# REGULATED DEFICIT IRRIGATION BASED ON THRESHOLD VALUES OF TRUNK DIAMETER FLUCTUATION INDICATORS IN TABLE OLIVE TREES

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## Abstract

The aim of this study was to establish threshold TGR and MDS values which could be used in regulated deficit irrigation in future work. Three irrigation treatments were performed during three seasons in a 37 year-old table olive orchard in Seville (Spain). Control treatment was irrigated with 125% of the crop evapotranspiration. Regulated deficit irrigation (RDI) treatments were performed according to the phenological stage of the trees and different water stress levels. RDI trees were irrigated only when the threshold values of water stress level was reached. Water stress conditions were applied during the massive pit hardening period (phase II) or during this period and the shoot-flowering period (phase I). The water stress level was performed with the trunk growth rate (TGR) during phase I and recovery and maximum daily shrinkage signal (MDS signal) during phase II. Both parameters were calculated as relative values of the Control trees. TGR threshold values varied from equal to Control or 0.25 μm day$^{-1}$ less than Control. MDS signal (ratio between MDS in RDI vs MDS Control) threshold values varied from 0.5 to 0.75. This scheduled changed the amount of applied water between high and low fruit load seasons. The total amount of applied water in RDI trees oscillated between 38 to 160 mm, depending of the season and the treatment. The yield was not significantly different between Control and deficit treatments. Fruit volume and number of fruits was affected for the irrigation. Limitations and management of TDF in irrigation scheduling is discussed.

## 1. Introduction

Irrigation scheduling in fruit trees is commonly calculated according to water balance in full or deficit conditions. The water deficit schedule in olive trees is traditionally based on severe water withdrawal around the beginning of massive pit hardening (75% crop evapotranspiration in Goldhamer 1999; no irrigation in Moriana et al 2003 and Iniesta et al., 2009). However, in recent studies zero irrigation conditions before pit hardening and subsequent recovery have been proposed with significant water saving without yield decreases (Magliulo et al 2003; Lavee et al 2007; Tognetti et al 2007). In addition, sustained deficit irrigation (SDI) is presented as an alternative schedule with significant water saving. SDI consists of a progressive deficit; usually applied water is defined as a percentage of the crop evapotranspiration throughout the season (Moriana et al 2003; Iniesta et al 2009; Martin-Vertedor et al., 2011; Caruso et al 2013). SDI scheduling produces that the water deficit level and the phenological moment of the most severe water stress are un-controlled. In fact, all these proposals are really only a local adaptation of irrigation scheduling to an optimum water stress level according to the soil and climatic conditions. All those traditional studies concluded with a recommendation of reductions in water irrigation based on crop evapotranspiration ($ET_c$), though a sharp change in environmental conditions during a sensitive phenological stage (such as flowering) would affect the results, as reported by Moriana et al. (2003) and suggested by Lavee et al. (2007). Therefore, the level of water stress, or, even better, the level and duration of water stress should be recommended instead of the amount of applied water. In recent decades this idea - the recommendation of water stress level instead of water amount - has contributed to the use of plant water status measurements as an irrigation scheduling tool. In several fruit trees water management based on these techniques has been very successful (i.e. almond, trunk diameter fluctuations, Goldhamer and Fereres, 2004; vineyard, water potential, Girona et al., 2006; olive, water potential, Gucci et al. 2007; peach, trunk diameter fluctuations, Conejero et al., 2011). However, some of these studies used a non-continuous measurement, such as water potential (Girona et al., 2006; Gucci et al., 2007), which makes automatic and telematic irrigation scheduling difficult.

Trunk diameter fluctuation is a water status measurement that has been considered as an irrigation scheduling tool in recent decades and permits continuous monitoring (Ortuño et al., 2010; Fernández and Cuevas, 2010). The trunk and stem in all the plants present a daily cycle of shrinking and swelling (Klepper et al., 1971). The most common parameters used in irrigation scheduling are the maximum daily shrinkage (MDS) and the maximum daily diameter (Goldhamer and Fereres, 2001). However, trunk diameter fluctuations, like other plant water status measurements, are strongly related to the evaporative demand of the atmosphere, which makes irrigation scheduling more difficult. Goldhamer and Fereres (2001) suggested the use of reference trees (trees over-irrigated in the orchard) in order to calculate the relative values of MDS and maximum daily diameter which minimise this effect. The reference trees technique has permitted deficit irrigation scheduling in several fruit trees (i.e. Goldhamer and Fereres, 2004; Conejero et al., 2011).

MDS is the traditional parameter used in fruit crops (almond, apple, peach, plum, lemon, Ortuño et al., 2010) and is strongly related to transpiration (subalpine Norway spruce, Herzog et al., 1995). However, the results found in the literature for olive trees do not show clear differences in MDS under mild water stress conditions (Moriana and Fereres, 2002; Moriana et al., 2003; Moriana et al., 2010; Cuevas et al., 2012). This behaviour is probably due to the relationship between MDS and water potential. In all species, MDS increases with the decrease of water potential until a value is reached from which MDS decreases sharply (Ortuño et al., 2010). This decrease has been related to severe water stress conditions that reduce the transpiration of the tree (Hinckley and Bruckerhoff, 1975). In olive trees, at moderate water stress, clear differences in water potential produce similar values of MDS (Moriana et al., 2000; Moriana and Fereres, 2002; Moriana et al., 2011; Cuevas et al., 2012). However, lower values of MDS than the maximum expected could be observed (Moriana et al., 2011), because the deficit irrigation strategy in olive trees supposes severe water stress conditions (Goldhamer, 1999).

Maximum daily diameter is not commonly used in the irrigation scheduling of fruit trees (Ortuño et al., 2010). However, this indicator, or a related form of it, is considered more sensitive than MDS in some trees (peaches, Goldhamer et al 1999; olive, Moriana and Fereres, 2002; Cuevas et al., 2012). One of the main problems in the use of maximum daily diameter as an indicator for irrigation scheduling is the strong relationship with fruit load (Moriana et al., 2003; Nortes et al., 2005; Intrigliolo and Castel, 2006; Pérez-López et al., 2008) which makes it very difficult to establish a threshold value. In addition, an absolute value of maximum daily diameter is not useful because depend of the initial value and especially recovery is difficult to identified (Moriana and Fereres, 2002). Then, the slope of maximum daily diameter, the trunk growth rate (TGR), was suggested in olive trees as indicator (Moriana an Fereres, 2002).

The works that scheduled the irrigation using water status indicator are scarce in the literature. Although there are previous studies which reported the response of trunk diameter fluctuations to water stress in olive trees, there have been no studies that use this technique for irrigation scheduling in this species. Problems such as the threshold values or the control of irrigation rate (information that the sensors do not provide) are the main limitating factors to adopting this technique. The present work is designed to establish threshold TGR and MDS values which could be used in regulated deficit irrigation in future work. In addition, this work describes problems and limitations in the parameters used. Our hypothesis is that the use of relative values of TGR and MDS, obtained from the relationship between the data of reference trees (over-irrigated) and deficit treatments, will permit successful control of deficit irrigation. Different indicators and threshold values were used according to the phenological stage of the trees. When moderate or null water stress was needed the comparison of TGR between control and deficit trees was used. While MDS signal (ratio between MDS of deficit trees and MDS of control) was selected during the massive pit hardening, when severe water stress conditions were scheduled.

## 2. Material and Methods

### *2.1. Site description*

Experiments were conducted at La Hampa, the experimental farm of the Instituto de Recursos Naturales y Agrobiología (CSIC). This orchard is located at Coria del Río near Seville (Spain) (37º17’’N, 6º3’W, 30 m altitude). The experiment was performed on 37-year-old table olive trees (Olea europaea L cv Manzanillo) for 3 consecutive seasons (from 2008 to 2010). Tree spacing followed a 7 m x 5 m square pattern. The trees were irrigated before the experiment with the same amount of water. The sandy loam soil (about 2 m deep) of the experimental site was characterized by a volumetric water content of 0.33 $m^3$ $m^{-3}$ at saturation, 0.21 $m^3m^{-3}$ at field capacity and 0.1 $m^3m^{-3}$ at permanent wilting point, and 1.30 (0-10cm) and 1.50 (10-120 cm) g $cm^{-3}$ bulk density. Pest control, pruning and fertilization practices were those commonly used by growers and weeds were removed chemically within the orchard. Drip irrigation was carried out during the night using one lateral pipe per tree row and five emitters per plant, delivering 8 L $h^{-1}$ each. Micrometeorological data, namely air temperature, solar radiation, relative humidity of air and wind speed at 2 m above the soil surface were measured every 1 minute and 30 minutes average were obtained by an automatic weather station located some 40 m from the experimental site. Daily reference evapotranspiration ($ET_o$) 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.

### *2.2 Experimental design and treatment description*

The experimental design was a completed randomized experiment with 3 treatments of irrigation. Preliminary studies (texture samples) have shown that this orchard was very homogenous in soil conditions, so a block design did not improve statistical results. In addition, the experimental orchard was small (2520 $m^2$). Therefore, in order to maximize the number of trees within the plot, each treatment was in a plot with six trees located in a single row with two adjacent guard rows. This experimental design was the only one that permitted an experimental parcel with more than 1 tree. The irrigation treatments were designed according to the phenological stage of the trees and different parameters of trunk diameter fluctuations. The seasonal cycle of the trees were divided in 4 phases according to Rallo (1997):

Phase I occurred from the shoot flush until the beginning of the period of massive pit hardening (around day of the year (DOY) 169). (Shoot flush is around the mid-February, day of the year (DOY) 45)

Phase II occurred from massive pit hardening until the last week of August. We considered that the beginning of massive pit hardening began when a decrease in the growth rate of the longitudinal diameter of the fruit was measured (Gijón et al., 2010). There is no morphological indicator to establish the end of this phase. In order to obtain a complete rehydration before harvest, the last week of August was considered the end of this period in all the seasons (around DOY 240).

Phase III was the period of rehydration and occurred from the end of August until harvest (around DOY 275).

Phase IV. Postharvest. Typical date of the beginning of postharvest is beginning of October.

The water stress levels were estimated according to the trunk diameter fluctuation indicators. Rains produced an unreal daily cycle of trunk diameter fluctuations. Therefore the date where rain was measured and three days later, irrigation was not scheduled in RDI treatments. Maximum daily shrinkage (MDS) was calculated as the difference between the maximum daily diameter, which occurs at the beginning of the day, and the minimum daily diameter, which occurs mid-afternoon (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 those of day "n" (Cuevas et al., 2010). According to Goldhamer and Fereres' (2001) approach, water stress level was defined in comparison with an over-irrigated Control. The MDS signal was established as the ratio between the value of MDS in the deficit treatment and MDS in Control trees (Goldhamer et al., 1999).

TGR was used in the phenological phases when water stress level was less severe (phase I) or, even, null (phase III), because this parameter has been reported as being more sensitive to water stress in olives than MDS (Moriana and Fereres, 2002; Moriana et al., 2010). To improve the clarity of results maximum daily diameter (MXD, mm) instead of TGR (μm $day^{-1}$) is presented. TGR is the rate in the MXD Figures. MDS was used during phase II when the most severe water stress conditions were imposed and values of MDS signal below 1 may be expected.

The irrigation treatments were:

- *Control treatment*. Irrigation requirements were determined according to daily reference evapotranspiration ($ET_o$) and a crop factor based on the time of the year and the percentage of ground area shaded by the tree canopy (Fernández et al., 1998). The crop coefficient values ($K_c$) considered were 0.76 in May, 0.70 in June, 0.63 in July and August, 0.72 in September and 0.77 in October (Fernández et al. 2006). The value of the coefficient in relation to the percentage of ground covered by the crop (Kr) was 0.7. Trees were irrigated with 125% crop evapotranspiation ($ET_c$) until harvest.
- *Regulated Deficit Irrigation 2 (RDI-2).* No water stress was performed in phase I and III. In these phases, irrigation was applied when TGR was lower than Control. Moderate water stress were applied during phase II, and irrigation was applied when the MDS signal was lower than 0.75. This value of MDS signal (and the one described below) was estimated from the

MDS vs stem water potential relationship of Moriana et al (2000). In this latter work the maximum values of MDS was around 800 μm. We assumed that the minimum stem water potential should be around -2.5 MPa; the equation of this work estimated that MDS would be around 600 mm, therefore around 0.75 MDS signal.

- *Regulated Deficit Irrigation 12 (RDI-12).* No water stress was performed in phase III and the management was the same, in this phase, as RDI-2. Moderate water stress conditions were applied in phase I and severe water-deficits were performed in phase II. In phase I, irrigation was applied when the average of TGR in the treatment was 0.25 μm day$^{-1}$ lower than the average in the Control. This value was considered in previous studies as moderate water stress (Moriana et al., 2010). In phase II irrigation was applied when the MDS signal was lower than 0.5. As in the previous treatment, we considered a level of water stress around -3.5 MPa and this correspond to a MDS around 400 μm, then a 0.5 MDS signal.

None of the treatments were irrigated after harvest. However, because of the lateness of autumn rains during 2008 season, all of them were irrigated as in phase III.

The trunk diameter sensors indicate the water status of the tree but they do not give information about the amount of water to be applied. Because trees were continuous monitoring, irrigation was changed daily according to the variation of the threshold value considered (MDS or TGR depend of the phenological stage). The objective of this irrigation scheduling is to maintain the water stress level of the tree. Goldhamer and Fereres (2001) suggested variations of 10% in the applied water when the parameter selected (in that work MDS signal) was higher than the threshold value.

Conejero et al (2011) reported that variations of 10% were too small to produce a fast change in the values of MDS signal. Therefore, we consider that the irrigation rate should be different according to the measurement obtained. If the measurement was very different to the threshold value the applied water should be greater than if the value was similar. Three levels of irrigation rate were estimated in relation to the maximum average daily $ET_c$ of the orchard. This value was estimated with the average data of $ET_o$ in the last ten years and with the $K_c$ and $K_r$ values used in the Control treatment. The irrigation rate varied as follow:

- When the average value of the selected parameter was 15% lower than the threshold, 1 mm (the quarter of the maximum daily $ET_c$) of irrigation was applied on this date.
- When the average value was 15-30% lower than the threshold, 2 mm (the half of the maximum daily $ET_c$) of irrigation was applied on this date.
- When the average value was 30% lower than the threshold, 4 mm (the maximum average daily $ET_c$) of irrigation was applied on this date.

As an example, TGR data and irrigation event of Control and RDI-2 treatments (from day of the year (DOY) 232 until DOY 252) during part of the recovery period of the 2009 season is presented (Fig. 1). The period of recovery started at DOY 236, previous to this date Control TGR are higher than RDI-2 TGR. In the recovery period, irrigation approach is that both TGR are equivalent, so when RDI-2 TGR is lower than Control TGR, there was an irrigation event (vertical bars) in RDI-2. There was not an immediately response, usually the first event of irrigation reduced the differences but we needed a second irrigation that provided higher TGR values in RDI-2 than in Control. The daily applied water was 4 mm because the difference between TGRs was higher than 30%. Only at DOY 251, when TGR in RDI-2 presented slightly lower values than Control, the irrigation was 1 mm. This figure (Fig. 1) is also a good example of the daily changes in Control TGR. In this treatment, though irrigation was daily, TGR values were very variable, with negative and positive values which were not related to any meteorological data. So, although TGR was the indicator analysed, in order to improve clarity, Maximum daily diameter (MXD) instead of TGR will be presented.

### *2.3. Measurements*

All the measurements were made on the six control trees located in each plot. Trunk diameter fluctuations were measured throughout the experimental periods, using a set of linear variable displacement transducers (LVDT) (model DF±2.5 mm, accuracy ±10 μm, 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 10 s and the datalogger (model CR10X with AM 416 multiplexer, Campbell Sci. Ltd., Logan, USA) was programmed to report 15 min means. Maximum daily shrinkage (MDS) and trunk growth rate (TGR) were calculated from the daily curves as described above.

The water status of trees for each treatment was characterised by the midday stem water potential and maximum leaf conductance. 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). The daily cycle of olive leaf conductance has a maximum value during the morning with a sharp decrease until midday when a constant minimum value is reached until mid-afternoon (Moriana et al., 2002). Abaxial leaf conductance was measured around 10 a.m. in order to estimate the maximum daily value in two fully expanded sunny leaves per tree with a steady state porometer (LICOR 1600, Lincoln, Nebraska, U.S.A).

At the beginning of each season ten shoots per tree, in the six trees where trunk diameter fluctuations were measured in each treatment, were selected randomly. For each shoot the length, number of inflorescences and fruits were measured periodically. The fruit volume was estimated from a survey of ten fruits per tree in the same trees where trunk diameter fluctuations were measured. Two measurements were made for each fruit: the longitudinal dimension and the transversal (at the equatorial point) dimension. The pattern of the longitudinal dimension indicated the beginning of the massive pit hardening when the rate of growth of this measurement changed (Gijón et al., 2010). At the end of each season, the marked shoots were cut and leaf area was measured. Leaf area was measured with an area meter (LICOR 3100, Lincoln, Nebraska, U.S.A). Vegetative growth (shoot length and leaf area) was measured only in 2009 and 2010 seasons.

Soil moisture was measured with a portable FDR sensor (HH2, Delta-T, U.K.) with a calibration obtained in previous works. The measurements were made in three plots per treatment. The access tubes for the FDR sensor were placed in the irrigation line around 30 cm from an emitter (Fernández et al., 1991). The data were obtained at 1 m depth with a 10 cm interval.

The irrigation treatments were also evaluated form the point of view of quantity and quality of yield. In table olives the quality of fruit is related to two parameters; the pulp-stone ratio (PS ratio) and the fruit size. High values of PS ratio are considered an indicator of better quality fruits. The pulp stone ratio was measured by the fresh weight of 18 fruits per treatment. The fruit size was estimated in 6 trees per treatment with the number of fruits per kilogram.

The data were subjected to one-way ANOVA and the mean separation was made via a Tukey's test. The probability levels for significant differences were at $P<0.05$. The number of samples measured is specified in the text and figures.

## 3. Results

The meteorological data are the common for the Mediterranean climate (Table 1 and Fig. 2). The variations in $ET_o$ between the phenological phases are related to the duration of each one. The phase of rehydration (phase III, Table 1) was the shortest and usually took around one month. The rain was concentrated in winter and spring (Table 1, phase I and postharvest, Fig. 2). However, in two of the three seasons considered (2009 and 2010) the total amount of rain was higher than the average of the last 40 years (681 and 1032 mm, respectively vs 550 mm). Applied water in the deficit treatments was reduced by more than 80% compared to the Control treatment (Table 1 and Fig. 2). Control trees were continuously irrigated along the season (Fig. 2) in order to obtain an over-irrigated treatment. The applied water in RDI treatments was greater in phase I and, especially, in phase III (Table 1 and Fig. 2). The low amount of applied water during phase I of 2008 season in RDI treatments (Fig. 2) was produced for several days of rains in which irrigation was not scheduled. In addition, RDI-2 treatment showed a clear differentiation of the irrigation during phase II between the high (2008 and 2010) and low (2009) fruit load seasons.

Significant differences were found in soil water storage in the profile (0-1 m depth) during the three experimental seasons between Control and deficit irrigation treatments, but not between the two RDI treatments (Fig. 3). Although the values obtained in the RDI treatments were clearly lower than in Control, the differences were significant only on some days (Fig. 3) mainly during phase II (massive pit hardening period). Soil moisture in RDI treatments decreased sharply from the beginning of the period of massive pit hardening and increased during the recovery period.

The pattern of irrigation affected the distribution of soil moisture in the profile. Soil moisture (θ) data at 1 m. depth are shown for Control and RDI-12, as an example, on three different dates for the 2010 season (Fig. 4, a similar pattern was found in the rest of season). Significant ($p<0.05$) lower values of θ were found only in the first 0.3 m. at DOY (day of the year) 143 (Fig. 4a) and 228 (Fig. 4b) but only at a depth of 0.2 and 0.3 m at DOY 244 (Fig. 4c). During the pit hardening phase, the highest decreases in θ were measured in the first 0.3 m, but there was a clear decreasing trend in the entire soil profile.

During the three years, midday stem water potential values (SWP) in Control treatment decreased from the beginning until mid-summer (around DOY 210), this fall was sharper during the 2008 season with a minimum value around -2 MPa (Fig. 5). There were no significant differences between RDI treatments during the three experimental seasons. The main differences in SWP between RDIs and Control occurred mainly after massive pit hardening started and were significant ($p<0.05$) only in the 2008 and 2009 seasons, though a clear trend of lower values was found for RDI treatments also in 2010. The lack of significant differences in 2010 between Control and RDI treatments were probably due to the high rainfall recorded in this year (Table 1).

The SWP values were almost similar at the end of the recovery period, without significant differences, in the 2008 and 2009 seasons. The lack of recovery during the 2010 season was likely related to problems with irrigation (pump was not working suitably) in this period.

The pattern of maximum leaf conductance was clearly different between seasons (Fig. 6), with higher values during the years of high fruit load (2008, Fig. 6a and 2010, Fig. 6c) than in the year with low fruit load (Fig. 6b, 2009). No significant differences were found between RDI treatments. The most significant differences in all the years between Control and RDI treatments were found in Phase II. Only in the 2010 season no significant differences were found (Fig. 6c). The values of RDI-12 treatment were significantly lower than Control for most of the time in Phase II in 2008 (Fig. 6a) and 2009 (Fig. 6b) seasons. The data of RDI-2 tended to give lower values than Control in phase II, but such differences were not always significant.

Trunk growth rate (TGR) was used in the irrigation scheduling of RDI treatments in phases I and III. The differences between RDI treatments were not significant in any of the seasons. TGR values were very different according to the phenological stage and fruit load (graph slopes in Fig. 7 and Table 2). In all the seasons during the phase I, Control and RDIs trees presented a positive TGR (Fig. 7 and Table 2), except for RDI-12 in the driest season (2008, Fig. 7a). In this phase, significant differences were found only at the end of the period (Fig. 7) and, therefore, the average values were similar in most of the seasons (Table 2). The greater TGR in RDI-12 than in Control and RDI1 during the 2010 season (Fig. 7c and Table 2) was related to substantial rainfall.

The significant differences of TGR between Control and RDI treatments occurred, in all the seasons, mainly during phase II (Fig. 7). In a few days of phase I, TGR of RDI-2 was lower than Control but with low amount of water (Table 1) the average was similar (Table 2). During phase I, TGR values of RDI-12 was more affected for rains which produces a greater increase than in the other treatments (Fig 7). The greater differences of TGR in phase I between RDI-12 and Control in 2008 (Table 2) was also due to rains since in these days irrigation was not scheduling. During phase II and in seasons of high fruit load TGR in Control trees were slightly below 0 (2008 and 2010, Fig. 7a and c, Table 2), while it was positive in the low fruit load season (2009, Fig. 7b, Table 2). During this phase in RDI treatments, TGR decreased in 2008 and 2009 compared with Control (Fig. 7 a and b, Table 2). These differences were lower during 2010.

In the recovery phase, significant differences in TGR, between Control and RDI treatments, were found only at the beginning of this phase (Fig. 7), so the average values were similar in all years (Table 2). The average TGR in this phase was positive and higher than during pit hardening (Fig. 7 and Table 2). The problem with the irrigation system during the 2010 season produced no clear differences in TGR between this period and pit hardening as in the other seasons.

The MDS signal in RDI-2 was similar in the three seasons and only a few values significantly different from 1 were found (Fig. 8). During phase I, the MDS signal in this treatment was near 1, with a sharp increase at the end of this phase. However, during phase II, MDS signal decreased progressively until values below 1 and near to the threshold value (0.75). The MDS signal values reached the threshold (0.75) faster in high fruit load seasons (2008 and 2010) than in low fruit load season. Such differences produced that the amount of irrigation were higher in high than in low fruit load season during phase II (Table 1). The amount of applied water in phase II during high fruit load season was enough to maintain the MDS signal value near to the threshold (average signal 0.88 in 2008 and 0.82 in 2010).

On the other hand, the seasonal pattern of the MDS signal in RDI-12 was similar to RDI-2 during 2008 (Fig 7a) but very different in the 2009 and 2010 seasons (Fig 7b and c). The RDI-12 signals of 2009 and 2010 were significantly higher than 1 on most of the dates. Therefore, the amount of applied water during phase II was strongly reduced in all the seasons because MDS signal was very different to the threshold value (0.5).

Data for shoot length during the 2009 (Fig. 9a) was similar in the pattern to the rest of the seasons, but with longer period and greater growth in this low fruit load season than in the high ones (data not shown). Shoot growth in 2009 occurred even during pit hardening in all the treatments (Fig. 9a). In Control and RDI-2 shoots grew until the end of August (DOY 240) while in RDI-12 growth stopped around DOY 200. The shoot length was significantly greater in RDI-12 than Control and RDI-2, the same trend, though without significant differences, were found in 2010 (data not shown). Such differences were permanent during all the season with RDI-2. Control treatment was not significantly lower than RDI-12 from DOY 200. The foliar area of the marked shoots was measured only in 2009 and 2010 and data are presented in Table 3. The leaf area per shoot was clearly different between the low (2009) and high (2010) fruit load (Table 3). Significant differences were found only in the 2009 season when RDI-2 was lower than Control and RDI-12. Although the data from the 2010 season were not significantly different, this trend - lower leaf area in RDI-2 than in the rest - was repeated.

The number of inflorescences in the marked shoots present significant differences between treatments in the low fruit load season (Fig. 9b) but not in the high ones (data not show). Data for number of inflorescence during the 2009 (Fig. 9b) was similar in the pattern to the rest of the seasons. In all the seasons and treatments the number of inflorescences decreased from full bloom until the beginning of pit hardening with a reduction of around 50%. Such reductions were similar in all the treatments and fruit loads. In 2009 season, at full bloom, Control trees exhibit a significantly higher number of inflorescences per shoot than the RDI treatments (Fig. 9b). The low average values at this season in all the treatments were likely related with the strong alternate bearing of the orchard. The number of fruits per inflorescence at the end of the season was not significantly different between irrigation treatments in any of the seasons (Table 3). However, RDI-2 tended to produce lower values than Control in 2009 (low fruit load season) with 50% fewer fruits per inflorescence. The reduction compared to Control was also clear, though not significant, in RDI-12 in 2008 and 2009.

The pattern of fruit volume was similar during the three seasons with a continuous increase in all the treatments (Fig. 10). In the high fruit load seasons (Fig. 10a and c) the fruit tended to be smaller than in the low fruit load season (Fig. 10b). Significant differences between treatments were found throughout the seasons in the three years of the experiment. During 2008 and 2010, the high fruit load seasons, the differences in fruit volume between Control and RDI treatments were the highest at harvest, being 14% and 20% higher in Control than in RDI-2 and RDI-12 respectively (Figs. 10a and 10b). However, in the low fruit load season (2009, Fig. 10b) the differences were lower than 10% and only significant between RDI-12 and the other two treatments. Fruit growth was stopped in RDI-2 in 2010 (Fig. 10c, from DOY 206 to 214) and in RDI-12 in 2008 and 2010 (Fig. 10a, around DOY 234; Fig. 10c from DOY 206 to 221). The fruit growth rate was affected from pit hardening in both RDI treatments, except in RDI-2 during the 2009 season (Fig. 10b). The Control fruit growth rate, from the beginning of pit hardening until harvest, varied from 0.020 (2008) to 0.036 (2009 and 2010) $mm^3$ $day^{-1}$ while in RDI-2 were 0.014 (2008), 0.035 (2009) and 0.030 (2010) $mm^3$ $day^{-1}$ and in RDI-12 were 0.015 (2008), 0.030 (2009) and 0.027 (2010) $mm^3$ $day^{-1}$.

There was a substantial alternate bearing between the high fruit load seasons (2008 and 2010) with an average of 16.5 metric tons per hectare (MT $ha^{-1}$) in Control trees and the low fruit load season (2009) with 2.3 MT $ha^{-1}$ (around 15% of the high fruit load year, Table 4). This alternate cycle was also clear and more pronounced in the RDI treatments with 18.0 vs 1.4 MT $ha^{-1}$ in RDI-2 (8% of the high fruit load years) and 14.2 vs 0.8 MT $ha^{-1}$ in RDI-12 (6% of the high fruit load year). Although no significant differences in yield were found, RDI-12 tended to produce lower values than Control or RDI-2 in all the seasons. The reductions in yield in RDI-12 compared to Control were 20% (2008), 65% (2009) and 7% (2010). While in RDI-2 such reductions were 8% (2008) and 39% (2009), and higher yield than Control (28%) in the 2010 season (Table 4).

PS ratio was lower in RDI-2 than Control in all the seasons, significantly so in 2009 and 2010. Such reductions were not significant between RDI-12 and Control, though values tended to be lower. During the low fruit load season (2009), PS ratio sharply increased compared to high fruit load season (2008 and 2010) in Control and

RDI-12 but it did not in RDI-2. Fruit size is also an important parameter in table olives. No significant differences in the number of fruits per kilogram were found between treatments in any of the seasons (Table 4). During the 2008 season, the fruits were the smallest in comparison to the other years.

## 4. Discussion

Trunk diameter fluctuation indicators scheduled a regulated deficit irrigation. The scheduling presented two main problems: the reference trees and the pattern of the parameters in relation to the threshold values. Reference trees (Goldhamer and Fereres, 2001) are the unique methodology to schedule irrigation with these indicators when no baseline and/or threshold values are available. Over-irrigated trees are, clearly, a not sustainable strategy in the long term because the growth of these trees will be greater than the rest of the orchard and, at the end, it will be not comparable. However, in a three years experiment it should have been appropriate. Only during 2008 season reference trees presented a problem to the irrigation scheduling. The great yield of Control trees produced a lower SWP with minimum values around -2.0 MPa (the lowest of the three years, Fig. 5) though the soil moisture and leaf conductance were permanently high (Figs. 3 and 6). Great yields affect water relations of olive trees, even in conditions of no water stress (Martín-Vertedor et al, 2011). This decrease of SWP likely produced the decrease of TGR in Control. In the case, that the scheduling would have been related with TGR in this phase the water stress level would be higher. In our case, since MDS signal was the selected parameter water stress was according to the ones predetermined.

The other problem is to control the values of TGR and MDS signal around the thresholds selected. The values obtained in MDS signal in RDI-2 were near to the ones expected (Fig. 8). Only in 2009 seasons these values were delay to the end of the phase II which is likely related with the low yield (Martín-Vertedor et al, 2011) as also showed SWP and leaf conductance (Figs. 5 and 6). However, the systematically higher values of the MDS signal in RDI-12 compared to RDI-2 in the 2009 and 2010 seasons limits the use of this parameter. Then the estimation of MDS signal baselines should calculate each season and even with each plot with different irrigation conditions. Such respond are likely related to an adaptation of the trees. Genard et al. (2001) suggested that trunk diameter fluctuations are related to several physiological responses of the trees. Drought adaptation, such as variation in hydraulic efficiency or variations in xylem growth, has been suggested in olive trees (Tognetti et al., 2009; López-Bernal et al. 2010) and in other deciduous trees (Fereres and Goldhamer, 1990; Drew et al., 2011) which were grown in continuous deficit irrigation conditions.

Yields were not significantly different between treatments though RDI-12 tended clearly to lower values (cumulative values (all years together) were 35.6 MT ha$^{-1}$ (Control) and 37.4 MT ha$^{-1}$ (RDI-2) 29.3 MT ha$^{-1}$). The reduction in yield in RDI-12 was likely related to several factors, such as the number of fruits per inflorescence and fruit volume. The values of SWP in the deficit treatments in the present work are lower than those suggested for olive trees (Dell'Amico et al., 2012; Moriana et al., 2012), but the level and the duration of the period of water stress was probably not severe enough to reduce yield in RDI-2. This moderate water stress is probably related to the high rains in the 2009 and 2010 seasons (Table 1), the high holding capacity of the soil and the low crown volume of the trees, common in this region of Spain (García-Ortiz et al.

1997). The results in the literature suggest that if the water stress during phase II is neither too severe (Goldhamer et al., 1999) nor too long (Moriana et al., 2003; Iniesta et al. 2009; Caruso et al., 2013) there is a not clear reduction in yield. The yield reductions traditionally are associated with lower tree growth (Caruso et al., 2013). But shoot growth was not reduced in RDI-12 and, apparently, was enough to obtain a great yield in RDI-2 in 2010. Such conditions of water stress during the phase II in TGR average can be identified with values between 0 and -5 μm day$^{-1}$. However, there are no clear reference values obtained from the MDS signal because of the variations in RDI-12 discussed above.

Therefore, at this level of water stress TGR seems to be the most useful indicator for irrigation scheduling. The seasonal pattern of this parameter in Control trees changed with the fruit load. TGR was almost nil when massive pit hardening started during a high fruit load season (Fig. 7), results consistent with those found in the literature (Moriana et al 2003; Moriana and Fereres, 2004; Pérez-López et al., 2008). During the low fruit load season, no variations in the TGR average were found from the beginning of the measurements until mid-summer (around the end of July and beginning of August) when a sharp increase began (Fig. 7). Similar patterns were reported in olives (Moriana et al, 2003; Moriana and Fereres, 2004; Pérez-López et al., 2008). These changes in the seasonal pattern are not a limitation for the use of this indicator in irrigation scheduling.

The management of a threshold value in TGR would be suitable only during phase II and phase III when a slightly shrinkage of the trunk (-5 μm day$^{-1}$), according to our results, will be required. This value will be a threshold to irrigate but the respond of deficits trees to irrigation with great increase in TGR (Fig. 7) likely produced that the average TGR value will be greater (Table 2). On the other hand, during periods of active growth, especially in phase I the management of TGR in irrigation scheduling without a baseline is not clear. In the present study no robust relationships were found between TGR and environmental variables (data not shown). If absolute values of TGR, according only to the phenological stage, are used for irrigation scheduling, the variability of this parameter found in the literature (Moriana and Fereres, 2004; Pérez-López et al., 2008; Tognetti et al., 2009) indicates that there is not a reliable threshold, yet in this period.

## 5. Conclusions

Deficit irrigation has been scheduled satisfactorily with trunk diameter fluctuation parameters. Using only the data obtained in the TGR and MDS signal, deficit and recovery periods were successfully performed. The pattern of TGR was similar to the SWP. The MDS signal change between deficit treatments is likely due to drought adaptation responses. Therefore, TGR seems to be more reliable indicator than MDS.

The TGR seasonal pattern changed with the beginning of massive pit hardening when there was a significant yield on the tree. Before massive pit hardening TGR values were similar in all treatments, regardless of fruit load. In the massive pit hardening phase (phase II), a moderate water stress condition is indicated by a negative TGR (around -5 $\mu m\ day^{-1}$). This level of water stress, in this phenological phase, did not affect or reduce the yield. However, all these recommendations are likely related to the local conditions and it is not clear whether they may be extrapolated to other orchards with different conditions.

Moderate water stress conditions did not affect clearly shoot growth, probably due to growth occurred during phase I (with mild or not water stress conditions) and to the high variability of the measurements. However, fruit numbers per inflorescence and the pattern of fruit growth was affected in the most stressed treatments. The effect on the yield was not significant but the trends suggest an accumulative effect related to a reduction in fruit numbers and fruit volume in the least irrigated trees.

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**Figure captions**

Fig. 1. Pattern of TGR during the recovery period of 2009 season (DOY 232-252). Only data of Control (■) and RDI-2 (□) is shown as example of response in TGR to the irrigation. Vertical line represents the beginning of the recovery period. Vertical bars represent the irrigation events. No rains were recorded in this period of time. In the bottom of the graph maximum daily temperature (solid line) and reference evapotranspiration (dash line) is presented.

Fig. 2. Pattern of applied water and distribution of rain during the irrigation period in 2008 (a), 2009 (b), 2010 (c) seasons in Control (■), RDI-2 (□) and RDI-12 (▲) treatments.

Fig. 3. Pattern of total soil moisture data during the 2008 (a), 2009 (b) and 2010 (c) seasons in Control (■), RDI-2 (□) and RDI-12 (▲) treatments. Each symbol is the average of 3 replicates. Vertical bars represented standard error. Soil moisture was measured every 0.1 m from 0.1 to 1 m depth. Vertical lines and “pit hard” indicate the phase of the massive pit hardening. Asterisks in the bottom indicate significant differences (Tukey’s test; $p<0.05$) between treatments.

Fig. 4. Soil moisture distribution in 1 m depth in DOY 143 (beginning of the experiment, a), 228 (at the end of the pit hardening, b) and 244 (in the recovery period, c) of 2010 season in Control (■) and RDI-12 (▲). Each symbol is the average of 3 measurements. Horizontal bars represented standard error. Soil moisture was measured

every 0.1 m from 0.1 to 1 m depth. Asterisks in the right indicate significant differences (Tukey's test; $p<0.05$) between treatments.

Fig. 5. Pattern of midday stem water potential (SWP) during 2008 (a), 2009 (b), 2010 (c) seasons in Control (■), RDI-2 (□) and RDI-12 (▲) treatments. Each symbol is the average of 6 measurements. Vertical lines indicated the beginning of the massive pit hardening (left) and the beginning of the recovery period (right). Asterisks in the bottom indicate significant differences (Tukey's test; $p<0.05$) between Control and RDI treatments at that date. No significant differences between RDI treatments were found.

Fig. 6. Pattern of maximum leaf conductance during 2008 (a), 2009 (b), 2010 (c) seasons in Control (■), RDI-2 (□) and RDI-12 (▲) treatments. Each symbol is the average of 12 measurements. Vertical lines indicated the beginning of the massive pit hardening (left) and the beginning of the recovery period (right). Asterisks in the bottom indicate significant differences (Tukey's test; $p<0.05$) between Control and RDI treatments at that date. No significant differences were found between RDI treatments.

Fig. 7. Pattern of maximum daily diameter during 2008 (a), 2009 (b), 2010 (c) seasons in Control (——), RDI-2 (— —) and RDI-12 (…..) treatments. Each symbol is the average of 6 measurements. Vertical lines indicated the beginning of the massive pit hardening (left) and the beginning of the recovery period (right). Asterisks in the bottom indicate significant lower values ($p<0.05$, Tukey) in the TGR between RDI1 and Control treatment. Crosses in the bottom indicate significant lower values (Tukey's test;

$p<0.05$) in the TGR between RDI-12 and Control treatment. TGR is the slope of the graphs of this figure (see Table 2 for average values of TGR).

Fig. 8. Pattern of Maximum daily shrinkage (MDS) signal during 2008 (a), 2009 (b), 2010 (c) seasons in RDI-2 (□) and RDI-12 (▲) treatments. Each symbol is the average of 6 measurements. Vertical lines indicated the beginning of the massive pit hardening (left) and the beginning of the recovery period (right). Asterisks in the bottom indicate significant differences (Tukey's test;$p<0.05$) between RDI 2 and Control treatments (up starts) and between RDI-12 and Control treatment (bottom starts) at that date.

Fig.9. Pattern of shoot growth (a) and the number of inflorescences (b) in marked shoot during 2009 in Control (■), RDI-2 (□) and RDI-12 (▲) treatments. Each symbol is the average of 60 measurements. Vertical bars represented standard error. Vertical lines indicated the beginning of the massive pit hardening (left) and the beginning of the recovery period (right). Asterisks in the graphs indicate significant differences (Tukey's test;$p<0.05$) between treatments at that date.

Fig. 10. Pattern of the fruit volume during 2008 (a), 2009 (b), 2010 (c) seasons in Control (■), RDI-2 (□) and RDI-12 (▲) treatments. Each symbol is the average of 60 measurements. Vertical bars represented standard error and are presented when symbol is smaller. Vertical lines indicated the beginning of the massive pit hardening (left) and the beginning of the recovery period (right). Asterisks in the graphs indicate significant differences (Tukey's test; $p<0.05$) between treatments at that date.

Table 1. Irrigation and climatic data during the three seasons of the experiment. The irrigation amount is presented as total applied water and the distribution according to the phenological phase. In the climatic data also seasonal reference evapotranspiration (ETo), rain and the distribution along the irrigation season of both variables are presented. * In brackets the total length of each phenological phase. **In brackets are ETo and rain from the beginning of irrigation during phase I

| | | Irrigation (mm) | | | $ET_o$ (mm) | Rain (mm) |
|---|---|---|---|---|---|---|
| | | Control | RDI 2 | RDI 12 | | |
| 2008 | Phs. I (125)* | 197 | 10 | 5 | 525 (259)** | 330 (38)** |
| | Phs. II (67)* | 274 | 56 | 0 | 452 | 11 |
| | Phs. III (36)* | 106 | 42 | 26 | 141 | 61 |
| | Posthar. | 42 | 11 | 14 | 160 | 146 |
| | Total | 619 | 119 | 45 | 1278 | 548 |
| 2009 | Phs. I (122)* | 159 | 38 | 1 | 528(206)** | 242 (4)** |
| | Phs. II (67)* | 292 | 7 | 1 | 453 | 0 |
| | Phs. III (45)* | 134 | 65 | 61 | 195 | 14 |
| | Posthar. | 0 | 0 | 0 | 154 | 425 |
| | Total | 585 | 110 | 63 | 1330 | 681 |
| 2010 | Phs. I (120)* | 190 | 63 | 6 | 544 (237)** | 610 (37)** |
| | Phs. II (69)* | 394 | 57 | 9 | 478 | 13 |
| | Phs. III (30)* | 126 | 40 | 23 | 135 | 4 |
| | Posthar. | 0 | 0 | 0 | 233 | 405 |
| | Total | 710 | 160 | 38 | 1390 | 1032 |

Table 2. Average trunk growth rate (TGR) and mean standard error in each phenological phase of the three seasons. Note that these values are the slope average of the Fig. 7.

| | | TGR (μm day$^{-1}$) | | |
|---|---|---|---|---|
| | | Control | RDI 2 | RDI 12 |
| | Phs. I | 7.0±11.4 | 3.4±12.2 | -6.2±13.3 |
| 2008 | Phs. II | -5.2±20.0 | -14.8±13.9 | -19.5±8.7 |
| | Phs. III | 14.2±25.1 | 20.8±24.8 | 28.8±25.4 |
| | Phs. I | 12.7±8.0 | 14.7±11.7 | 13.5±11.7 |
| 2009 | Phs II | 16.6±24.5 | 2.9±22.9 | 1.7±25.0 |
| | Phs III | 28.8±8.4 | 26.1±16.8 | 26.3±11.6 |
| | Phs. I | 14.8±9.0 | 14.6±12.6 | 22.7±15.8 |
| 2010 | Phs. II | -2.6±8.9 | -5.3±13.2 | -3.0±19.5 |
| | Phs. III | -3.2±6.2 | -4.9±10.8 | -1.7±12.0 |

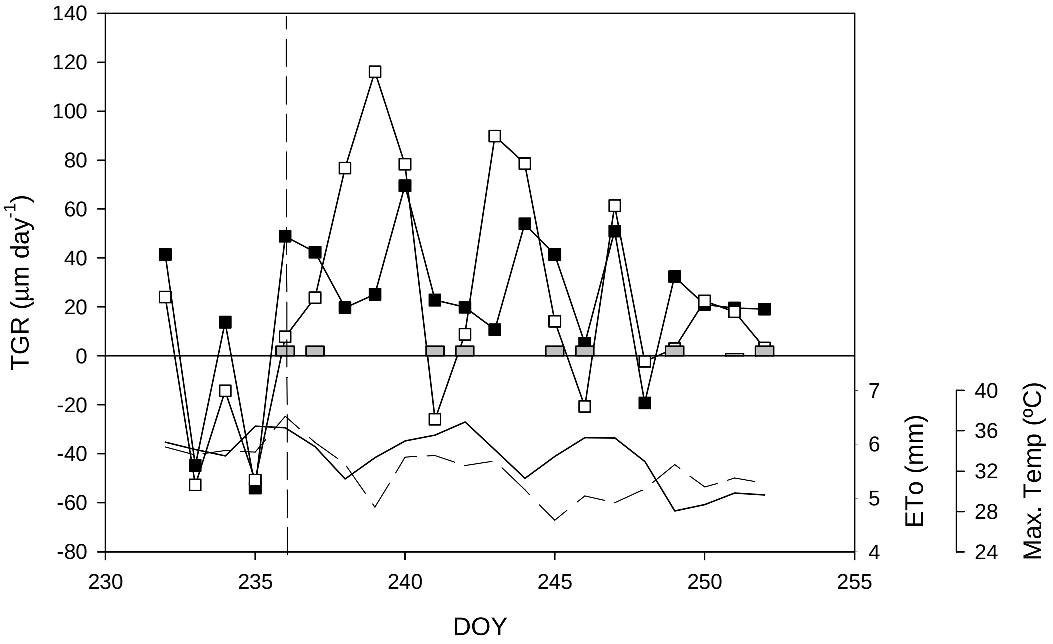
Table 3. Leaf area and number of fruit per inflorescence in marked shoots during the three years of the season. Different letters in the same column indicate significant differences ($p<0.05$, Tukey's Test).

| | Leaf Area ($cm^2$) | | Number Fruit (per inflorescence) | | |
|---|---|---|---|---|---|
| | 2009 | 2010 | 2008 | 2009 | 2010 |
| Control | 67.0±3.5 a | 46.1±4.3 | 1.4±0.1 | 1.6±0.2 | 1.4±0.1 |
| RDI 2 | 55.3±2.7 b | 44.0±2.6 | 1.5±0.1 | 0.9±0.2 | 1.3±0.0 |
| RDI 12 | 69.9±3.2 a | 47.8±2.2 | 1.0±0.2 | 0.8±0.0 | 1.4±0.0 |

Table 4. Yield (metric tons per hectare, MT $ha^{-1}$) and fruits quality at harvest during the three seasons of the experiment. The quality was evaluated with the pulp-stone ratio (PS ratio) and the number of fruit per kilogram of fruit (Fruit $Kg^{-1}$). Yield and the number of fruit per kilogram data are the average of 6 trees, the rate PS is the average of 18 measurements (3 per tree per treatment). Columns with different letter indicate significant differences ($p<0.05$; Tukey Test).

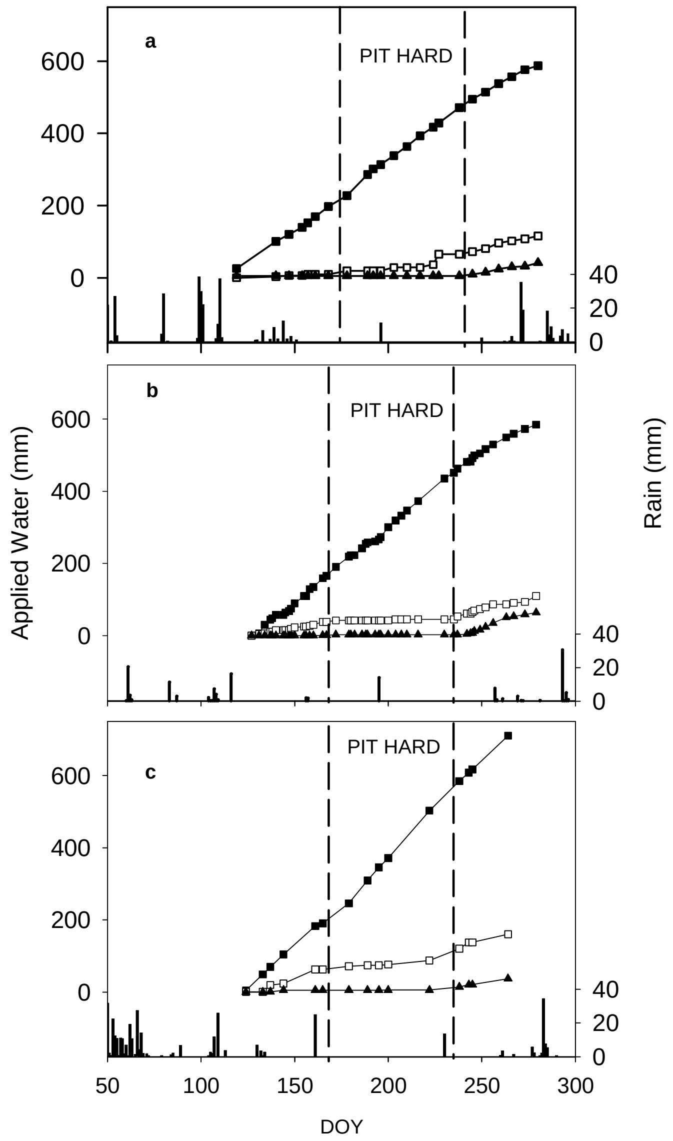
| | 2008 | | | 2009 | | | 2010 | | |
|---|---|---|---|---|---|---|---|---|---|
| | Yield (MT $ha^{-1}$) | PS Ratio | Fruit $Kg^{-1}$ | Yield (MT $ha^{-1}$) | PS Ratio | Fruit $Kg^{-1}$ | Yield (MT $ha^{-1}$) | PS Ratio | Fruit $Kg^{-1}$ |
| Control | 18.3±0.31 | 5.4±0.2 | 308±14 | 2.3±0.51 | 5.7±0.2 ab | 229±14 | 15.0± 1.7 | 4.8±0.14 a | 281±31 |
| RDI-2 | 16.8±1.42 | 4.5±0.4 | 379±29 | 1.4±0.52 | 4.2±0.6 b | 225±10 | 19.2± 2.9 | 4.0±0.12 b | 284±5 |
| RDI-12 | 14.6±2.5 | 4.4±0.4 | 358±22 | 0.8±0.17 | 6.0±0.3 a | 228±3 | 13.9± 1.3 | 4.2±0.11 ab | 288±11 |

**Figure 1**



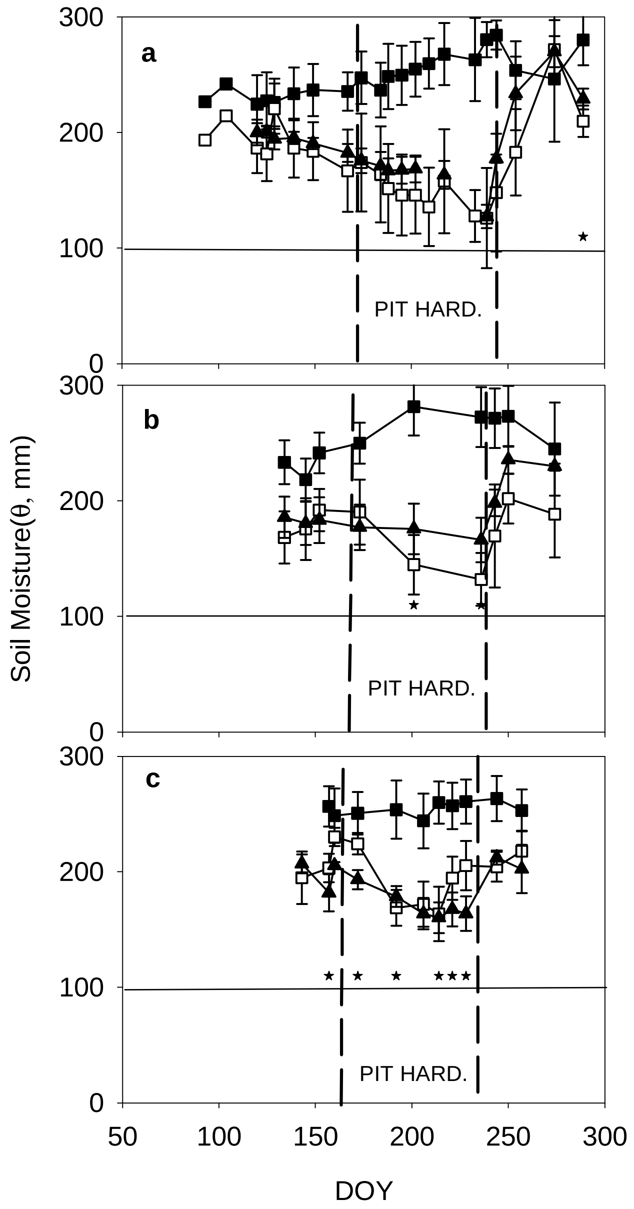
TGR (µm day-1)
140
120
100
80
60
40
20
0
-20
-40
-60
-80
230
235
240
245
250
255
DOY
7
6
5
4
ETo (mm)
40
36
32
28
24
Max. Temp (ºC)

**Figure 2**



a
PIT HARD
600
400
200
0
40
20
0
b
PIT HARD
Applied Water (mm)
Rain (mm)
c
PIT HARD
50
100
150
200
250
300
DOY

Figure 3



a
b
c
PIT HARD.
PIT HARD.
PIT HARD.
Soil Moisture(θ, mm)
DOY
0
100
200
300
50
100
150
200
250
300

**Figure 4**

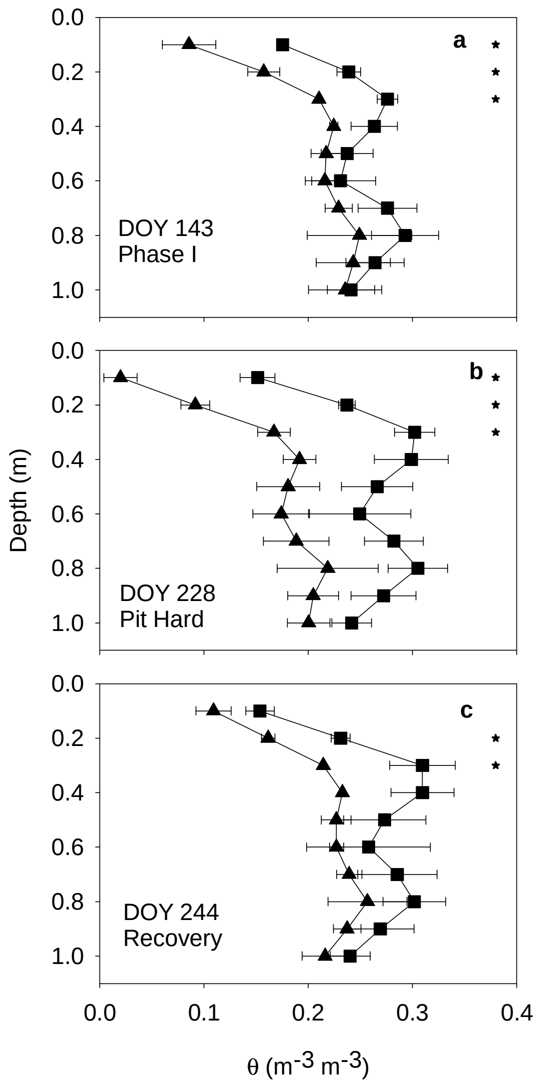
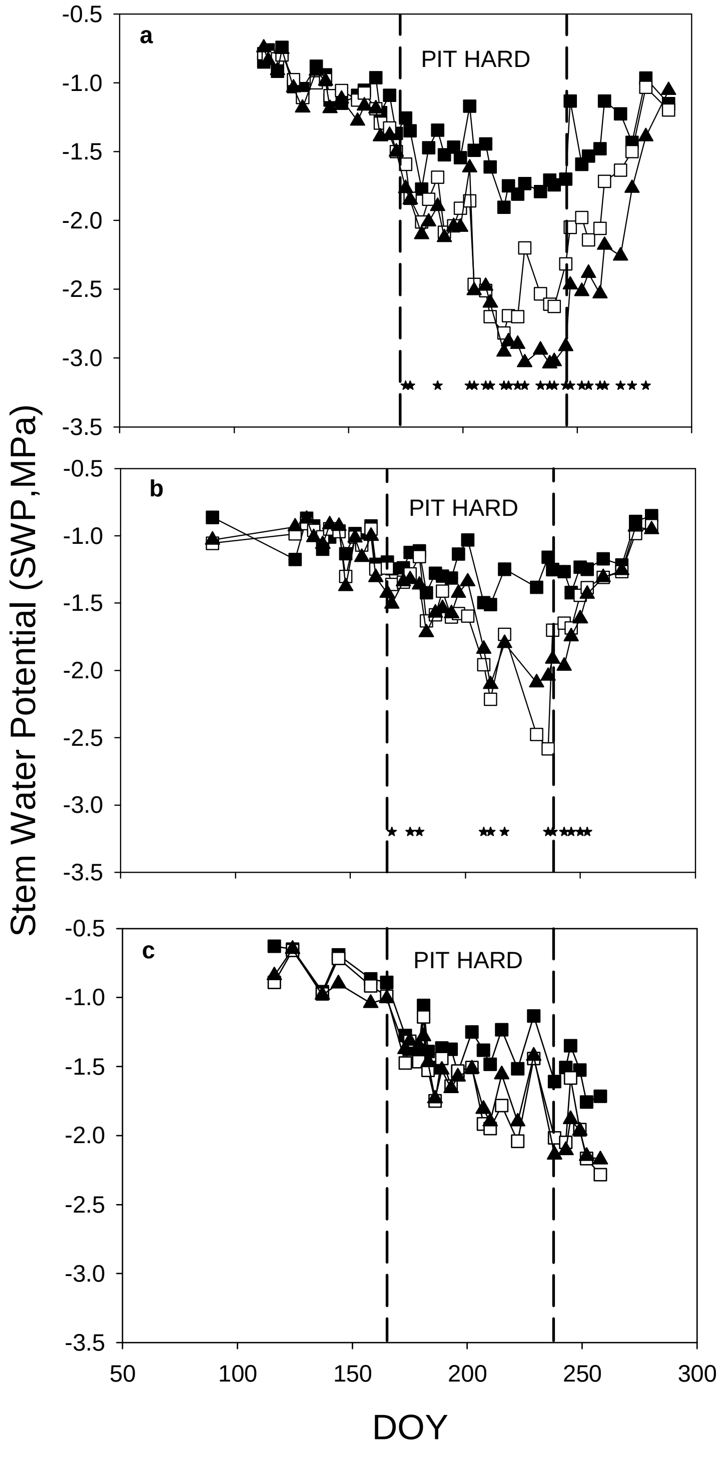
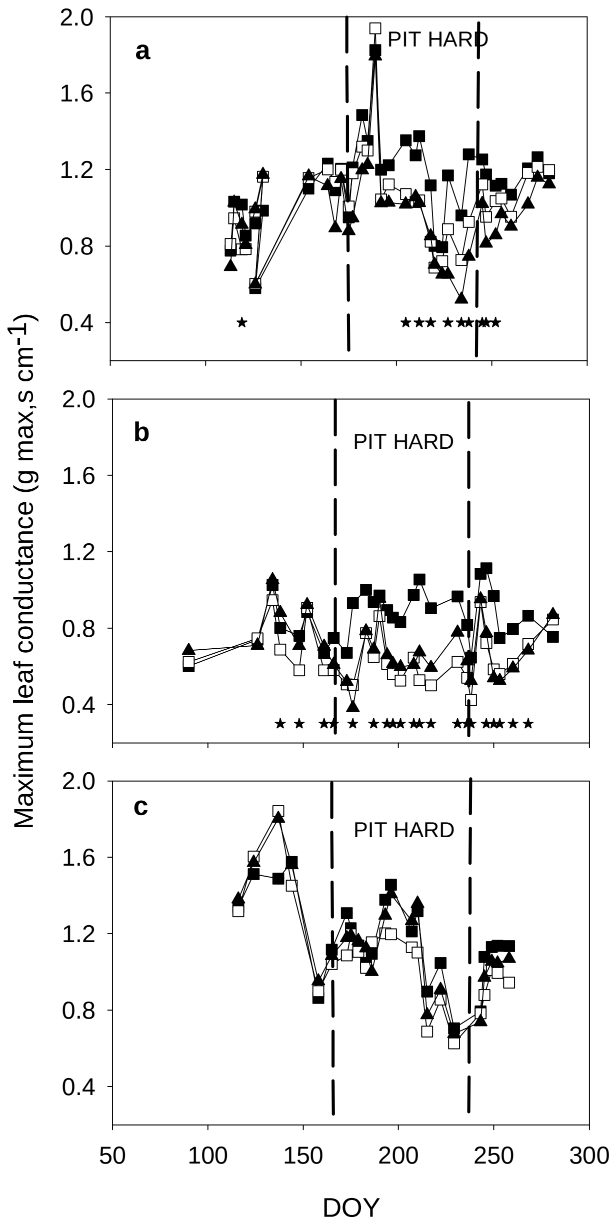

a
DOY 143
Phase I
b
DOY 228
Pit Hard
c
DOY 244
Recovery
Depth (m)
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.1
0.2
0.3
0.4
θ (m-3 m-3)

**Figure 5**



Stem Water Potential (SWP,MPa)
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
-3.5
a
PIT HARD
b
PIT HARD
c
PIT HARD
50
100
150
200
250
300
DOY

**Figure 6**



a
b
c
PIT HARD
PIT HARD
PIT HARD
2.0
1.6
1.2
0.8
0.4
Maximum leaf conductance (g max,s cm-1)
50
100
150
200
250
300
DOY

**Figure 7**

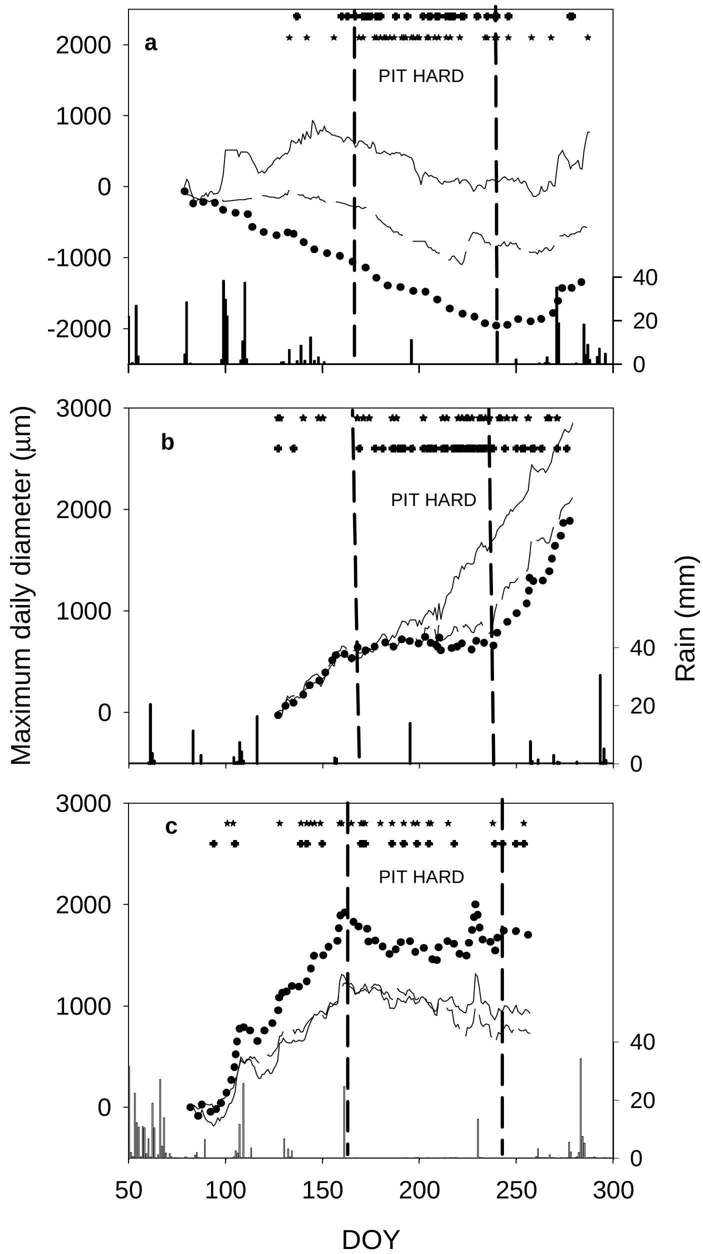
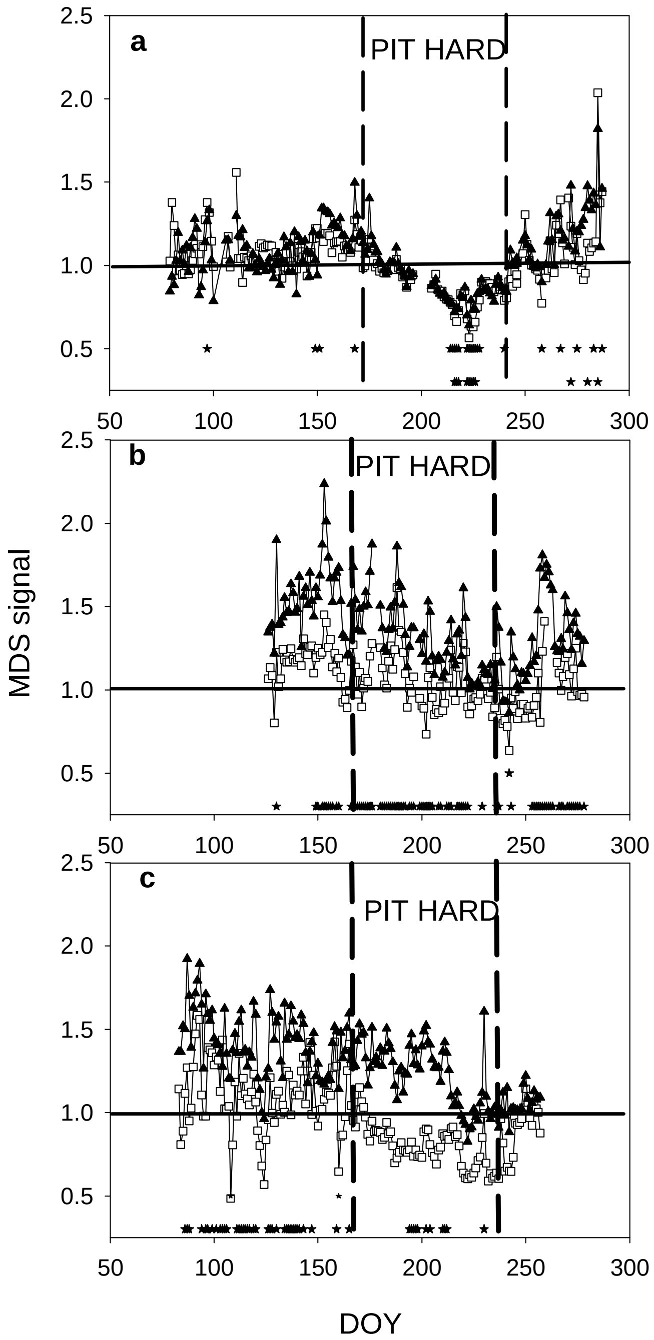
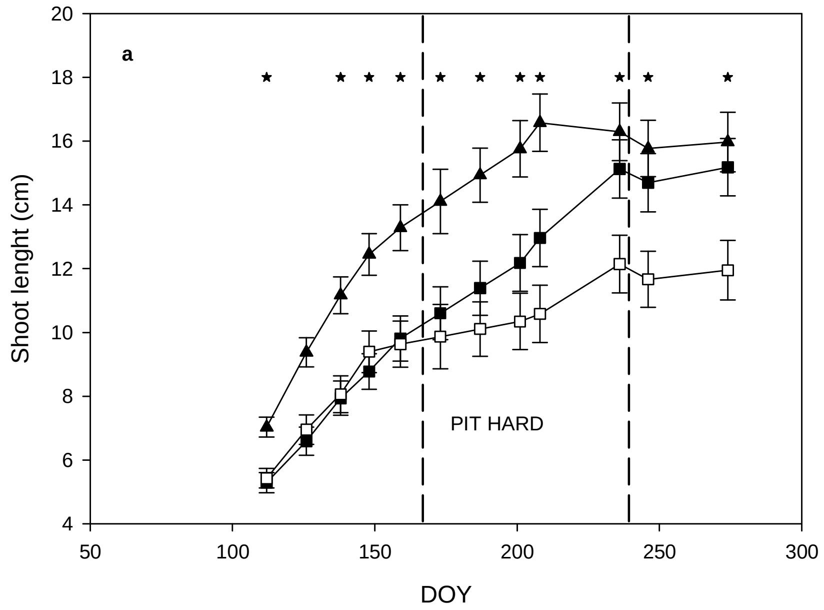

a
b
c
PIT HARD
PIT HARD
PIT HARD
2000
1000
0
-1000
-2000
3000
2000
1000
0
3000
2000
1000
0
40
20
0
40
20
0
40
20
0
50
100
150
200
250
300
DOY
Maximum daily diameter (µm)
Rain (mm)

**Figure 8**

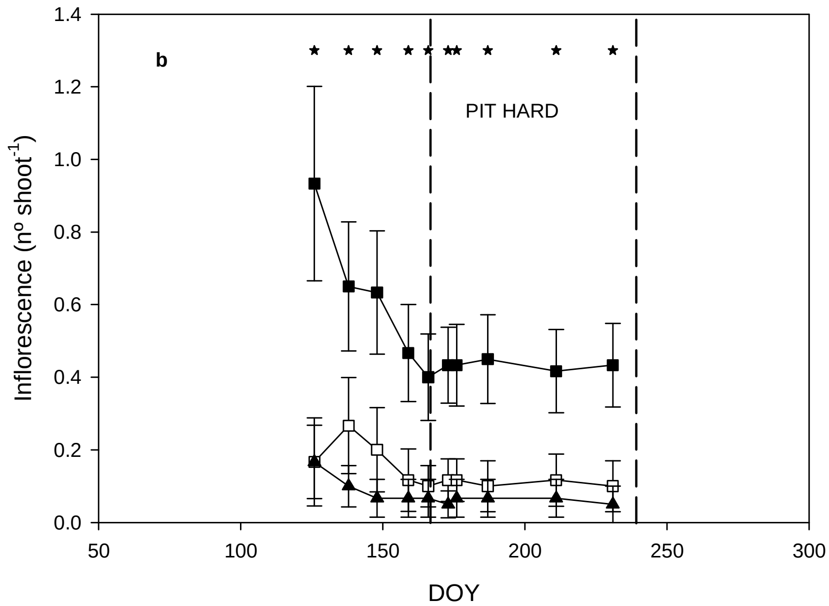


a
b
c
PIT HARD
PIT HARD
PIT HARD
MDS signal
DOY
2.5
2.0
1.5
1.0
0.5
50
100
150
200
250
300

**Figure 9**

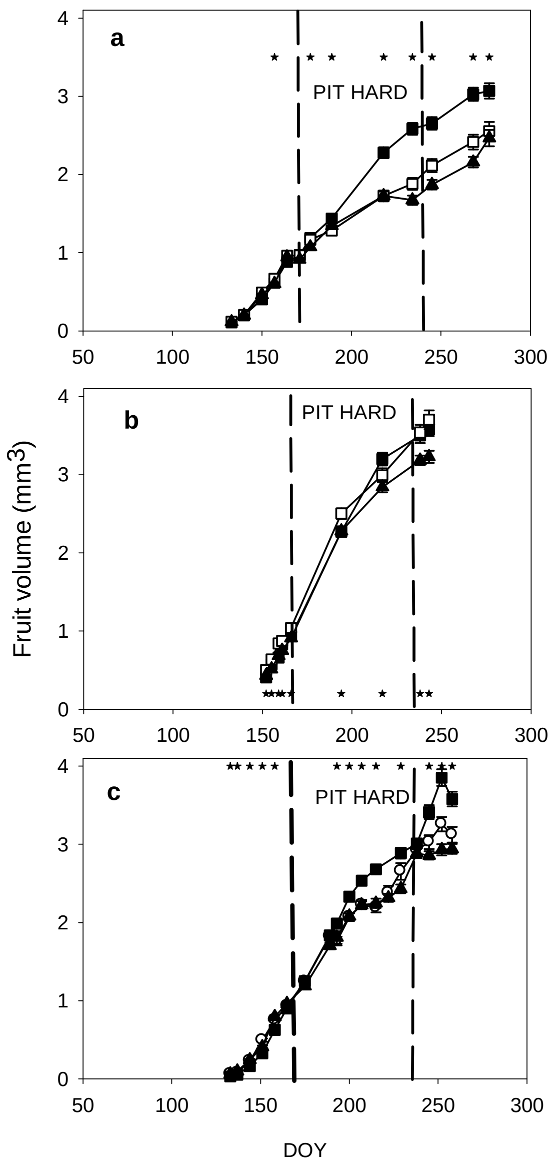


a
Shoot lenght (cm)
DOY
PIT HARD
20
18
16
14
12
10
8
6
4
50
100
150
200
250
300

b
Inflorescence (nº shoot-1)
DOY
PIT HARD
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
50
100
150
200
250
300

**Figure 10**


a
PIT HARD
b
PIT HARD
c
PIT HARD
Fruit volume (mm3)
DOY
0
1
2
3
4
50
100
150
200
250
300