likely to reduce the influence of the environment on this indicator but it is not known if it would be a reliable indicator in moderate water stress conditions. Corell et al (2013) recently reported on a methodology for the estimated MDS baseline at the beginning of the season which could reduce some of the limitations presented above.

These limitations in the usefulness of MDS in olive trees have produced that other indicators such as trunk growth rate (TGR) have been considered for irrigation scheduling (Moriana et al., 2013). TGR is clearly affected for the fruit load and during pit hardening period in mature trees almost no growth is detected (Moriana et al., 2003). However, even in these conditions, TGR in full irrigated olive trees is very variable and extremely negative values are measured (Moriana et al., 2013). Such response suggests an environmental effect which has been poorly described in olive trees.

The aim of this work is analysed this two source of variations in MDS and TGR indicators. In one way, the present work compares the relationships MDS vs. water potential and MDS signal vs. water potential for three sets of seasonal data in order to study the pattern in moderate water stress conditions. On the other way, the relationship between TGR and meteorological data is analysed.

Materials and Methods

Experimental orchard description

Experiments were conducted at La Hampa, the experimental farm of the Instituto de Recursos Naturales y Agrobiología (IRNAS-CSIC). This orchard is located in Coria del Río, near Seville (Spain) (37º17''N, 6º3'W, 30 m altitude). The sandy loam soil (about 2m deep) of the experimental site was characterized by a volumetric water content of $0.33 m^3 m^{-3}$ at the saturation point, $0.21 m^3 m^{-3}$ at field capacity and $0.1 m^3 m^{-3}$ at the permanent wilting point, and a bulk density of 1.30 (0-10cm) and 1.50 (10-120cm) $g\ cm^{-3}$. The experiment was performed on 43-year-old table olive trees (*Olea europaea* L cv Manzanillo) from the 2008 to the 2014 seasons. Tree spacing followed a 7m x 5m square pattern. Pest control and fertilization practices were those commonly used by the growers and no weeds were allowed to develop within the orchard. Irrigation was carried out during the night by drip, using one lateral pipe per row of trees and five emitters per plant, delivering $8 L\ h^{-1}$ each. The irrigation requirements were determined according to the daily reference evapotranspiration (ET_o) and a crop factor based on the time of year and the percentage of ground area shaded by the tree canopy (Fernández et al., 1997).

Maximum daily shrinkage (MDS) study was performed only with data of the seasons from 2011 to 2013. Trunk growth rate (TGR) data were obtained from seasons

2008, 2010, 2012, 2013 and 2014 of this orchard and only in 2012 also in a contiguous orchard with the same age and cultivar but 7*7 m spaced. The study of both indicators was performed only in the period of pit hardening.

Trunk diameter fluctuation indicators

The maximum daily shrinkage (MDS) was calculated as the difference between the maximum daily diameter and the minimum daily diameter (Goldhamer et al., 1999). Trunk growth rate (TGR) in day “n” was calculated as the difference between the maximum daily diameter of day “n+1” minus that of day “n” (Cuevas et al., 2010). According to Goldhamer and Fereres’ approach (2001), the MDS signal was established as the ratio between the value of MDS with a deficit treatment and the estimated MDS with full irrigation. Estimations of the MDS with full irrigation values for each treatment were performed with the data obtained for the last 15 days before the beginning of pit hardening, according to the Corell et al (2013) methodology. In brief, this methodology suggests estimating the seasonal baseline using the relationship between MDS and the maximum temperature of the 15 days previous to pit hardening and assumes that the slope of the equation is the same as the one calculated by Moriana et al (2011). The baseline of each treatment was the linear equation that runs through the average point of the MDS/Maximum temperature data and has a slope of 36 (MDS in µm, Moriana et al 2011). The water potential average data during the period previous to pit hardening are presented in Table 1. No significant differences were measured in each season, though RDI treated trees tended to produce lower values than the Control ones. However, in all cases the midday stem water potential was greater than -1.2MPa, the threshold value suggested for this phenological period in fully irrigated trees (Moriana et al., 2012).

Treatment description

Full irrigated Control trees from 2008 to 2014 were used to obtain relationship between TGR and environmental variables. Control trees were irrigated with 100% of crop evapotranspiration (ETc) in order to obtain non-limiting soil water conditions during the entire season. MDS data were obtained from three different irrigation treatments performed from 2011 to 2013 seasons. These regulated deficit irrigation (RDI) treatments considered the phenological stage of the trees in the water stress conditions. The beginning of pit hardening, the most resistant to water stress phenological stage, was determined according to Rapoport et al. (2013) and the recovery phase started in the last week of August (three weeks before harvest). The RDI scheduling was performed according to the trunk diameter variation indicators (Maximum Daily Shrinkage, MDS, and Trunk Growth Rate, TGR). The threshold values used in the present work were selected from previous data (Moriana et al., 2013). The treatments were:

- Control. Trees were irrigated with 100% of crop evapotranspiration (ET_c) in order to obtain non-limiting soil water conditions during the entire season.
- Regulated deficit irrigation 2 (RDI 2). The objective of this treatment was to create a moderate water stress during the pit hardening and then a slow recovery. Irrigation was scheduled taking into account the maximum daily shrinkage (MDS) and the trunk growth rate (TGR) indicators. Before the period of massive pit hardening (from April to late June) water was supplied only when TGR was lower than 20μm day^{-1}. During the pit hardening, irrigation was supplied only when the MDS signal was lower than 0.9. Finally, the recovery started during

the last week of August and in this period, water was supplied when TGR was lower than -5μm day^{-1}. This schedule was used during 2011 and 2012 seasons but the water status during pit hardening of this treatment and the next one were similar in these seasons (data not shown). For this reason, RDI 2 was changed during the 2013 season, and during the pit hardening water was supplied when TGR was lower than -10μm day^{-1}.

- RDI 12. The objective of this treatment was to create a moderate water stress before the pit hardening, a severe water stress during pit hardening and a slow recovery. Before the pit hardening, water was supplied only when TGR was lower than 10μm day^{-1}. During the pit hardening, the threshold value for the MDS signal was 0.75. In the recovery period the irrigation schedule was the same as in RDI 2.

The main features that could affect the tree water relations are presented in Table 2. The present work is focus on pit hardenign period (phase II). The length of this period was similar in all the seasons, only in 2011 the beginning was estimated clearly before. The environmental conditions during this period (almost all Summer) were the traditional at the Mediterranean basin with higher Reference evapotranspiration (ETo) and low or null rainfall (Table 2). Only applied water of the treatments which data are used in the presented work are presented (Table 2). Control trees were irrigated with more water than those undergoing the RDI treatments. The volume of water supplied in both RDI treatments was similar, only were clearly different during the 2013 season for the changes in the irrigation scheduling. Control yield was also different between seasons (Table 2), however all the treatments presented the similar pattern in each season (data not shown). There was an alternate bearing period from 2008 to 2012 season, with very high yields in 2008, 2010 and 2014 and almost null in 2011. Only the seasons with significant fruit load that produced a trunk growth stop during pit hardening period were considered for the TGR analysis (2008, 2010, 2012, 2013, 2014).

Measurements

All the measurements were made on six trees used for each treatment. Trunk diameter fluctuations were measured throughout the experiment periods, using a set of linear variable displacement transducers (LVDT) (model DF±2.5mm, accuracy ±10μm, Solartron Metrology, Bognor Regis, UK) attached to the main trunk with a special bracket made of Invar, an alloy of Ni and Fe with a thermal expansion coefficient close to zero (Katerji et al., 1994). Measurements were taken every 10s and the datalogger (model CR10X with AM 416 multiplexer, Campbell Sci. Ltd., Logan, USA) was programmed to report 15 min means.

The water status of trees for each treatment was defined by the midday stem water potential. Leaves near the main trunk were covered with aluminium foil at least one hour before measurements were taken. The water potential was measured at midday in one leaf per tree, using the pressure chamber technique (Scholander et al., 1965).

Micrometeorological 30 min data, namely air temperature (minimum, maximum and average), solar radiation, relative humidity of air and wind speed at 2 m above the soil surface were collected by an automatic weather station located some 40 m from the experimental site. Daily reference evapotranspiration (ETo) was calculated using the Penman-Monteith equation (Allen et al., 1998). Mean daily vapour pressure deficit (VPDm) was calculated from the mean daily vapour pressure and relative humidity. The daily increment (Δ) of each variable at day "n" was calculated as the difference between the value at the day "n+1" and "n". Linear regression analysis was carried out to explore relationships between variables (TGR and climatic variables). Differences between regression lines were determined with a T-test of the slope and y-intercept. Since no significant relationships were obtained in most of the regressions only the four best results will be presented in other to improve the data clarity.

Results

MDS baseline usefulness

Figure 1 shows the relationship between Ψ and the Maximum Daily Shrinkage (MDS). Ψ ranged from -1.0MPa to -2.6MPa, while MDS varied from 300μm to around 800μm. There was no clear relationship between both indicators, although the trend was a large increase of MDS from the lowest values of Ψ until around -1.6MPa. The same values are represented in Figure 2, but the MDS signal calculated for each treatment was considered instead. The scatter is also high and there was no significant relationship between both indicators. However in Figure 2, there is a reference value in the y-axis. Conditions of full irrigation produce values of the MDS signal around 1. In Figure 2, most of the Control data in the 2012 season (9 of 12) and all of them in 2013 presented an MDS signal lower than 1.1, but in the 2011 season, this only happened in 3 out of 11. Moreover, for all the Control values where Ψ was higher than -1.4MPa, the MDS signal was lower than 1.1 in 2012 and 2013, but only in 2 out of 6 cases in 2011. In RDI treatments, most of the values with a Ψ lower than -1.4MPa presented a MDS signal lower than 1.1 (5 out of 6 values when considering all the seasons).

In order to obtain a clearer pattern, data from MDS (Figure 1) were grouped in Ψ intervals (Figure 3). These changes reduced the scatter of the relationship and a clearer curvilinear pattern emerged. Most of the Control data were below 600μm of MDS and there was a progressive increase of MDS with the decrease in Ψ from -

1.6MPa. This pattern changed at around -1.8MPa when the maximum MDS was reached. Then, there was also a clear trend for MDS to decrease with Ψ values lower than -2MPa. The lowest Ψ Control values were in the range of 600-800μm, similar values to those from RDI treatments and close to the maximum MDS measured.

The data of Figure 2 were grouped in the same Ψ intervals as in the previous Figure. An MDS signal equal to 1 represents a theoretical value of conditions with full irrigation. Figure 4 shows a confidence interval of around 10%, therefore MDS signal values from 0.9 to 1.1 could be included in the group with full irrigation. All the Control data are within the interval 1-1.1 of the MDS signal, though the water potential changed from near -1.4MPa to slightly under -1.8MPa. There is also a clear differentiation between data for 2011 and the rest of seasons. Most of the MDS signal data in this season are above 1.1, even in the Control group, though Ψ values were near -1.4MPa (Figure 4). On the other hand, all of the RDI data from -1.6 to -2MPa clearly presented an MDS signal higher than 1.1, with maximum average values around 1.4. When the Ψ values were lower than -2MPa, MDS signals were under 1.1 (Figure 4).

Relationship between trunk growth rate (TGR) and environment

The best relationship between TGR and meteorological data for each season is presented at Table 3. Most of the relationships calculated were not significant (data not shown). The ones presented here are only the best four for each season and orchard in order to improve the clarity of results. None of the regressions that included absolute value of the meteorological data and the daily value of TGR were significant (data not shown). When TGR values were related with the increment of each meteorological variable in some years the regression was significant, but they were still very poor (data not shown). Only when these increments were related with the TCT of the next day the signification was improved. The data of the best relationships between previous meteorological data and TGR for each year are presented at Table 3, only data of the year 2008 is not presented. Average daily relative humidity ((Δ-1)RHav), temperature (average or maximum) and daily average vapour pressure deficit ((Δ-1)VPDav) were the best relationship with TGR. Only (Δ-1)VPDav and (Δ-1)RHav were one of the best in all the years considered (Table 3). Determination coefficient in these variables changed from 0.34 to 0.61 in (Δ-1)VPDav and from 0.2 to 0,52 in (Δ-1)RHav (Table 3). None of the other variables or any multivariable equations improved the results of these two. In all the relationships of Table 3, TGR decreased with an increase of the evaporative demand. The slope in the (Δ-1)VPDav vs TGR relationship was the greatest in all the seasons considered (between -48.6 to -65.5 μmdía^{-1}KPa^{-1}, while in the others from 3.0 in (Δ-1) RHav to -18.8 (Δ-1)Tav (increment of the day before in average temperature).

Similar relationships were obtained when data from a different near orchard was considered (orchard 7*7; 2012 season, Table 3). Accuracy of the equation was improved in this orchard, but (Δ-1)VPDav was again the best variable. This equation explained the 75% of the data variability and the slope was 4 times greater than the rest of the equations (Table 3). The equation of this orchard was significantly different from the ones of the 7*5 orchard.

Although the (Δ-1)VPDav vs TGR relationships presented different slopes between years (Table 3), such differences were not significant (Fig. 5) for the 7*5 orchard. The equation that considered the pool data presented a R^2 around 0.45. The slope of this equation suggests an important effect of the VPD in the TGR (around 55 μm día^{-1} per KPa). This equation was significantly different from the ones obtained in 7*7 orchard. However, in the interval ±1 KPa of VPD, where most of the data are presented, both equations are very similar (Fig. 5).

The accuracy of the equations in the 7*5 orchard was very different between seasons (Table 3). When R^2 is related with the fruit yield of each season, a clear trend to lower influence of VPD with an increase of fruit load is obtained (Fig. 6). Fig. 6 suggests that R^2 in the equations, and therefore the VPD influence on TGR, decreased sharply from around 13 MT ha^{-1}.

Discussion

MDS baseline usefulness

The relationship between the MDS signal and the midday stem water potential (Ψ) was similar to that described in the literature (olives, Moriana et al 2000; other fruit trees, Ortuño et al 2010). When there was no water stress, the values for the relationship between the MDS signal and the water potential (around -1.4MPa) were grouped around 1, while in the MDS vs. Ψ relationship, these values showed a greater scattering. Such results suggest that the MDS signal reduced the environmental noise which is common in MDS values in the range near -1.4MPa.

The fruit load was a factor likely to affect the MDS signal vs. Ψ relationship. Conditions of full irrigation or very low water stress (Ψ higher than -1.6MPa) in a low fruit load season presented greater values than expected (Figure 4, higher than 1). The fruit load is a factor that affects MDS values. In olive trees, Moriana et al (2011) reported a significantly different lower slope in the baseline for the low fruit load than for the high fruit load. Goldhamer and Fereres (2001) suggested that an active trunk growth decreases the MDS in fruit trees. However, lower values for the MDS vs. Ψ relationship were not found in low fruit load conditions in the present work (Figures 1 and 3). Since the MDS signal is a ratio, such response would be related to an estimation of values lower than expected in conditions of full irrigation (the denominator in the ratio). Therefore, the estimation of the MDS baseline at the beginning of a low fruit load season, according to the Corell et al (2013) methodology, could underestimate the value with full irrigation and then, produce a significant increase in the MDS signal during the pit hardening.

The relationship between MDS signal and Ψ showed a clear increase in the MDS signal from -1.6MPa to -2MPa (Figure 4). Such increase was also observed in the MDS vs. Ψ relationship, although the variations were narrow and similar to some values of the Control trees (Figure 3). In both relationships, values below -2MPa were similar to the ones obtained with a Ψ higher than -1.4MPa. This pattern of increase and decrease has been observed in olive (Moriana et al., 2000) and other fruit trees (Ortuño et al., 2010) and has limited the usefulness of MDS in olive trees (Moriana and Fereres, 2002; Moriana et al 2003; Moriana et al., 2010; Fernández et al 2011). Although the MDS signal also presented this pattern, MDS signal values greater than 1.1 always indicated moderate water stress conditions. However, MDS signal values do not display a linear increase because the decrease of MDS signal starts in this interval of water potential. Therefore, in the interval 1.1-1.4, a higher MDS signal will not be necessarily imply a lower Ψ. Then, although there is still an uncertain zone in the range between -1.4MPa and -2MPa, at least conditions of water stress could be identified.

Relationship between trunk growth rate (TGR) and environment

TGR is poor related with environment in the literature and in the present work. Predicted models of the daily TDF has reported no clear results for the overlap effect of growth and water status (Deslauriers et al, 2007). Only in young olives trees, when trunk growth is continuous during all the irrigation season because of the absence of fruit development, significant relationships have been reported (Pérez-López et al., 2008; Cocozza et al., 2012). Deslauriers et al (2007) suggested in several species that the relationship between TGR and temperature is strongly related with the rehydration phase of the daily curve of trunk diameter variations. In the present work, no relationships with any of the Deslauriers' phases have been obtained. Fernández et al (2011) in the same olive orchard did not obtain either any relationship. This lack of results was likely related with the greater number of species and meteorological conditions in the Deslauriers work than in Fernández and the present works. According with the data of the present work, the influence of VPD was very important but strongly affected for the yield. Both results are not new in olive literature. Evaporative demand affects the daily cycle of leaf conductance (Xiloyannis et al., 1988) and the relationship between leaf conductance and water potential (Moriana et al., 2002). Water relations are strongly affected for fruit development (Rallo and Suárez, 1989; Martín-Vertedor et al., 2011). TGR in olive trees is very different in low than in high fruit load conditions (Moriana et al., 2003), but, according to the present work, excessive fruit yield will also affect. Moriana et al (2013) reported in two of the data set used in the present work (2008 and 2010 seasons) a continuous decrease in the TGR values in full irrigated conditions. Finally, the influence of VPD in TGR values was delayed in one day and the increase in VPD affect the TGR of the next day. Such result suggests that TGR variations could be controlled with chemical or hydraulic changes in the trunk tissues as in the root signal, described also in olive trees (Fernández et al., 2006).

Conclusions

The patterns of the relationships MDS signal vs. Ψ and MDS vs. Ψ were similar. However, the MDS signal estimated according to Corell et al (2013) resulted in a reduced scattering in conditions of full irrigation and clearly identified water stress conditions in the range of -1.4MPa to -2MPa. This range of Ψ corresponded to MDS signal values between 1.1 and 1.4. However, since the decrease in MDS signal starts within this range, higher values do not indicate more severe water stress conditions. Ψ values lower than -2MPa produced values of MDS signal around 1, therefore, they cannot be used for detecting water stress conditions. Conditions of low fruit load could limit the usefulness of this approach. Significant relationship between TGR and environmental variables were obtained only when a 1 day delayed was considered. TGR values during pit hardening were strongly affected for the increase in the average VPD of the day before when the fruit load was not excessive.

Acknowledge

This research was supported by the Spanish Ministerio de Ciencia e Innovación (MICINN), (AGL2010-19201-CO4-03). Thanks are due to J. Rodriguez and A. Montero for help with field measurements.

References

Allen, R.G., Pereira, L.S., Raes, D., Smith. M., 1998. Crop evaportranspiration. Guideline for computing crop water requirements. FAO irrigation and drainage paper nº 56. Roma. FAO

Cocozza, C., Giovannelli, A., Lasserre, B., Cantini, C., Lombardi, F., Tognetti, R. 2012. A novel mathematical procedure to interpret the stem radius variation in olive tres. Agric. Forest Meteorol. 161,80-93.

Corell, M., Girón, I.F., Moriana, A., Dell'Amico, J., Morales, D., Moreno, F. 2013. Extrapolating base-line trunk shrinkage reference equations across olive orchards. Agric. Water Manage. 126,1-8.

Cuevas, M.V., Torres-Ruiz, J,M., Álvarez, R,, Jiménez, M.D., Cuerva, J., Fernández, J.E. 2010. Usefulness of trunk diameter variations for irrigation scheduling in a mature olive tree orchard. Agric. Water Manage. 97, 1293–1302.

Deslauriers, A., Anfodillo, T., Rossi, S., Carraro, V. 2007. Using simple causal modeling to understand how water and temperature affect daily stem variation in trees. Tree Physiol. 27, 1125-1136.

Fernández, J.E. and Cuevas, M.V., 2010. Irrigation scheduling from stem diameter variations: a review. Agric. Forest Meteorol. 150, 135–151.

Fernández, J.E., Moreno, F., Girón, I.F., Blázquez, O.M., 1997. Stomatal control of water use in olive tree leaves. Plant Soil 190, 179-192.

Fernández, JE., Díaz-Espejo, A., Infante, J.M., Durán, P., Martín-Palomo, MJ., Chamorro, V., Girón I.F., Villagarcía, L. 2006. Water relations and gas exchange in olive trees under regulated deficit irrigation and partial rootzone drying. Plant Soil 284, 273-291.

Fernández, J.E., Torres-Ruiz, J.M., Díaz-Espejo, A., Montero, A., Alvárez, R., Jiménez, M.D., Cuerva, J., Cuevas, M.V. 2011a. Use of maximum trunk diameter measurements to detect water stress in mature Arbequina olive trees under deficit irrigation. Agric. Water Manage. 98, 1813-1821.

Fernádez, JE., Moreno, F., Martín-Palomo, MJ., Cuevas, MV., Torres-Ruiz, JM, Moriana, A. 2011b. Combining sap flow and trunk diameter measurements to assess water needs in mature olive orchards. Environ. Exp. Bot. 72, 330-338.

Goldhamer, D.A. and Fereres, E., 2001. Irrigation scheduling protocols using continuously recorded trunk diameter measurements. Irrig. Sci. 20, 115-125.

Goldhamer, D.A., Fereres, E., Mata, M., Girona, J., Cohen, M., 1999. Sensitivity of continuous and discrete plant and soil water status monitoring in peach tress subjected to deficit irrigation. J. Amer. Soc. Hort. Sci. 124, 437-444.

Herzog, K.M., Hüsler, R., Thum, R., 1995. Diurnal changes in the radius of a subalpine Norway spruce stem: their relation to the sap flow and their use to estimate transpiration. Trees 10, 94-101.

Katerji, N., Tardieu, F., Bethenod, O., Quetin, P., 1994. Behavior of Maize stem diameter during drying cycles: comparison of two methods for detecting water stress. Crop Sci. 34, 165-169.

Klepper, B., Browing, V.D., Taylor, H.M., 1971. Stem diameter in relation to plant water status. Plant Physiol. 48, 683-685.

Martín-Vertedor, A.I., Pérez-Rodríguez, J.M., Prieto, H., Fereres, E., 2011. Interactive responses to water deficits and crop load in olive (Olea europaea L., cv. Morisca).Water use, fruit and oil yield. Agric. Water Manage. 98, 941–949.

Moriana, A. and Fereres, E., 2002. Plant Indicators for Scheduling Irrigation for Young Olive Trees. Irrig. Sci. 21, 83-90

Moriana, A., Fereres, E., Orgaz, F., Castro, J., Humanes, M.D., Pastor, M., 2000. The relations between trunk diameter fluctuations and tree water status in olive tree (Olea europea L). Acta Hortic. 537, 293-297.

Moriana, A., Orgaz, F., Fereres, E., Pastor, M., 2003. Yield responses of a mature olive orchard to water deficits. J. Amer. Soc. Hort. Sci. 128,425-431.

Moriana, A., Girón, I., Martín-Palomo, M.J., Conejero, W., Ortuño, M.F., Torrecillas, A., Moreno, F., 2010. New approach for olive trees irrigation scheduling using trunk diameter sensors. Agric. Water Manage 97,1822-1828.

Moriana, A., Moreno, F., Girón, I., Conejero, W., Ortuño, M.F., Morales, D., Corell, M., Torrecillas, A., 2011. Seasonal changes of maximum daily shrinkage reference equations for irrigation scheduling in olive trees: influence of fruit load. Agric. Water Manage. 99, 121-127.

Moriana, A., Pérez-López, D., Prieto, M.H., Ramírez-Santa-Pau, M., Pérez-Rodriguez, J.M. 2012. Midday stem water potential as a useful tool for estimating irrigation requirements in olive trees. Agric. Water Manage. 112:43-54.

Moriana, A., Corell, M., Girón, I.F., Conejero, W., Morales, D., Torrecillas, A., Moreno, F. 2013. Regulated deficit irrigation based on threshold values of trunk diameter fluctuation indicators in table olive trees. Sci Hort 164, 102-111.

Ortuño, M.F., Conejero, W., Moreno, F., Moriana, A., Intrigliolo, D.S., Biel, C., Mellisho, C.D., Pérez-Pastor, A., Domingo, R., Ruiz-Sánchez, M.C., Casadesus, J., Bonany, J., Torrecillas, A., 2010. Could trunk diameter sensors be used in woody crops for irrigation scheduling?. A review of current knowledge and future perspectives. Agric. Wat. Management 97,1-11.

Pérez-López, D.; Moriana, A.; Rapoport, H; Olmedilla, N.; Ribas, F. (2008) New approach for using trunk growth rate and endocarp development in the irrigation scheduling of young olive orchards. Scientia Hort. 155, 244-251

Pérez-López, D., Pérez-Rodríguez, J.M., Moreno, M.M., Prieto, M.H., Ramírez-Santa-Pau, M., Gijón, C., Guerrero, J., Moriana, A. 2013. Influence of different cultivars-locations on maximum daily shrinkage indicators: Limits to the reference baseline approach. Agric. Water Manage. 127, 31-39.

Rallo, L. and Suarez, M.P. 1989. Seasonal distribution of dry matter within the olive fruit-bearing limb. Adv. Hort. Sci. 3, 55-59.

Rapoport, H.F., Pérez-López, D., Hammami, S.B.M., Aguera, J., Moriana, A. 2013. Fruit pit hardening: physical measurements during olive growth. Ann. Appl. Biol. 163, 200-208.

Scholander, P.F., Hammel, H.T., Bradstreest, E.A., Hemmingsen, E.A., 1965. Sap pressure in vascular plant. Science 148, 339-346.

Xiloyannis,C; Pezzarossa,B; Jorba,J; Angelini,P (1988): Effects of soil water content on gas exchange in olive trees. Adv. Hort. Sci. 2, 58-63.

Figure Captions

Fig. 1. Relationship between Midday stem water potential vs Maximum daily shrinkage during the three seasons. Each symbol is the average of 6 measurements. The period of measurement was from the beginning of pit hardening until harvest. Symbols: 2011 season, triangles; up and empty Control trees, down and empty RDI 2, up and black RDI 12. 2012 season, square; empty Control trees, mid-filled RDI 2; black RDI 12. 2013 season, circle; empty Control trees, mid filled RDI 2; black RDI 12. Vertical dash line indicated the reference value of stem water potential (-1.4 MPa).

Fig. 2. Relationship between Midday stem water potential vs Maximum daily shrinkage signal (MDS signal) during the three seasons. Each symbol is the average of 6 measurements. The period of measurement was from the beginning of pit hardening until harvest. Symbols: 2011 season, triangles; up and empty Control trees, down and empty RDI 2, up and black RDI 12. 2012 season, square; empty Control trees, mid-filled RDI 2; black RDI 12. 2013 season, circle; empty Control trees, mid filled RDI 2; black RDI 12. Vertical dash line indicated the reference value of stem water potential (-1.4 MPa). Horizontal dash line indicated the reference value of MDS signal (1).

Fig. 3. Relationship between Midday stem water potential vs Maximum daily shrinkage during the three seasons. Each point is the average of all the data of Figure 1 grouped according to water potential intervals: values higher than -1.4 MPa, between -1.4 until -1.75 MPa, between -1.75 until -2 MPa and lower than -2 MPa. Vertical and horizontal bars at the symbol represent the standard error in MDS and water potential respectively. Vertical dash line shows the reference of stem water potential (-1.4 MPa). Symbols: 2011 season, triangles; up and empty Control trees, down and empty RDI 2, up and

black RDI 12. 2012 season, square; empty Control trees, mid-filled RDI 2; black RDI 12. 2013 season, circle; empty Control trees, mid filled RDI 2; black RDI 12.

Fig. 4. Relationship between Midday stem water potential vs Maximum daily shrinkage signal (MDS signal) during the three seasons. Each point is the average of all the data of Figure 2 according to the water potential interval of: values higher than -1.4 MPa, between -1.4 until -1.75 MPa, between -1.75 until -2 MPa and lower than -2 MPa. Vertical and horizontal bars at the symbol represent the standard error in MDS signal and stem water potential respectively. Vertical dash line shows the reference of stem water potential (-1.4 MPa). Horizontal dash lines represent the reference of MDS signal (1) and an interval of ±10%. Symbols: 2011 season, triangles; up and empty Control trees, down and empty RDI 2, up and black RDI 12. 2012 season, square; empty Control trees, mid-filled RDI 2; black RDI 12. 2013 season, circle; empty Control trees, mid filled RDI 2; black RDI 12.

Fig. 5. Relationship between trunk growth rate (TGR) and increment of the vapour pressure deficit the day before ((Δ-1)VPD). Black square and solid line represent all the data of the 7*5 m orchard (Table 3, n=257, TGR=-54.15 (Δ-1)VPD, R^2=0.46***, Error=31.0 μm día^{-1}). White square and dash line represent data from 7*7 orchard (Table 3, n=60, TGR=-79.39 (Δ-1)VPD, R^2=0.75***, Error=27.8 μm día^{-1}).

Fig. 6. Relationship between the determination coefficient (R^2) of the regressions between increment of the vapour pressure deficit the day before ((Δ-1)VPD) and TGR

(Table 3) vs the yield. The highest yield and lowest R^2 correspond to the regression obtained in the 2008 season (data not shown).

	2011	2012	2013
Control	-0.84±0.03	-1.00±0.02	-0.89±0.07
RDI 2	-0.92±0.04	-1.04±0.03	-0.84±0.07
RDI 12	-0.98±0.03	-1.05±0.03	-0.86±0.06

Table 1. Midday stem water potential (MPa) during the three seasons of the MDS experiment. The values presented are the average of the period previous to pit hardening. Measurements were performed in 5 different dates (2011, from April to June), in 12 different dates (2012, from March to June) and in 11 different dates (2013, from March to June).

Seasons	DOY Ph II	ETo Ph II	Rain Ph II	Yield		AW	
					Control	RDI 2	RDI 12
2008	172-246		11.1	18.3±0.3	619		
2010	166-235		15.6	15.0±1.7	710		
2011	157-235	519	1.8	2.5±0.5	285	132	100
2012	173-232	368	0.0	6.6±0.7	412	130	111
2013	176-233	361	0.0	9.0±1.1	369	207	106
2014	168-236	390	6.1	14.7±1.6	279		

Table 2. Features of the experimental seasons used in the present work. In all the seasons is presented: the length of the pit hardening phase (DOY PH II, beginning and end date), reference evapotranspiration in the pit hardening phase (ETo PhII, mm), rainfall in the pit hardening phase (Rain Ph II, mm), yield in Control treatments (MT ha^{-1}), seasonal applied water in the treatments used in each season (AW, mm).

Variable	n	R^2	Standar Error	Equation
		2010	**Orchard 7*5**	**DOY 166-235**
(Δ–1) VPDav	70	0.34***	42.4 µm	TGR=-48.6(Δ–1)DPVmed
(Δ–1) Tav	70	0.40***	40.1 µm	TGR=-18.8(Δ–1)Tmed
(Δ–1) Tmax	70	0.27***	44.7 µm	TGR=-9.2(Δ–1)Tmax
(Δ–1) RHav	70	0.20**	46.7 µm	TGR=2.1(Δ–1)HRmed
		2012	**Orchard 7*5**	**DOY 173-232**
(Δ–1) VPDav	60	0.61***	24.8 µm	TGR=-50.8(Δ–1)DPVmed
(Δ–1) RHav	60	0.52***	27.3 µm	TGR=3.0(Δ–1)HRmed
(Δ–1) RHmin	60	0.36***	31.6 µm	TGR=2.2(Δ–1)HRmin
(Δ–1) Tmax	60	0.31***	32.8 µm	TGR=-8.0(Δ–1)Tmax
		2013	**Orchard 7*5**	**DOY 176-233**
(Δ–1) VPDav	58	0.61***	21.8 µm	TGR=-65.5(Δ–1)DPVmed
(Δ–1) Tav	58	0.29***	28.8 µm	TGR=18.7-13.5(Δ–1)Tmed
(Δ–1) RHav	58	0.27***	29.3 µm	TGR=18.0+2.3(Δ–1)HRmed
Δ RHav	58	0.24***	30.0 µm	TGR=17.9+2.14ΔHRmed
		2014	**Orchard 7*5**	**DOY 168-236**
(Δ–1) VPDav	69	0.47***	28.5 µm	TGR=-63.1(Δ–1)DPVmed
(Δ–1) RHav	69	0.39***	30.5 µm	TGR=2.8(Δ–1)HRmed
(Δ–1) Tav	69	0.38***	31.0 µm	TGR=-15.2(Δ–1)Tmed
(Δ–1) Tmax	69	0.36***	31.4 µm	TGR=-9.1(Δ–1)Tmax
		2012	**Orchard 7*7**	**DOY 173-232**
(Δ–1) VPDav	60	0.75***	28.0 µm	TGR=-79.2(Δ–1)DPVmed
(Δ–1) RHav	60	0.53***	38.0 µm	TGR=4.3(Δ–1)HRmed
(Δ–1) Tav	60	0.48***	39.9 µm	TGR=-20.3(Δ–1)Tmed
(Δ–1) Tmax	60	0.47***	40.5 µm	TGR=-13.7(Δ–1)Tmax

Table 3. Results in the different seasons of the relationship between several meteorological variables and trunk growth rate (TGR) of full irrigated trees. In all the seasons the orchard is the same, only in 2012 data from a next orchard is included. In each season the four best results are presented. In all of them **(Δ-1)VPDav** (increment of the daily average vapour pressure deficit the day before) was one of the best and is presented in first position, the rest are organised according to the determination coefficient (R^2). **(Δ–1) Tav**, increment of daily average temperature the day before; **(Δ–1) Tmax**, increment of daily maximum temperature the day before; **(Δ–1) RHav**, increment of daily average relative humidity the day before; **(Δ–1) RHmin**, increment of dailiy minimum relative humidity the day before; **Δ RHav** increment of daily average relative humidity

Figure 1

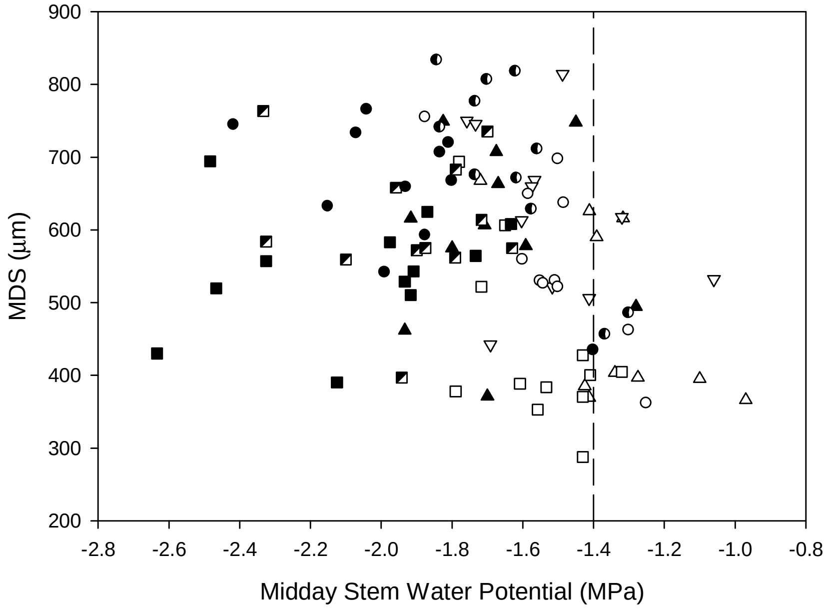

Figure 1. Relationship between Midday stem water potential vs Maximum daily shrinkage during the three seasons. Each symbol is the average of 6 measurements. The period of measurement was from the beginning of pit hardening until harvest. Symbols: 2011 season, triangles; up and empty Control trees, down and empty RDI 2, up and black RDI 12. 2012 season, square; empty Control trees, mid-filled RDI 2; black RDI 12. 2013 season, circle; empty Control trees, mid filled RDI 2; black RDI 12. Vertical dash line indicated the reference value of stem water potential (-1.4 MPa).

Figure 2

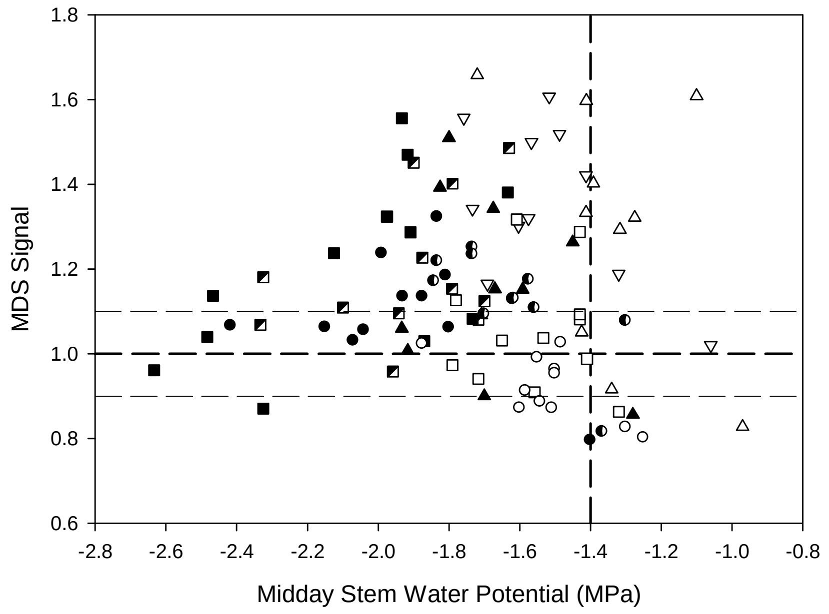

Figure 2. Relationship between Midday stem water potential vs Maximum daily shrinkage signal (MDS signal) during the three seasons. Each symbol is the average of 6 measurements. The period of measurement was from the beginning of pit hardening until harvest. Symbols: 2011 season, triangles; up and empty Control trees, down and empty RDI 2, up and black RDI 12. 2012 season, square; empty Control trees, mid-filled RDI 2; black RDI 12. 2013 season, circle; empty Control trees, mid filled RDI 2; black RDI 12. Vertical dash line indicated the reference value of stem water potential (-1.4 MPa). Horizontal dash line indicated the reference value of MDS signal (1).

Figure 3

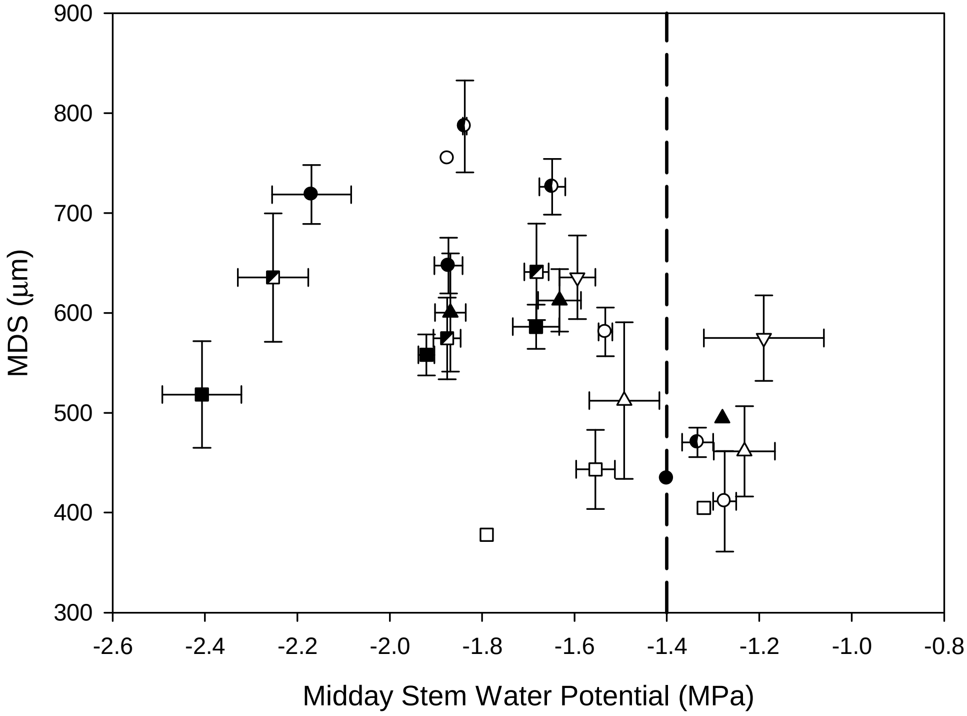

Figure 3. Relationship between Midday stem water potential vs Maximum daily shrinkage during the three seasons. Each point is the average of all the data of Figure 1 grouped according to water potential intervals: values higher than -1.4 MPa, between -1.4 until -1.75 MPa, between -1.75 until -2 MPa and lower than -2 MPa. Vertical and horizontal bars at the symbol represent the standard error in MDS and water potential respectively. Vertical dash line shows the reference of stem water potential (-1.4 MPa). Symbols: 2011 season, triangles; up and empty Control trees, down and empty RDI 2, up and black RDI 12. 2012 season, square; empty Control trees, mid-filled RDI 2; black RDI 12. 2013 season, circle; empty Control trees, mid filled RDI 2; black RDI 12.

Figure 4

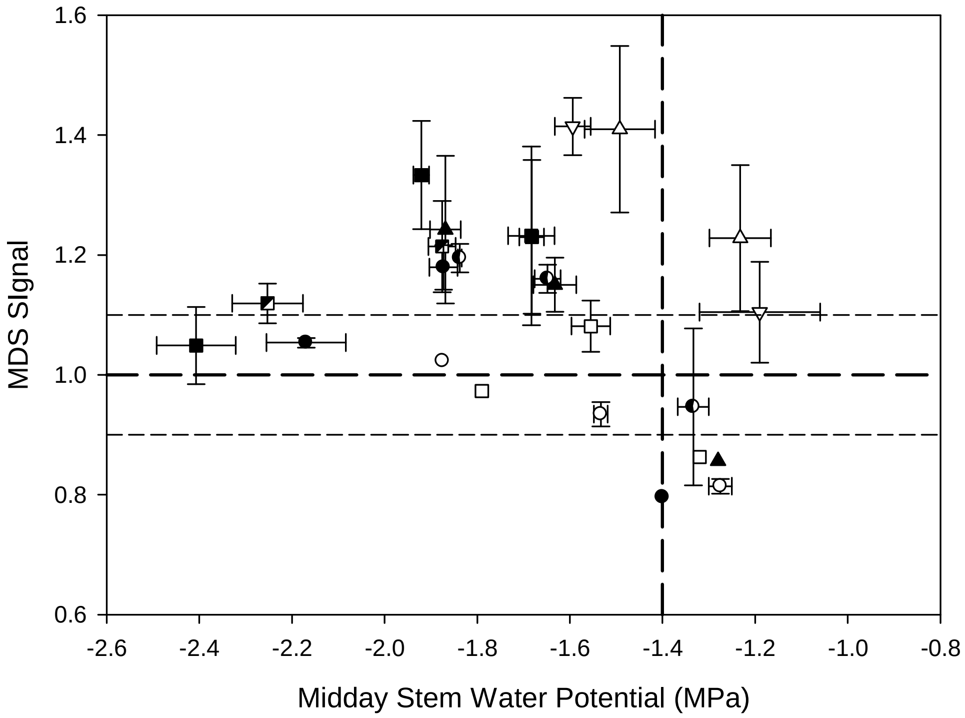

Figure 4. Relationship between Midday stem water potential vs Maximum daily shrinkage signal (MDS signal) during the three seasons. Each point is the average of all the data of Figure 2 according to the water potential interval of: values higher than -1.4 MPa, between -1.4 until -1.75 MPa, between -1.75 until -2 MPa and lower than -2 MPa. Vertical and horizontal bars at the symbol represent the standard error in MDS signal and stem water potential respectively. Vertical dash line shows the reference of stem water potential (-1.4 MPa). Horizontal dash lines represent the reference of MDS signal (1) and an interval of ±10%. Symbols: 2011 season, triangles; up and empty Control trees, down and empty RDI 2, up and black RDI 12. 2012 season, square; empty Control trees, mid-filled RDI 2; black RDI 12. 2013 season, circle; empty Control trees, mid filled RDI 2; black RDI 12.

Figure 5

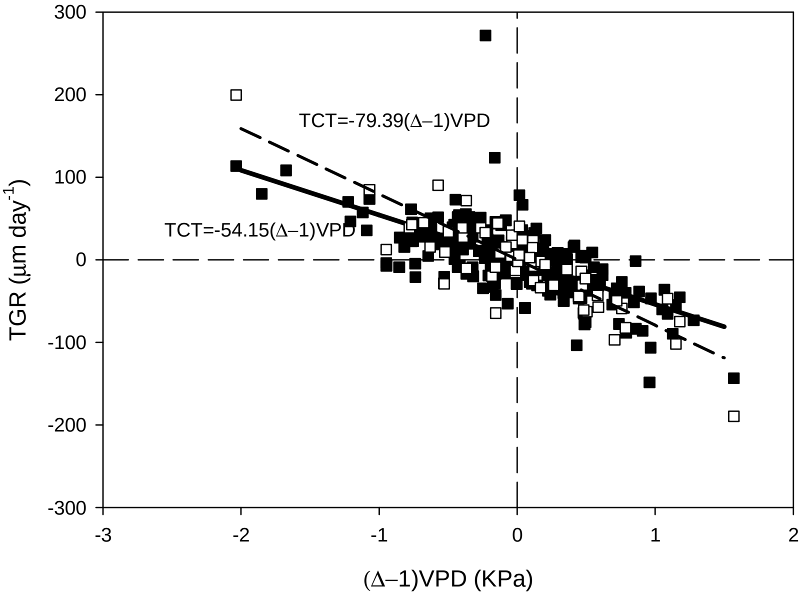

Fig. 5. Relationship between trunk growth rate (TGR) and increment of the vapour pressure deficit the day before ((Δ-1)VPD). Black square and solid line represent all the data of the 7*5 m orchard (Table 3, n=257, TGR=-54.15 (Δ-1)VPD, R^2=0.46***, Error=31.0 μm día^{-1}). White square and dash line represent data from 7*7 orchard (Table 3, n=60, TGR=-79.39 (Δ-1)VPD, R^2=0.75***, Error=27.8 μm día^{-1})

Figure 6

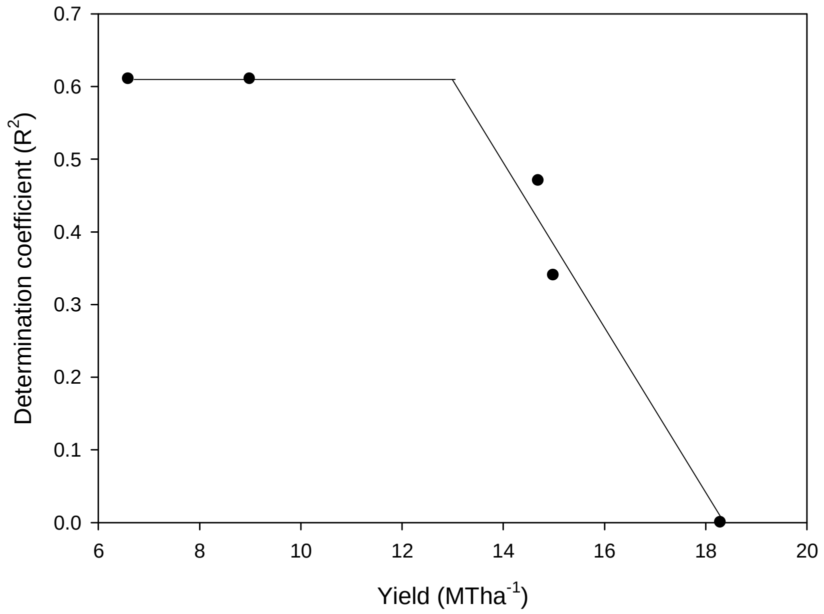

Fig. 6. Relationship between the determination coefficient (R^2) of the regressions between increment of the vapour pressure deficit the day before ((Δ-1)VPD) and TGR (Table 3) vs the yield. The highest yield and lowest R^2 correspond to the regression obtained in the 2008 season (data not shown).