1 **Limitations and usefulness of Maximum Daily Shrinkage (MDS) and trunk growth**

2 **rate (TGR) indicators in the irrigation scheduling of table olive trees.**

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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.

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.

125   The aim of this work is analysed this two source of variations in MDS and TGR

126   indicators. In one way, the present work compares the relationships MDS vs. water

127   potential and MDS signal vs. water potential for three sets of seasonal data in order to

128   study the pattern in moderate water stress conditions. On the other way, the relationship

129   between TGR and meteorological data is analysed.

130

Materials and Methods

Experimental orchard description

133   Experiments were conducted at La Hampa, the experimental farm of the

134   Instituto de Recursos Naturales y Agrobiología (IRNAS-CSIC). This orchard is located

135   in Coria del Río, near Seville (Spain) (37º17''N, 6º3'W, 30 m altitude). The sandy loam

136   soil (about 2m deep) of the experimental site was characterized by a volumetric water

137   content of $0.33m^3\,m^{-3}$ at the saturation point, $0.21m^3\,m^{-3}$ at field capacity and $0.1m^3\,m^{-3}$

138   at the permanent wilting point, and a bulk density of 1.30 (0-10cm) and 1.50 (10-

139   120cm) g cm^{-3}. The experiment was performed on 43-year-old table olive trees (*Olea*

140   *europaea* L cv Manzanillo) from the 2008 to the 2014 seasons. Tree spacing followed a

141   7m x 5m square pattern. Pest control and fertilization practices were those commonly

142   used by the growers and no weeds were allowed to develop within the orchard.

143   Irrigation was carried out during the night by drip, using one lateral pipe per row of

144   trees and five emitters per plant, delivering 8L h^{-1} each. The irrigation requirements

145   were determined according to the daily reference evapotranspiration (ET$_o$) and a crop

146   factor based on the time of year and the percentage of ground area shaded by the tree

147   canopy (Fernández et al., 1997).

148   Maximum daily shrinkage (MDS) study was performed only with data of the

149   seasons from 2011 to 2013. Trunk growth rate (TGR) data were obtained from seasons

150   2008, 2010, 2012, 2013 and 2014 of this orchard and only in 2012 also in a contiguous

151   orchard with the same age and cultivar but 7*7 m spaced. The study of both indicators

152   was performed only in the period of pit hardening.

153

154   *Trunk diameter fluctuation indicators*

155   The maximum daily shrinkage (MDS) was calculated as the difference between the

156   maximum daily diameter and the minimum daily diameter (Goldhamer et al., 1999).

157   Trunk growth rate (TGR) in day "n" was calculated as the difference between the

158   maximum daily diameter of day "n+1" minus that of day "n" (Cuevas et al., 2010).

159   According to Goldhamer and Fereres' approach (2001), the MDS signal was established

160   as the ratio between the value of MDS with a deficit treatment and the estimated MDS

161   with full irrigation. Estimations of the MDS with full irrigation values for each

162   treatment were performed with the data obtained for the last 15 days before the

163   beginning of pit hardening, according to the Corell et al (2013) methodology. In brief,

164   this methodology suggests estimating the seasonal baseline using the relationship

165   between MDS and the maximum temperature of the 15 days previous to pit hardening

166   and assumes that the slope of the equation is the same as the one calculated by Moriana

167   et al (2011). The baseline of each treatment was the linear equation that runs through the

168   average point of the MDS/Maximum temperature data and has a slope of 36 (MDS in

169   μm, Moriana et al 2011). The water potential average data during the period previous to

170   pit hardening are presented in Table 1. No significant differences were measured in each

171   season, though RDI treated trees tended to produce lower values than the Control ones.

172   However, in all cases the midday stem water potential was greater than -1.2MPa, the

173   threshold value suggested for this phenological period in fully irrigated trees (Moriana

174   et al., 2012).

Treatment description

176   Full irrigated Control trees from 2008 to 2014 were used to obtain relationship between

177   TGR and environmental variables. Control trees were irrigated with 100% of crop

178   evapotranspiration (ETc) in order to obtain non-limiting soil water conditions during the

179   entire season. MDS data were obtained from three different irrigation treatments

180   performed from 2011 to 2013 seasons. These regulated deficit irrigation (RDI)

181   treatments considered the phenological stage of the trees in the water stress conditions.

182   The beginning of pit hardening, the most resistant to water stress phenological stage,

183   was determined according to Rapoport et al. (2013) and the recovery phase started in

184   the last week of August (three weeks before harvest). The RDI scheduling was

185   performed according to the trunk diameter variation indicators (Maximum Daily

186   Shrinkage, MDS, and Trunk Growth Rate, TGR). The threshold values used in the

187   present work were selected from previous data (Moriana et al., 2013). The treatments

188   were:

189   • Control. Trees were irrigated with 100% of crop

190   evapotranspiration (ET_c) in order to obtain non-limiting soil water

191   conditions during the entire season.

192   • Regulated deficit irrigation 2 (RDI 2). The objective of

193   this treatment was to create a moderate water stress during the pit

194   hardening and then a slow recovery. Irrigation was scheduled taking into

195   account the maximum daily shrinkage (MDS) and the trunk growth rate

196   (TGR) indicators. Before the period of massive pit hardening (from

197   April to late June) water was supplied only when TGR was lower than

198             $20\mu m\ day^{-1}$. During the pit hardening, irrigation was supplied only when

199   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

225   season, with very high yields in 2008, 2010 and 2014 and almost null in 2011. Only the

226   seasons with significant fruit load that produced a trunk growth stop during pit

227   hardening period were considered for the TGR analysis (2008, 2010, 2012, 2013, 2014).

228   *Measurements*

229   All the measurements were made on six trees used for each treatment. Trunk

230   diameter fluctuations were measured throughout the experiment periods, using a set of

231   linear variable displacement transducers (LVDT) (model DF±2.5mm, accuracy ±10μm,

232   Solartron Metrology, Bognor Regis, UK) attached to the main trunk with a special

233   bracket made of Invar, an alloy of Ni and Fe with a thermal expansion coefficient close

234   to zero (Katerji et al., 1994). Measurements were taken every 10s and the datalogger

235   (model CR10X with AM 416 multiplexer, Campbell Sci. Ltd., Logan, USA) was

236   programmed to report 15 min means.

237   The water status of trees for each treatment was defined by the midday stem

238   water potential. Leaves near the main trunk were covered with aluminium foil at least

239   one hour before measurements were taken. The water potential was measured at midday

240   in one leaf per tree, using the pressure chamber technique (Scholander et al., 1965).

241   Micrometeorological 30 min data, namely air temperature (minimum, maximum

242   and average), solar radiation, relative humidity of air and wind speed at 2 m above the

243   soil surface were collected by an automatic weather station located some 40 m from the

244   experimental site. Daily reference evapotranspiration (ETo) was calculated using the

245   Penman-Monteith equation (Allen et al., 1998). Mean daily vapour pressure deficit

246   (VPDm) was calculated from the mean daily vapour pressure and relative humidity. The

247   daily increment (Δ) of each variable at day "n" was calculated as the difference between

248   the value at the day "n+1" and "n". Linear regression analysis was carried out to explore

249   relationships between variables (TGR and climatic variables). Differences between

250 regression lines were determined with a T-test of the slope and y-intercept. Since no

251 significant relationships were obtained in most of the regressions only the four best

252 results will be presented in other to improve the data clarity.

253

254 **Results**

255 *MDS baseline usefulness*

256 Figure 1 shows the relationship between Ψ and the Maximum Daily Shrinkage (MDS).

257 Ψ ranged from -1.0MPa to -2.6MPa, while MDS varied from 300μm to around 800μm.

258 There was no clear relationship between both indicators, although the trend was a large

259 increase of MDS from the lowest values of Ψ until around -1.6MPa. The same values

260 are represented in Figure 2, but the MDS signal calculated for each treatment was

261 considered instead. The scatter is also high and there was no significant relationship

262 between both indicators. However in Figure 2, there is a reference value in the y-axis.

263 Conditions of full irrigation produce values of the MDS signal around 1. In Figure 2,

264 most of the Control data in the 2012 season (9 of 12) and all of them in 2013 presented

265 an MDS signal lower than 1.1, but in the 2011 season, this only happened in 3 out of 11.

266 Moreover, for all the Control values where Ψ was higher than -1.4MPa, the MDS signal

267 was lower than 1.1 in 2012 and 2013, but only in 2 out of 6 cases in 2011. In RDI

268 treatments, most of the values with a Ψ lower than -1.4MPa presented a MDS signal

269 lower than 1.1 (5 out of 6 values when considering all the seasons).

270 In order to obtain a clearer pattern, data from MDS (Figure 1) were grouped in

271 Ψ intervals (Figure 3). These changes reduced the scatter of the relationship and a

272 clearer curvilinear pattern emerged. Most of the Control data were below 600μm of

273 MDS and there was a progressive increase of MDS with the decrease in Ψ from -

274   1.6MPa. This pattern changed at around -1.8MPa when the maximum MDS was

275   reached. Then, there was also a clear trend for MDS to decrease with Ψ values lower

276   than -2MPa. The lowest Ψ Control values were in the range of 600-800μm, similar

277   values to those from RDI treatments and close to the maximum MDS measured.

278   The data of Figure 2 were grouped in the same Ψ intervals as in the previous

279   Figure. An MDS signal equal to 1 represents a theoretical value of conditions with full

280   irrigation. Figure 4 shows a confidence interval of around 10%, therefore MDS signal

281   values from 0.9 to 1.1 could be included in the group with full irrigation. All the Control

282   data are within the interval 1-1.1 of the MDS signal, though the water potential changed

283   from near -1.4MPa to slightly under -1.8MPa. There is also a clear differentiation

284   between data for 2011 and the rest of seasons. Most of the MDS signal data in this

285   season are above 1.1, even in the Control group, though Ψ values were near -1.4MPa

286   (Figure 4). On the other hand, all of the RDI data from -1.6 to -2MPa clearly presented

287   an MDS signal higher than 1.1, with maximum average values around 1.4. When the

288   Ψ values were lower than -2MPa, MDS signals were under 1.1 (Figure 4).

289   *Relationship between trunk growth rate (TGR) and environment*

290   The best relationship between TGR and meteorological data for each season is

291   presented at Table 3. Most of the relationships calculated were not significant (data not

292   shown). The ones presented here are only the best four for each season and orchard in

293   order to improve the clarity of results. None of the regressions that included absolute

294   value of the meteorological data and the daily value of TGR were significant (data not

295   shown). When TGR values were related with the increment of each meteorological

296   variable in some years the regression was significant, but they were still very poor (data

297   not shown). Only when these increments were related with the TCT of the next day the

298   signification was improved. The data of the best relationships between previous

299 meteorological data and TGR for each year are presented at Table 3, only data of the

300 year 2008 is not presented. Average daily relative humidity ((Δ-1)RHav), temperature

301 (average or maximum) and daily average vapour pressure deficit ((Δ-1)VPDav) were

302 the best relationship with TGR. Only (Δ-1)VPDav and (Δ-1)RHav were one of the best

303 in all the years considered (Table 3). Determination coefficient in these variables

304 changed from 0.34 to 0.61 in (Δ-1)VPDav and from 0.2 to 0,52 in (Δ-1)RHav (Table 3).

305 None of the other variables or any multivariable equations improved the results of these

306 two. In all the relationships of Table 3, TGR decreased with an increase of the

307 evaporative demand. The slope in the (Δ-1)VPDav vs TGR relationship was the greatest

308 in all the seasons considered (between -48.6 to -65.5 μmdía^{-1}KPa^{-1}, while in the others

309 from 3.0 in (Δ-1) RHav to -18.8 (Δ-1)Tav (increment of the day before in average

310 temperature).

311   Similar relationships were obtained when data from a different near orchard was

312 considered (orchard 7*7; 2012 season, Table 3). Accuracy of the equation was

313 improved in this orchard, but (Δ-1)VPDav was again the best variable. This equation

314 explained the 75% of the data variability and the slope was 4 times greater than the rest

315 of the equations (Table 3). The equation of this orchard was significantly different from

316 the ones of the 7*5 orchard.

317   Although the (Δ-1)VPDav vs TGR relationships presented different slopes

318 between years (Table 3), such differences were not significant (Fig. 5) for the 7*5

319 orchard. The equation that considered the pool data presented a R^2 around 0.45. The

320 slope of this equation suggests an important effect of the VPD in the TGR (around 55

321 μm día^{-1} per KPa). This equation was significantly different from the ones obtained in

322 7*7 orchard. However, in the interval ±1 KPa of VPD, where most of the data are

323 presented, both equations are very similar (Fig. 5).

324   The accuracy of the equations in the 7*5 orchard was very different between

325   seasons (Table 3). When R^2 is related with the fruit yield of each season, a clear trend to

326   lower influence of VPD with an increase of fruit load is obtained (Fig. 6). Fig. 6

327   suggests that R^2 in the equations, and therefore the VPD influence on TGR, decreased

328   sharply from around 13 MT ha^{-1}.

329

330   **Discussion**

331   *MDS baseline usefulness*

332   The relationship between the MDS signal and the midday stem water potential (Ψ) was

333   similar to that described in the literature (olives, Moriana et al 2000; other fruit trees,

334   Ortuño et al 2010). When there was no water stress, the values for the relationship

335   between the MDS signal and the water potential (around -1.4MPa) were grouped around

336   1, while in the MDS vs. Ψ relationship, these values showed a greater scattering. Such

337   results suggest that the MDS signal reduced the environmental noise which is common

338   in MDS values in the range near -1.4MPa.

339   The fruit load was a factor likely to affect the MDS signal vs. Ψ relationship.

340   Conditions of full irrigation or very low water stress (Ψ higher than -1.6MPa) in a low

341   fruit load season presented greater values than expected (Figure 4, higher than 1). The

342   fruit load is a factor that affects MDS values. In olive trees, Moriana et al (2011)

343   reported a significantly different lower slope in the baseline for the low fruit load than

344   for the high fruit load. Goldhamer and Fereres (2001) suggested that an active trunk

345   growth decreases the MDS in fruit trees. However, lower values for the MDS vs. Ψ

346   relationship were not found in low fruit load conditions in the present work (Figures 1

347   and 3). Since the MDS signal is a ratio, such response would be related to an estimation

348   of values lower than expected in conditions of full irrigation (the denominator in the

349 ratio). Therefore, the estimation of the MDS baseline at the beginning of a low fruit load

350 season, according to the Corell et al (2013) methodology, could underestimate the value

351 with full irrigation and then, produce a significant increase in the MDS signal during the

352 pit hardening.

353   The relationship between MDS signal and Ψ showed a clear increase in the

354 MDS signal from -1.6MPa to -2MPa (Figure 4). Such increase was also observed in the

355 MDS vs. Ψ relationship, although the variations were narrow and similar to some values

356 of the Control trees (Figure 3). In both relationships, values below -2MPa were similar

357 to the ones obtained with a Ψ higher than -1.4MPa. This pattern of increase and

358 decrease has been observed in olive (Moriana et al., 2000) and other fruit trees (Ortuño

359 et al., 2010) and has limited the usefulness of MDS in olive trees (Moriana and Fereres,

360 2002; Moriana et al 2003; Moriana et al., 2010; Fernández et al 2011). Although the

361 MDS signal also presented this pattern, MDS signal values greater than 1.1 always

362 indicated moderate water stress conditions. However, MDS signal values do not display

363 a linear increase because the decrease of MDS signal starts in this interval of water

364 potential. Therefore, in the interval 1.1-1.4, a higher MDS signal will not be necessarily

365 imply a lower Ψ. Then, although there is still an uncertain zone in the range between -

366 1.4MPa and -2MPa, at least conditions of water stress could be identified.

367

368 *Relationship between trunk growth rate (TGR) and environment*

369 TGR is poor related with environment in the literature and in the present work.

370 Predicted models of the daily TDF has reported no clear results for the overlap effect of

371 growth and water status (Deslauriers et al, 2007). Only in young olives trees, when

372 trunk growth is continuous during all the irrigation season because of the absence of

373 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.

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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

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

546 12. 2013 season, circle; empty Control trees, mid filled RDI 2; black RDI 12.

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548 Fig. 4. Relationship between Midday stem water potential vs Maximum daily shrinkage

549 signal (MDS signal) during the three seasons. Each point is the average of all the data of

550 Figure 2 according to the water potential interval of: values higher than -1.4 MPa,

551 between -1.4 until -1.75 MPa, between -1.75 until -2 MPa and lower than -2 MPa.

552 Vertical and horizontal bars at the symbol represent the standard error in MDS signal

553 and stem water potential respectively. Vertical dash line shows the reference of stem

554 water potential (-1.4 MPa). Horizontal dash lines represent the reference of MDS signal

555 (1) and an interval of ±10%. Symbols: 2011 season, triangles; up and empty Control

556 trees, down and empty RDI 2, up and black RDI 12. 2012 season, square; empty

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

558 mid filled RDI 2; black RDI 12.

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560 Fig. 5. Relationship between trunk growth rate (TGR) and increment of the vapour

561 pressure deficit the day before ((Δ-1)VPD). Black square and solid line represent all the

562 data of the 7*5 m orchard (Table 3, n=257, TGR=-54.15 (Δ-1)VPD, R^2=0.46***,

563 Error=31.0 μm día^{-1}). White square and dash line represent data from 7*7 orchard

564 (Table 3, n=60, TGR=-79.39 (Δ-1)VPD, R^2=0.75***, Error=27.8 μm día^{-1}).

565

566 Fig. 6. Relationship between the determination coefficient (R^2) of the regressions

567 between increment of the vapour pressure deficit the day before ((Δ-1)VPD) and TGR

568   (Table 3) vs the yield. The highest yield and lowest R^2 correspond to the regression

569   obtained in the 2008 season (data not shown).

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	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

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

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578

Seasons	DOY Ph II	ETo Ph II	Rain Ph II	Yield	Control	AW 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		

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

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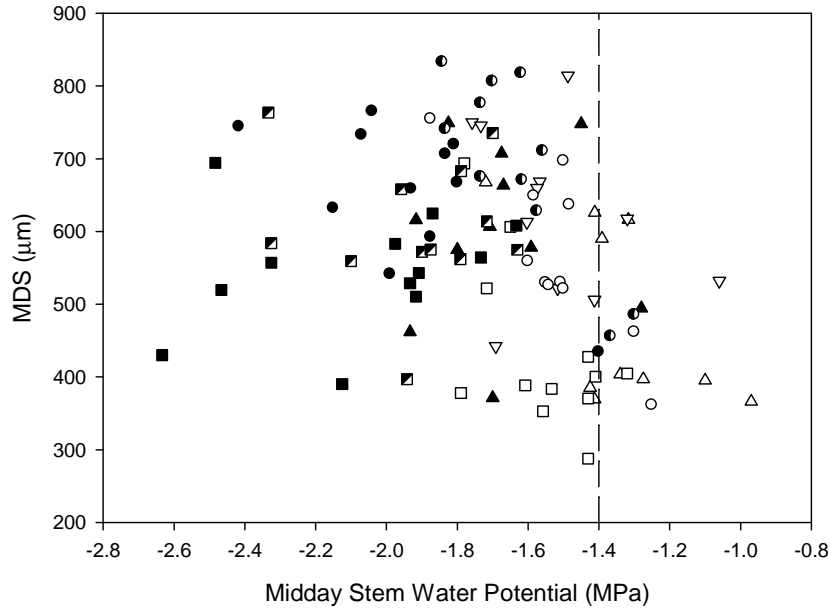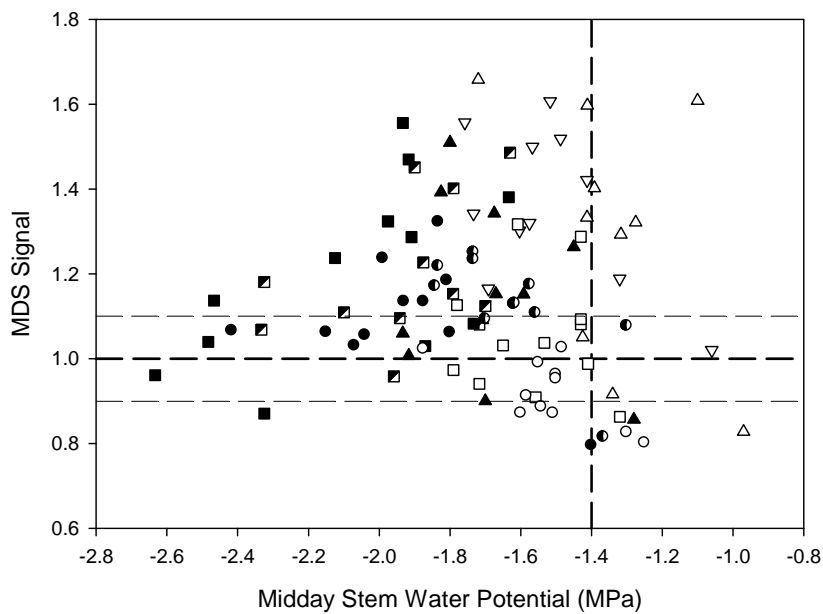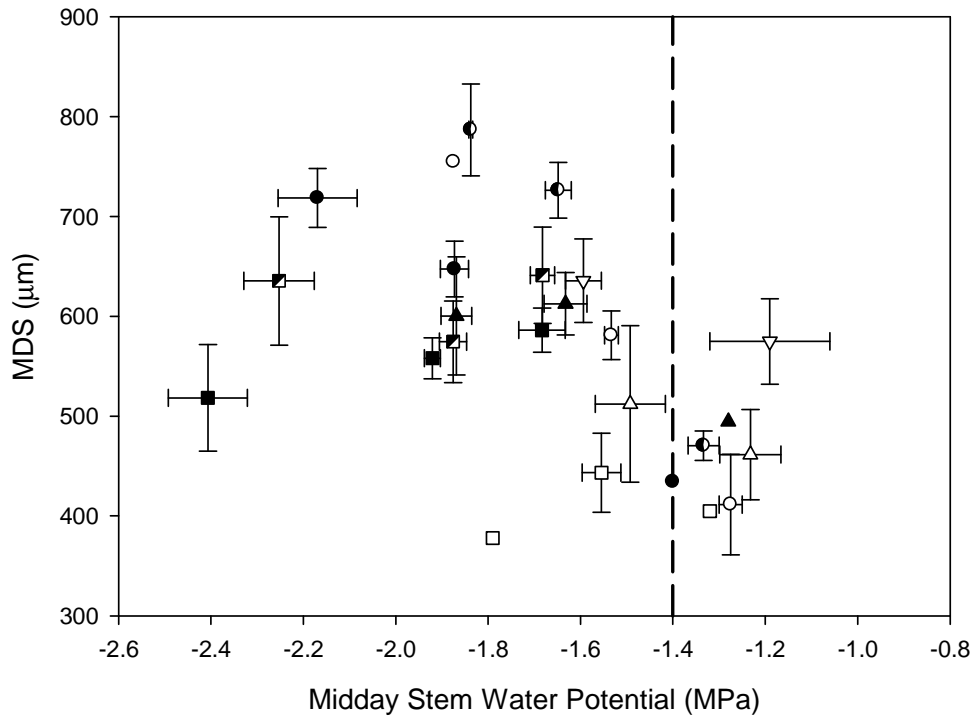
Figure 1

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.
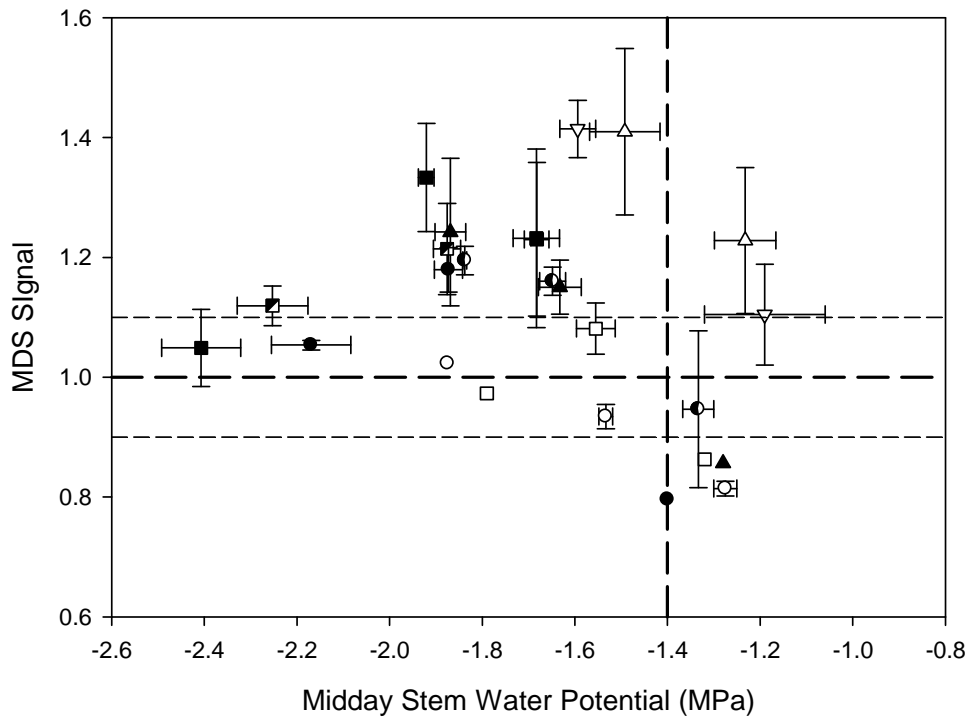
Figure 4

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.
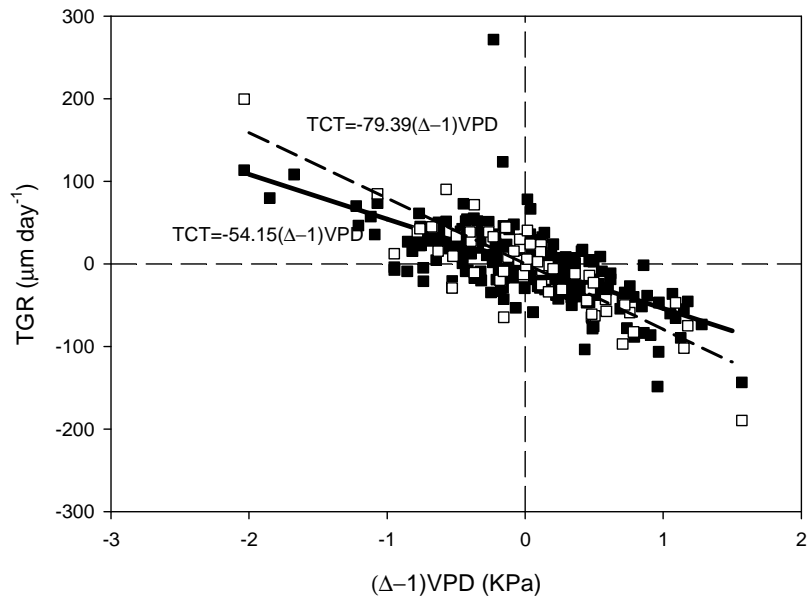
Figure 5

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})
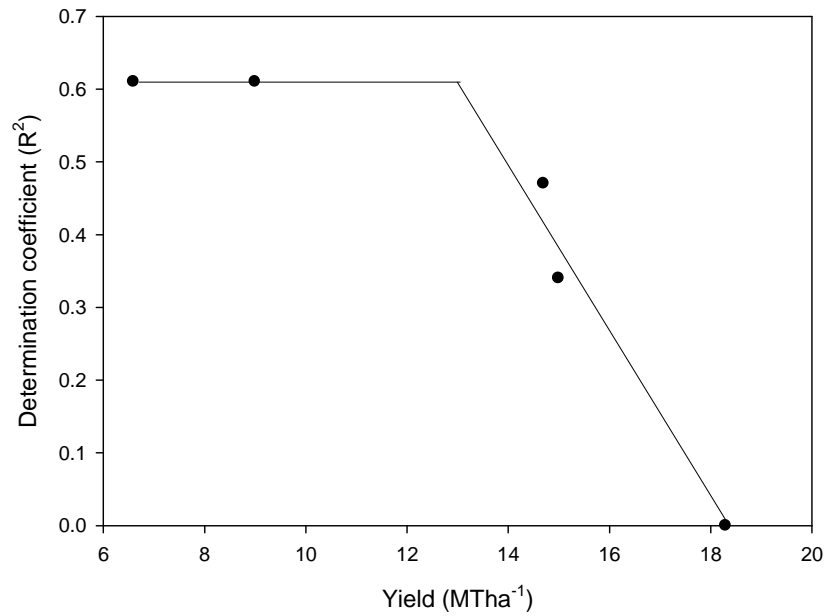
Figure 6

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).