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Plant-based sensing to monitor water stress: applicability to commercial orchards

J.E. Fernández

Irrigation and Crop Ecophysiology Group
Instituto de Recursos Naturales y Agrobiología de Sevilla (IRNAS, CSIC)
Avenida de Reina Mercedes n.º 10, 41012 Seville, Spain

Author details:
Phone: +34 954 62 47 11 (ext. 173) fax: +34 954 62 40 02
E-mail address: jefer@irnase.csic.es

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Abstract

Despite their potential for water stress monitoring, sap flow (SF), trunk diameter variation (TDV) and leaf turgor pressure (LTP) related measurements are rarely used in commercial orchards. The reasons for this lack of popularity are analysed here, as well as possible solutions for the identified limitations. I worked with data collected from different olive orchards as well as with findings from the literature reported for other fruit tree species. SF sensors are difficult to install but easy to maintain. TDV sensors are easier to install, but required greater maintenance. Both methods are highly demanding in terms of data processing, especially sap flow. The usefulness of SF records for monitoring water stress is curtailed on recovery periods, due to the delayed recovery of stomatal conductance. TDV records, on the other hand, depend on plant water status, but also on plant age, phenological stage and crop load, among other factors. For correct data interpretation, therefore, a deep understanding of the response of the monitored variable to plant and environmental conditions is required. For LTP related measurements we used ZIM probes. They showed to be easy to install and use, and robust enough to withstand field conditions for long irrigation seasons. Severe water stress, however, limited their performance. New approaches are being developed to increase the potential of the tested methods for being used in commercial orchards. These includes combining the plant-based methods with remote imagery, deriving more user-friendly water stress indices from the collected records and hiring the services of specialized companies which provides the user with easy-to-interpret summaries of the collected information. With the help of new tools and applications, and the hiring of specialized companies if required, the assessed plant-based methods can be reliable and

profitable tools for monitoring water stress and scheduling irrigation in commercial orchards.

1. Introduction

The need for a sustainable water use in agriculture has impelled the scientific community to develop new methods for monitoring water stress. Special interest has been paid to plant-based methods, since plant measurements have the advantage of integrating the soil and atmospheric water status, as well as the response of the plant to the surrounding conditions (Jones, 2004). Conventional plant-based methods to monitor water stress, such as those based on the use of Scholander-type chambers, are destructive and time and labour consuming. In the last decades, however, new methods have been developed for non-destructive, automatic and continuous measurements, easily implemented with data transmission systems for the user to have nearly real time access to the collected data from a remote computer, smart phone or similar. Most of these methods and related systems are highly sensitive and capable of working under field conditions for long periods of time. These characteristics confer them a great potential both for monitoring water stress and scheduling irrigation in commercial orchards (Fernández and Cuevas, 2010).

The new plant-based methods are based on a wide range of variables. Measurements of stem electrical conductivity with TDR probes inserted in the trunk (Nadler and Tyree, 2008; Nadler et al., 2008) and of electric potential differences between plant tissues (Gurovich and Hermosilla, 2009; Oyarce and Gurovich, 2011) can be used to monitor plant water status. The temperature of a fraction (Akkuzu et al., 2010; Çamoğlu 2013) or the whole canopy (Ben-Gal et al., 2010, Agam et al., 2013) has also proven to be a useful indicator of water stress for a variety of fruit trees, and airborne thermal images are being used to assess the heterogeneity in water status in commercial orchards (Zarco-Tejada et al., 2009; Gonzalez-Dugo et al., 2013). The most widely studied plant-based methods, however, are those based on measurements or estimations of sap flow (SF), trunk diameter variation (TDV) and leaf turgor pressure (LTP). Sap flow methods have a potential for in situ determinations of plant water consumption and transpiration dynamics (www.wgsapflow.com). Comparisons between several stress-related indices derived from SF records and other water stress indicators have been made (Escalona et al., 2002; Ortuño et al., 2006; Intrigliolo and Castel, 2006), and the potential of SF-related measurements to schedule irrigation has been explored (Fernández et al., 2001, 2008a,b). The usefulness of TDV records both for monitoring water stress and scheduling irrigation has been evaluated for a great number of species (Fernández and Cuevas, 2010; Ortuño et al., 2010), and comparative studies between TDV and other water stress indicators have also been made (Ehrenberger et al., 2012a; Cuevas et al., 2013). More recently, the leaf patch clamp pressure probe or ZIM-probe (Zimmerman et al., 2008) is being used to monitor water stress from estimations of relative changes in LTP (Fernández et al., 2011a; Bramley et al., 2013).

Several irrigation protocols based on the three methods mentioned above have been suggested and some of them have been successfully tested (Fernández et al., 2008a; Ortuño et al., 2010; Zimmermann et al., 2013). However, and although the methods are being widely used in research, their use with commercial purposes, i.e. to improve irrigation in commercial orchards, is much lower. Some believe that the new plant-based methods based on automatic and continuous recording are superior to conventional water stress indicators, and that they will become popular when prices of the sensors and related systems decrease. Others, however, find these methods too complicated to install and maintain, and their records too difficult to interpret, to be used in commercial orchards. No detailed studies, however, have been published on the reasons for these methods not being adopted by farmers and orchardists. I hypothesized that methods based on SF, TDV and LPT records are useful both for monitoring water stress and scheduling irrigation in commercial orchards, provided they are used in combination with new technologies and approaches that make them inexpensive and user-friendly. When used alone, or by non-trained users, they are expensive and errors can easily arise from difficulties on installation and maintenance, as well as on the analysis and interpretation of the data.

To test our hypothesis, in this work I review the potential of SF, TDV and LTP related records to monitor water stress in commercial orchards. I first identify main limitations on the performance of each method imposed by the plant response to environmental water conditions. I then address difficulties to the requirements of each method for installation, maintenance, and data processing and interpretation. Eventually I explore solutions that are being developed to overcome such limitations.

2. Experimental details and data collection

I have reviewed main findings on the use of SF, TDV and LPT related measurements reported by other authors for a variety of species and conditions. In addition, most of the figures and experimental approaches commented below are derived from the work on the topic made by my research group. We worked at three different olive (*Olea europaea* L.) orchards, all within a radius of 30 km from Seville, southwest Spain. La Hampa orchard had ‘Manzanilla de Sevilla’ trees (from now on ‘Manzanilla’) planted at 7 m × 5 m in 1969 (Cuevas et al., 2010). La Nava orchard had

‘Arbequina’ trees planted at 7 m × 6 m in 1998 (Fernández et al., 2011b). In both cases trees had a round canopy and a single trunk with 2-4 main branches from 0.7 to 1.2 m above ground. The Sanabria orchard had ‘Arbequina’ trees planted at 4 m × 1.5 m in 2007 (Fernández et al., 2013). In this case the trees had a monoconic canopy, with a single trunk and main branches from 0.6-0.7 m above ground. Both at La Hampa and La Nava the soil had a useful depth of 1.5-2 m, and a moderate-to-high water retention capacity. At the Sanabria orchard the soil was sandy, with a low soil water retention capacity and a maximum depth of 0.6 m. Climate in the area is Mediterranean, with a wet, mild season from October to April and a dry, hot season from May to September. Average potential evapotranspiration (ET_o) and rainfall (R) are ca. 1250 mm and ca. 500 mm, respectively. The three orchards were irrigated during the dry seasons, normally from May to early September (La Hampa) or late October (La Nava and Sanabria). Drip irrigation was applied in all cases, with one lateral per tree row and 4-5 drippers per tree. A variety of irrigation strategies were tested in the orchards, as detailed in the mentioned publications. Basically, we applied several deficit irrigation (DI) strategies, including low frequency irrigation (LFI), sustained deficit irrigation (SDI) and regulated deficit irrigation (RDI). We also had fully irrigated trees, with daily water supplies to replace the crop evapotranspiration (ET_c) minus the effective rainfall.

Details on water stress measurements at the three orchards are also given in the literature. Basically, SF measurements were made with the Green’s heat-pulse velocity system (Green et al., 2003; Fernández et al., 2006), TDV records were collected with linear variable displacement transducers (Fernández et al., 2011c) and Plantsens radial dendrometres (Fernández et al., 2011b), and LTP related measurements were made with ZIM-probes (Fernández et al., 2011a). Scholander-type pressure chambers were used to assess plant water status, and gas exchange measurements were made with portable gas analysers. Both frequency domain and time domain sensors were used to monitor soil water status. The collected values of volumetric soil water content (θ_v) were used to calculate the relative extractable water (REW), i.e. a value between 0 and 1 for which the actual water content was expressed relative to the difference between the minimum soil water content measured during the experiments (0) and the soil water content at field capacity (1).

3. Limiting factors to the use of plant-based indicators in commercial orchards

As reported in the Introduction, the limited acceptance of SF, TDV and LTP related measurements to improve water use in commercial orchards could be related to sensors and related equipment being expensive, and to the high time and training requirements for installing and maintaining the systems, and for processing and interpreting the collected data. Sometimes, however, the limitation is not in the method, but in a poor understanding of its fundamentals and applicability. In this section I warn potential users on the need for understanding the impact of main morphological and physiological features of the instrumented species on the collected data, and on the importance of choosing the right index for obtaining reliable information. Limitations related to installation and maintenance of the systems are also discussed. In Section 4 I address different approaches that can be used to minimize those drawbacks.

3.1. Characteristics of the instrumented plant

In addition to the soil water status and atmospheric conditions, the species, age, nutritional status, phenological stage, crop load and other of characteristics of the instrumented plant affect the performance of plant-based water stress indicators. There is abundant literature on the topic, for SF (Fernández et al., 2008a), TDV (Fernández and Cuevas, 2010; Ortuño et al., 2010) and LTP (Ehrenberger et al., 2012b; Bramley et al., 2013). The same can be said for conventional water stress indicators such as those based on plant water status and gas exchange measurements (Jones, 2004; Naor, 2006; Moriana et al., 2012; Naor et al., 2013).

Concerning the species, it has been reported that TDV records are more informative of the plant water status in peach, for example, than in olive or grapevine (Fernández and Cuevas, 2010). The species also conditions the method for SF measurements. Thus, while heat-balance methods can be suitable for trunks of reduced diameter with thin barks, invasive heat-pulse methods are required for measurements in large diameter trunks with thick, insulating barks (Vandegehuchte and Steppe, 2013). ZIM-probes may be difficult to use if species with rough leaves, since a close contact of the probe with the leaf surface is required for reliable measurements (Zimmerman et al., 2008). Plant age and size also influence TDV records, since phloem thickness and trunk growth rates, among other factors, change with both variables (Fernández and Cuevas, 2010). Both SF and LTP records, which are less related to trunk growth, are less affected by plant age and size. The performance of a water stress indicator can also be markedly affected by phenology. This has been reported when analysing trunk growth rates in olive (Pérez-López et al., 2008; Moriana et al., 2013) and grapevine (Intrigliolo and Castel, 2007). It is known that TDV records depend not only on water status but also on carbon status (Flore and Layne, 1997; Intrigliolo and Castel, 2004) so it is not surprising that the performance of TDV-derived indices depends on crop load and fruit development. From an experiment in olive, both the transpiration and tree's capacity to take up water from the soil increased with crop load (Naor et al., 2013). However, the relationships between the stem water potential (Ψ_{stem}) and stomatal conductance (g_{s}) were different for trees with different crop loads. These, and other examples mentioned in the literature, advise for a careful consideration of the plant characteristics when using plant-based measurements for water stress monitoring.

3.2. *Plant response to water stress conditions*

The performance of any plant-based water stress indicator depends on morphological and physiological adaptations of the plant to water conditions. For a correct data interpretation, the user must be aware of the impact of the mechanisms governing those adaptations on the collected records. Below I give examples on the extent at which both adaptive features of plants and changes in the environment may affect the performance of water stress indicators.

3.2.1 Osmotic adjustment

The potential of combining SF and TDV records to monitor water stress was assessed by Fernández et al. (2011c) at La Hampa orchard. They work with fully irrigated (FI) trees and trees under deficit irrigation (60DI). The latter received decreasing irrigation amounts until day of year (DOY) 199. From that day on, a recovery irrigation strategy was applied. In total, the FI trees received 107% of $\mathrm{ET_c}$ and the 60DI trees 61% of $\mathrm{ET_c}$. Figure 1 shows the seasonal courses of two water stress related indices, D_{MXTD} and $D_{E\mathrm{p}}$, derived from TDV and SF measurements in representative trees of both treatments. Values of D_{MXTD} were calculated as the daily difference between the maximum trunk diameter (MXTD) recorded in the 60DI trees and the MXTD recorded in the FI trees. The D_{Ep} values were calculated as the daily difference between the plant transpiration (E_p) derived from SF records in the 60DI trees and the E_p value derived from the SF records in the FI trees. In the figure the time courses of D_{MXTD} and D_{Ep} are plotted against REW values in the root zone of the trees (Fig. 1A). The figure shows that the D_{MXTD} index responded to soil water depletion in the DI60 treatment from DOY 189, when REW ≈ 0.5. The D_{Ep} index, however, showed a similar trend all along the experimental period, with no response to soil water depletion. The authors reported that the great capacity of the olive tree to take up water from drying soils was behind the lack of response of D_{Ep} to the decreasing soil water content, and that that feature certainly curtailed the usefulness of the D_{Ep} index for assessing crop water needs in commercial orchards. They also stated that the simultaneous recording of D_{Ep} and D_{MXTD} could overcome such limitation. This, however, could be acceptable for research purposes, but having two different methods for monitoring water stress will be difficult to afford in most commercial orchards.

The described results show that the high capability of the olive tree to take up water from drying soils curtails the earliness of D_{Ep}, i.e. delays its response to the onset of water stress. One of the physiological mechanisms responsible for that behaviour is osmotic adjustment. The plant transpiration is given by the equation $E_p = (\Psi_s - \Psi_l) / R_p$ [Eq. 1], where Ψ_s is the 'effective' soil water potential at the root surface, Ψ_l is the 'effective' leaf water potential for the whole canopy and R_p is the plant hydraulic resistance (Jones, 1983). A minimum Ψ_s-Ψ_l gradient ($\Delta\Psi$) is required for water to travel from roots to leaves and the plant to transpire. The Ψ_s value is given by the soil water and solute status, but the Ψ_l value can be adjusted, to some extent, by the plant. Thus, Ψ_l depends on the turgor potential (Ψ_P) and on the osmotic potential (Ψ_π), such that $\Psi_l = \Psi_P - \Psi_\pi$. The olive tree, as many other species of arid and semi-arid areas, is able to adjust Ψ_π under soil drying conditions, which leads to high values of $\Delta\Psi$ (Fernández, 2014). This physiological feature typical of the species contributes to explain the low water stress levels reported for olive trees growing in drying soils, especially in the case of old trees with large root zones (Fernández et al., 1997; Cuevas et al., 2010). These results are in agreement with the Ψ_s value for permanent wilting point in olive being much lower than -1.5 MPa, the accepted permanent wilting point for most species. Actually, measurable transpiration and photosynthesis activities have been detected in olive plants at $\Psi_\mathrm{s} < -5$ MPa (Moriana et al., 2003; Perez-Martin et al., 2009).

The user of water stress indices calculated from SF measurements, such as $D_{E\mathrm{p}}$, must bear in mind that the earliness of the index could be markedly curtailed when used in plants with an outstanding capacity to take up water from drying soils, such as olive. This applies mainly to plants growing in soils of medium to high soil water retention capacity. In cases of trees with small root zones growing in soils with low water-holding capacities, this limitation could be negligible. In an experiment at the Sanabria orchard $D_{E\mathrm{p}}$ and D_MXTD values were derived from measurements in 4-year-old 'Arbequina' trees. Those had very small root zones, of ca. 0.12 m^3, and the soil had a water retention capacity of 66 mm only. Under these conditions $D_{E\mathrm{p}}$ responded slightly earlier than D_MXTD to the onset of water stress (Cuevas et al., 2013).

Figure 1 about here

3.2.2. Root-to-shoot signalling

The capability of a plant to take up water from the soil depends not only on water availability, but also on water distribution. Figure 2 shows data from an experiment at La Hampa orchard, when trees were 39 years old (Torres-Ruiz, 2012). Three water treatments were considered: rain-fed, with negligible rainfall events during the period shown in the figure; drip irrigation, with trees drip irrigated daily from May 14 to October 2 with enough water to replace ET_c; pond irrigation, with trees irrigated with a grid of pipes covering a surface of 8 m × 6 m, with a dripper every 0.4 m × 0.4 m. The tree was in the middle of the grid and irrigation supplies were enough to keep non-limiting soil water conditions in the whole root zone, all throughout the irrigation season. In the Drip trees part of the roots remained under soil drying conditions during the irrigation season, since a fraction of the root zone only was wetted by the localized irrigation. In a parallel experiment we had 2-year-old 'Manzanilla' trees growing in pots. Each tree was planted in the middle of two 50 L pots, with about half of the root system within each pot. This allowed for reproducing the water treatments applied in the field. Data shown in Fig. 2 refers to the diurnal courses of Ψ_l and g_s measured at the end of the dry season, both in field (Fig. 2A,B) and potted (Fig. 2C,D) trees. While no differences in Ψ_l were found between Drip and Pond trees, either for field and potted conditions, significant differences in g_s were recorded. This has been defined for olive as a near-isohydric behaviour (Cuevas et al., 2010). Leaf transpiration (E_l) depends on g_s, such that $E_l = g_s D_{l\text{-}a} / 100P$ [Eq. 2], where $D_{l\text{-}a}$ is the leaf-to-air vapour pressure deficit and P the atmospheric pressure. Figure 2, therefore, illustrates the capacity of olive to limit transpiration through stomatal closure, a water-saving strategy widely observed in plants well adapted to drought. Basically, the plant tries to keep hydraulic functioning with minimum water consumption, by an effective control of transpiration through stomatal closure (Tognetti et al., 2009; Boughalleb and Hajlaoui, 2011). Thus, and although the responses of the stomata both to plant water status and environmental conditions are not well understood (Buckley, 2005), it seems that "stomatal guard cells respond by negative feedback to Ψ_p, which is related to Ψ_l and that to Ψ_x (xylem water potential). Thus, the plant can operate near the embolism threshold, generating the required $\Delta\Psi$ for transpiration at the same time that the risk for excessive R_p is minimized" (Fernández, 2014).

For plants of several species growing in soils with a highly variable water distribution, it has been reported that stomatal closure is induced by chemical signals generated in roots remaining in drying soil (Wilkinson and Davies, 2002; Chaves et al., 2010). In addition, the overall hydraulic conductance around the roots is expected to be lower in plants with a fraction of their root zone remaining dry, e.g. the Drip trees in Fig. 2, than in plants with the whole root zone wetted by irrigation, e.g. the Pond trees. Hydraulic signals with a capacity to induce stomatal closure can also be generated (Tardieu and Davies, 1993). Other findings suggest that signals emanating from roots in contact with drying soil are likely to integrate both chemical and hydraulic signals, and that soil-drying-induced ABA signals arising in the shoot (upon receipt of signals from the root) are more important for the regulation of stomatal aperture than ABA generated in the roots (Wilkinson and Hartung, 2009). Whatever the mechanism involved, Fig. 2 suggests that, for plants showing an isohydric or near-isohydric behaviour, transpiration rates are not always closely related to plant water status. Caution has to be taken, therefore, when using SF related measurements to monitor water stress in those types of plants. They can show a wide range of g_s values for similar water stress levels, which may leads to poor agreement between SF and leaf or stem water potential values. This is explained in detail in the next section.

Figure 2 also shows that Ψ_l and Ψ_{stem} may not always reflect properly the effect of stressing conditions on g_s. For olive, g_s is closely related to the net CO_2 assimilation (A) (Moriana et al., 2002; Naor et al., 2013), except for maximum values of g_s obtained under non-limiting conditions (Fernández et al., 2008c). It can be assumed, therefore, that Ψ_l and Ψ_{stem}, although being trusty indicators of plant water status, they may not always provide reliable information on the impact of water scarcity on crop performance. This leads to be cautious when using Ψ_{stem} vs. g_s and Ψ_{stem} vs. yield relationships already published for olive and other species with an isohydric or near-isohydric behaviour (Naor et al., 2004, 2013).

Figure 2 about here

3.2.3. Recovery from water stress

Understanding how the plant recovers from water stress is crucial for a rational water management, especially when certain DI strategies are used. This is the case of RDI, which implies drastic and sudden changes in water supplies and, therefore, periods of increasing water stress followed by re-watering periods. Olive roots are able to take up water from the soil immediately this is available, even if the tree has been under soil drying conditions for a long period (Fernández et al., 2001). Thus, Ψ_l recovers within a period of hours to a few days, depending both on the severity of the suffered water stress and on the amount of water supplied for re-watering. Both g_s and A, however, take longer to recover (Fernández et al., 1997; Perez-Martin et al., 2014). It has been suggested that ABA accumulated in roots during drought is delivered to the leaves during rehydration, thus contributing to the slow recovery of gas exchange (Lovisolo et al., 2008). Also reported is a possible effect of hydraulic signals generated in the leaf on the down-regulation of stomatal conductance (Torres-Ruiz et al., 2014). Whatever the reason, the slow g_s recovery after re-watering of the olive tree induces reduced transpiration (Eq. 2).

Figure 3 illustrate this phenomenon. Data refers to measurements made at the Sanabria orchard, from a few days before resuming daily irrigation for the 60RDI trees at the end of August to a few days after. In July and August, a period of low sensitivity to water stress, the 60RDI trees were irrigated two days per week only, with a total supply on that period of 20-30% of the crop water needs. In 2010 it took nearly one month for g_s to recover, and in 2012 the g_s values of the 60RDI trees remained below those of the FI trees. Only in 2011 g_s recovered a few days after resuming daily irrigation. In agreement with the g_s values, in 2010 D_{Ep} did not reach values close to one until the full recovery of g_s (Fig. 3D). In 2011 D_{Ep} values increased quickly, showing a full recovery of E_p in the 60RDI trees at some two weeks after the beginning of the re-watering phase (Fig. 3E). The dynamics of D_{Ep} in 2012 suggest that the E_p of the 60RDI trees did not recover (Fig. 3F). Fig. 3 shows, in fact, that the slow recovery of g_s in olive after re-watering may curtail the earliness and sensitivity of water stress indices derived from SF measurements, such as D_{Ep}.

Figure 3 about here

3.2.4. Weather conditions

Water stress indicators based on plant-based measurements are influenced by weather conditions (Jones, 2004; Naor, 2006). The influence is sometimes beyond the expected effect from certain meteorological conditions, such as the vapour pressure deficit and the incoming radiation, being main driving variables for the plant water consumption. On stormy days, for instance, both high air humidity and especially rain affects the swelling and shrinking of cortical tissues, to the point that TDV records become useless (Fernández and Cuevas, 2010). Concerning SF records, Figure 4 illustrates how a marked and sudden decrease in atmospheric demand curtails de performance of $D_{E\mathrm{p}}$. The figure refers to an experiment at the Sanabria orchard (Cuevas et al., 2013). It shows the seasonal courses of atmospheric demand, soil water status and the $D_{E\mathrm{p}}$ and D_{MXTD} indices for the irrigation season of 2010. High decreases of $\mathrm{ET_o}$ were recorded on the three days marked in the figure with vertical lines (Fig. 4A). The $D_{E\mathrm{p}}$ values increased from DOY 224 to DOY 229, when $\mathrm{ET_o}$ decreased. From DOY 230 to 235 they decreased as $\mathrm{ET_o}$ increased (Fig. 4C). This was despite of non-significant changes in soil water content for any of the two considered irrigation treatments (Fig. 4B). The D_{MXTD} values, however, were not affected by the changing atmospheric conditions (Fig. 4D). As suggested by Cuevas et al. (2013), a sudden decrease in $\mathrm{ET_o}$ can have a stronger influence in the E_{p} of the FI trees than in that of the 60RDI trees, leading to peak $D_{E\mathrm{p}}$ values non related to soil water conditions. This occurs when the E_{p} of the 60RDI trees is already markedly reduced, as compared to that of the FI trees, by the lack of water in the soil. Based on these results, the authors stated that “an increase in $D_{E\mathrm{p}}$ does not necessarily mean an improvement of the soil water status” and that “the user must take into account main peculiarities of the response of sap flow rates to environmental conditions, for correctly interpreting the information provided by the $D_{E\mathrm{p}}$ index". This last statement applies, actually, to any water stress indicator relying on plant-based measurements.

Figure 4 about here

3.3. *Installation, maintenance and data processing*

Installation and maintenance of most plant-based water stress indicators require specific training. This applies also to both the processing of the collected records to derive an appropriate index for the orchard conditions and to the interpretation of the information provided by the index. Sap flow methods are particularly demanding in terms of installation. Most of the SF methods suitable for fruit trees are invasive, such that sensors must be installed within the trunk of the trees. For some methods this implies careful drilling and sensor insertion (Fernández et al., 2006). TDV methods are less demanding in terms of installation, since attaching holders and dendrometres to the trunk is relatively easy. The maintenance of TDV sensors, however, is more demanding than that of SF sensors. Dendrometres may be affected by weed growing, animals, and traffic in the orchard. In addition, dendrometres could have to be readjusted several times along the irrigation season, due to trunk growth (Fernández and Cuevas, 2010). Of the three methods considered here, the ZIM-probe is the less demanding in terms of installation and maintenance. The probes are easily attached to leaves, and can stand orchard conditions for many months (Fernández et al., 2011a).

In terms of data processing, SF and TDV records are collected with the help of dataloggers which, depending on the models, are more or less user-friendly. Sap flow methods are based on time and temperature records provided by the system, which have to be analysed first to derive values of variables such us sap flux density (J_p) and sap flux (Q), and then to calculate different water stress indices (Fernández et al., 2001, 2008a). Data processing is also required to calculate most of the water stress indices that can be obtained from TDV records (Fernández and Cuevas, 2010). ZIM-probes are connected to radio transmitters that send the collected information to a datalogger nearby. This automatically sends the collected data to a server belonging to the maker, which provides the user with a link to visualize, through the Internet, the P_p records in tables and figures. As for the other methods, different water stress indices can be obtained from the ZIM records, some of them requiring complex calculations (Fernández et al., 2011a; Bramley et al., 2013). In summary, the use of SF, TDV and LTP methods require specific training for analysing the collected information, which limits the suitability of these plant-based methods to monitor water stress in commercial orchards.

An additional complication relies on choosing the most appropriate index for the orchard conditions. For SF measurements I have already shown that D_{Ep} could be adequate for trees with small root zones growing in soils with low water retention capacity, but it lacks earliness when used in mature trees with large root systems, especially if belonging to species with effective control of transpiration through stomatal closure. In these cases, the effect of stressing conditions on stomatal closure, and therefore on water consumption, could be better monitored by the ratio between J_p values derived from measurements deep into the xylem and those derived from measurements closer to the cambium (Fernández et al., 2008a). When using TDV records, it is widely accepted that the maximum daily shrinkage (MDS) is an appropriate water stress index for many species (Fernández and Cuevas, 2010). In olive, however, the trunk growth rate could be most appropriate than MDS (Cuevas et al., 2010; Moriana et al., 2010). In addition, it is know that, for several woody species including olive, the MDS vs Ψ_{stem} relationship has a parabolic form, with decreasing slope from ca. $\Psi_{\mathrm{stem}} < -1.5$ MPa (Ortuño et al., 2010). Under severe water stress conditions, the information given by the P_{p} records taken with the ZIM probe is limited by the increase of air in the spongy mesophyll of the leaf, which attenuates the pressure transfer through the leaf tissues (Fernández et al., 2011a; Ehrenberger et al., 2012b). Caution should also be taken when using a water stress indicator such as Ψ_{stem} in plants showing isohydric behaviour, as detailed above. These examples advice for a careful choice of the water stress index.

4. Improving the applicability of plant-based indicators to commercial orchards

What it is said above suggests that considerable training and expertise are required for using SF, TDV and LTP related measurements as water stress indicators. If this is added to sensors and related systems being not cheap, we could think of these methods as not suitable for monitoring water stress and scheduling irrigation in commercial orchards. New approaches, however, are being developed to decrease the impact of those limitations. These approaches, detailed below, make the systems less costly and easier to use, increasing their potential for use in commercial orchards.

4.1. Making the system inexpensive

The suitability of any water stress indicator for its use in commercial orchards depends mainly on the tree-to-tree variability, signal strength, sensitivity, reliability and robustness (Fernández and Cuevas, 2010). Other requirements for a water stress indicator to be used with commercial purposes are mentioned in Table 1. The tree-to-tree variability is quantified by the coefficient of variation (CV). High CV values mean that a greater number of trees must be instrumented to reduce the uncertainty or noise of the collected information. The variability must be considered relative to the signal strength, or signal intensity (SI). With the SI approach, the value of the index derived from measurements in the plants which water stress we want to monitor (actual value) is related to the value of the index derived from similar plants growing under non-limiting soil water conditions (reference value) (Goldhamer and Fereres, 2001). Thus, if the chosen index is MDS, SI = actual MDS / reference MDS. The use of reference plants accounts for the fact that absolute values of any plant-based water stress indicator mean little if not considered relative to similar measurements made in plants growing in soils with non-limiting available water. The sensitivity, or signal:noise ratio, relates CV and SI, such that sensitivity = SI / CV.

The SI approach has been widely used in research experiments in which water stress indices were derived from plant-based measurements (Fernández and Cuevas, 2010; Ortuño et al., 2010). In most commercial orchards, however, the variability in soil, plant and microclimate conditions is high. Therefore, the achievement of acceptably low CV values, as required by the SI approach, implies either to instrument a large number of trees or to choose the trees to be instrumented from an area, within the orchard, with highly uniform water-stress characteristics. None of these two options is satisfactory, the first because it is expensive and the second because it provides biased information. The use of remote imagery may provide, however, an acceptable alternative to choose the trees to sample. Recent developments on remote imagery techniques, involving miniaturized cameras installed in GPS controlled, unmanned aerial vehicles, allow for detailed, inexpensive infrared images of the orchard. These images can be used to divide the orchard into a small number of areas with contrasting water-stress characteristics (Gonzalez-Dugo et al., 2013; Jimenez-Bello et al., 2013). The trees to be instrumented can then be chosen within each area, such that a reduced number of trees may provide reliable information for the whole orchard. This approach allows for precise irrigation within the orchard, since the irrigation sectors can be reallocated to match the water requirements of each area. The combined used of plant-based measurements and remote imagery is, in fact, recommended for lowering the cost and increasing precision in plant-based water stress monitoring in commercial orchards (Fernández and Cuevas, 2010). Still, this approach will not avoid a certain tree-to-tree variability, since this also depends on the location of the sensor in the plant and other tree-dependent factors.

Table 1 about here

4.2. User-friendly data recording, processing and interpretation

As mentioned in Section 3.3, calculating a water stress related index from SF, TDV or LTP records may be complex, which certainly limits the use of these methods in commercial orchards. But this is not always the case. The J_P ratio mentioned in Section 3.3 is based on changes in SF radial profiles, and does not require calculating absolute values of Q (Fernández et al., 2008a). This simplifies data processing when SF is the chosen method for water stress monitoring. If we use TDV, the collected records can provide useful information on the level of water stress in the sampled trees, without any data processing. This can be seen, for instance, in the work by Fernández and

Cuevas (2011) with ‘Arbequina’ trees under two irrigation treatments, LFI and SDI. They showed that the time course of the TDV records collected from the LFI trees allowed to identify low, moderate or severe water stress levels in the sampled trees (Fig. 5).

Figure 5 about here

Similarly to the case of SF and TDV records, calculating reliable water stress indices from leaf patch output pressure (P_p) values recorded with the ZIM-probe does not always implies complex calculations. It has been proved, for a variety of species, that the shape of the daily P_p curve indicates the level of water stress suffered by the instrumented plant. An example for olive is given in Figs. 6 and 7. Figure 6 shows three different shapes of the P_p curve, and the corresponding levels of water stress as deduced from concomitant measurements of Ψ_{stem} with a Scholander-type pressure chamber. Measurements were made in 2010 for assessing the potential of P_p records for monitoring water stress at the Sanabria orchard (Fernández et al., 2011a). The three levels of water stress shown in the figure were identified as States 1, 2 and 3, after Ehrenberger et al. (2012b). In 2011, the occurrence of States 1, 2 and 3 at the orchard was compared with the seasonal course of Ψ_{stem}. Measurements were made in trees with different levels of water stress, belonging to the FI, 60RDI and 30RDI treatments. Results showed that this approach, which can be automatically displayed in nearly real time via the Internet, was effective for identifying low (State 1), moderate (State 2) and severe (State 3) levels of water stress in the orchard (Fig. 7). This is a powerful tool for growers with little training to adjust both the timing and quantity of irrigation.

Additional algorithms to fine tune the water stress indices from P_p records and to facilitate data processing are being developed.

Figures 6 and 7 about here

For certain orchard conditions, however, the most suitable index could not be one of the easily-derived indices mentioned above. In this case the orchardist still has the possibility of hiring the services of a specialized company which, in addition to installing the sensors and related equipment, collects and processes the data, and provides easy-to-interpret summaries through the Internet. The data analysis system of some of these companies includes weather forecast models which allows for an early adjustment of water supplies under changing weather conditions. In most cases the orchardist has to combine the information provided by these companies with in situ observations on phenological stage, crop load, shoot growth, and other crop characteristics related to water management. New data capture tools, such as digital pens, allow for an easy data collection and arrangement in spread data sheets, such that the additional information taken by the orchardist can be easily combined with that provided by the company. All these new tools and approaches increase the suitability of the new plant-based water stress indicators for commercial orchards.

5. Conclusions

The three plant-based methods evaluated in this work have a great potential for monitoring water stress and scheduling irrigation in commercial orchards. They allow for non-destructive, automatic and continuous data recording and are easily implemented with data transmission systems for a nearly real time access to the collected records from a remote computer. These are great advantages for improving water use in modern agriculture. But the methods have also drawbacks that curtail their use by farmers and orchardists. Some are difficult to use and maintain, and the sensors and related systems are expensive. In addition, the standard user often lacks the required knowledge on the impact both of the species' main ecophysiological features and environmental conditions on the monitored variable required for a proper interpretation of the collected records. These limitations, however, can be successfully overcame with the help of new approaches that are being developed to facilitate the use of these methods in commercial orchards. First, the cost of implementing these methods can be reduced to acceptable limits by using remote imagery, which reduces the number of plants to be instrumented. It also allows for precision irrigation even in large orchards with high water-stress variability. Second, some of the water stress indices that can be derived from any of the three tested methods are easy to obtain and use, and new applications are being developed by manufactures to decrease the complexity of data processing and interpretation. Finally, there are specialized companies that install and maintain the required equipment, and collect and interpret the data. These companies provide the user with online access to easy-to-interpret summaries both of the collected information and derived indices, at an affordable cost. Some of these companies have implemented weather forecast models that improve irrigation management under weather changing conditions. If combined with these new approaches, the plant-based methods evaluated here become useful tools for monitoring water stress and scheduling irrigation in commercial orchards.

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Fig. 1. Time courses of (A) the relative extractable water (REW, avg ± SE, $n = 7$) derived from soil water measurements at La Hampa orchard, in the root zones of 38-year-old 'Manzanilla' olive trees under two water treatments. The fully irrigated (FI) trees were irrigated daily, with an average water supply for the whole irrigation season of 107% of the crop water needs (ET_c). The deficit irrigated (60DI) trees received decreasing irrigation amounts until day of year (DOY) 199. From that day on, a recovery irrigation strategy was applied. The 60DI trees received a total of 61% of ET_c. Also shown are the values of two water stress indices, D_{MXTD} and $D_{E\mathrm{p}}$. The first (B) was calculated as the daily difference between the maximum trunk diameter (MXTD) of the 60DI trees and that of the FI trees. The second (C) was calculated as the difference between the daily transpiration (E_p) of the 60DI trees that of the FI trees. Both for D_{MXTD} and $D_{E\mathrm{p}}$, the mentioned differences were calculated with the average of three trees per treatment, after considering the values recorded at the beginning of the irrigation season as zero. The D_{MXTD} index showed greater earliness and sensitivity than $D_{E\mathrm{p}}$ (After Fernández et al., 2011c).

Fig. 2. Diurnal courses of leaf water potential (Ψ_l) and stomatal conductance (g_s) in sunlit leaves of (A, B) 39-year-old 'Manzanilla' trees in the field and (C, D) 2-year-old 'Manzanilla' trees in pots (avg ± SE, $n = 6$). Measurements were made at La Hampa orchard, at the end of the dry season of 2007. Measurements were made in rain-fed trees and in trees under two irrigation treatments. LI trees received enough water to replace the crop water needs, but they were under localized irrigation such that part of the root system remained under soil drying conditions during the irrigation season. In the Pond trees, the whole rhizosphere was kept under non-limiting soil water conditions all throughout the irrigation season. Different letters indicate significant differences

between the two irrigated treatments at $p < 0.05$. No letter means no effect. GMT = Greenwich mean time. The data show a near-isohydric behaviour of the olive trees.

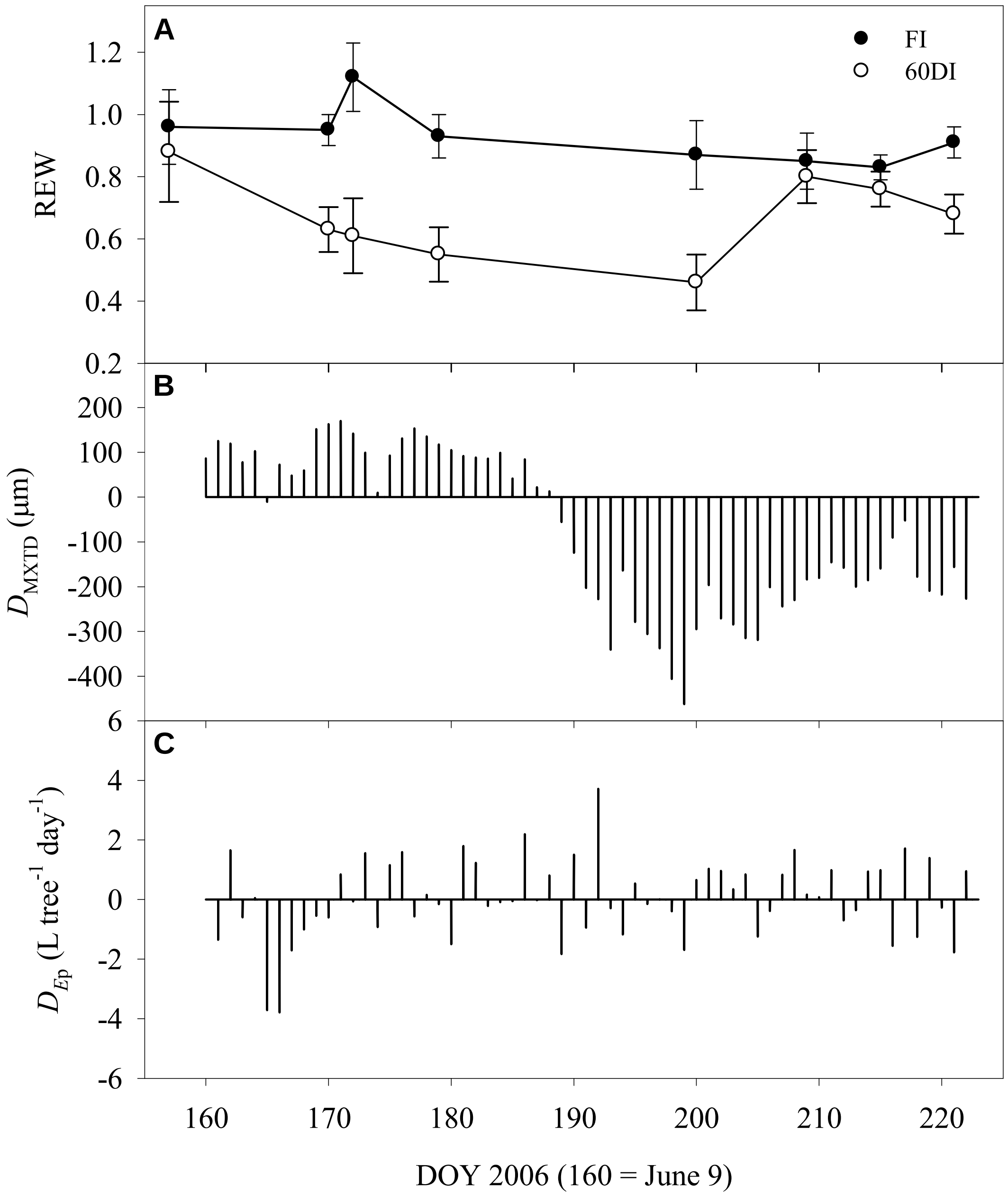
Fig. 3. Courses of (A, B, C) maximum stomatal conductance ($g_{\text{s-max}}$, avg ± SE, $n = 8$) measured in 'Arbequina' olive trees of the Sanabria orchard. Trees were under a full irrigation (FI) treatment supplying 100% of the crop water needs (ET_c) and a regulated deficit irrigation treatment supplying 60% of ET_c (60RDI). The shown periods correspond to a few days before and after the recovery irrigation applied to the 60RDI trees from the end of August, in three experimental years. In 2010 the trees were 4 year old. The arrows show the beginning of the re-watering periods. Different letters indicate significant differences between treatments at $p < 0.05$. No letter means no effect. Also shown are (D, E, F) the $D_{E\text{p}}$ values (see Fig. 1 for explanation) on the represented periods. DOY = day of year. The earliness of the $D_{E\text{p}}$ index was limited by the slow recovery of stomatal conductance typical in olive.

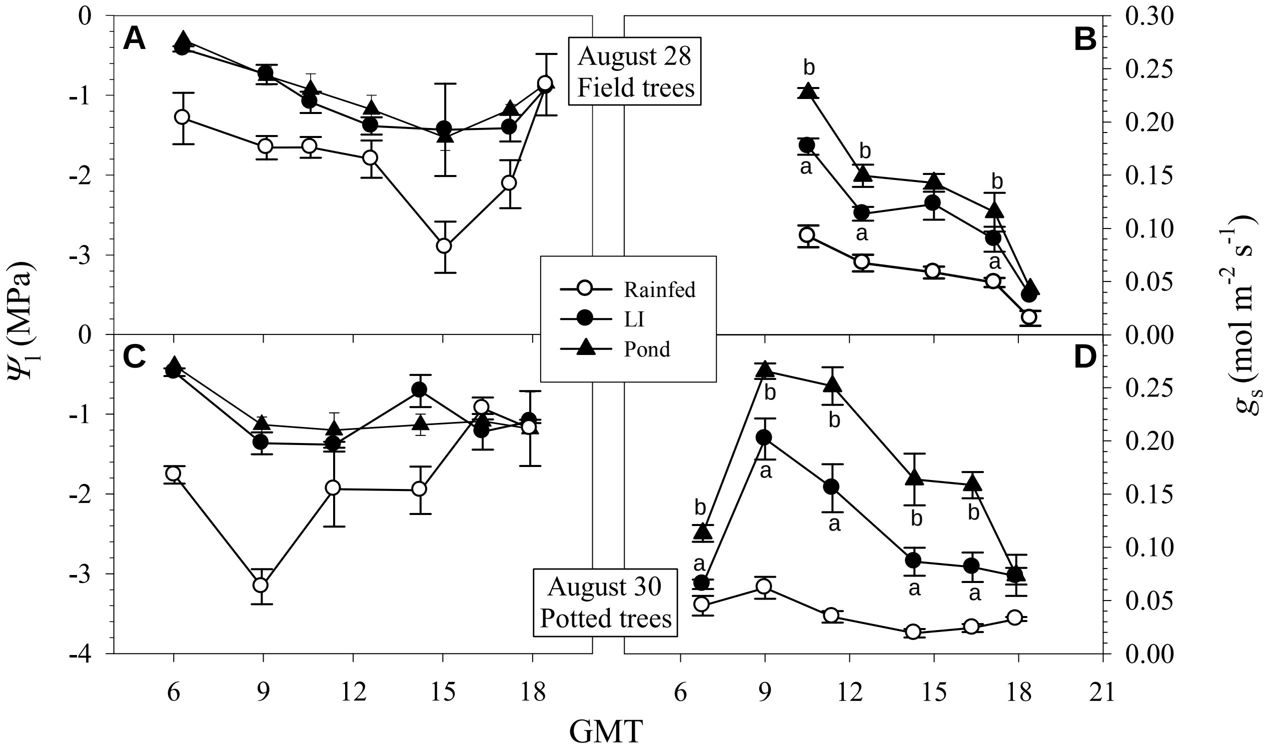
Fig. 4. Seasonal courses of (A) the FAO56 Penman-Monteith potential evapotranspiration (ET_o) calculated with records from a weather station close to the orchard; (B) the relative extractable water (REW, avg ± SE, $n = 8$) calculated from soil water measurements in the root zone of FI and 60RDI 'Arbequina' olive trees at the Sanabria orchard (see Fig. 3 for explanation on treatments). Different letters indicate significant differences between treatments at $p < 0.05$. No letter means no effect; (C) the $D_{E\text{p}}$ and (D) the D_{MXTD} values (see Fig. 1 for explanation). Vertical lines within graphs indicate three days on which marked decreases in ET_o were recorded. The $D_{E\text{p}}$ index lacked reliability on these days (After Cuevas et al., 2013).

Fig. 5. Time courses of (A) the trunk diameter variation (TDV) recorded in 12-year-old 'Arbequina' olive trees at La Nava orchard, under sustained deficit irrigation (SDI) and low frequency irrigation (LFI). Also shown are (B) the time courses of the average relative extractable water (REW) calculated from soil water measurements in the root zone of four trees per treatment. Dashed lined limits the periods of recovery from water stress (R), moderate stress (MS) and severe stress (SE) as deduced from the TDV values recorded in the LFI trees. DOY = day of year. (After Fernández and Cuevas, 2011)

Fig. 6. Daily leaf patch clamp pressure (P_p) curves recorded in 2010 by ZIM probes in 'Arbequina' olive trees of the Sanabria orchard under different levels of water stress. The shown curve shapes are typical of three levels of water stress identified in the figure by values both of leaf turgor pressure (P_c) and midday stem water potential (Ψ_{stem}) (After Fernández et al., 2011a and Ehrenberger et al., 2012b).

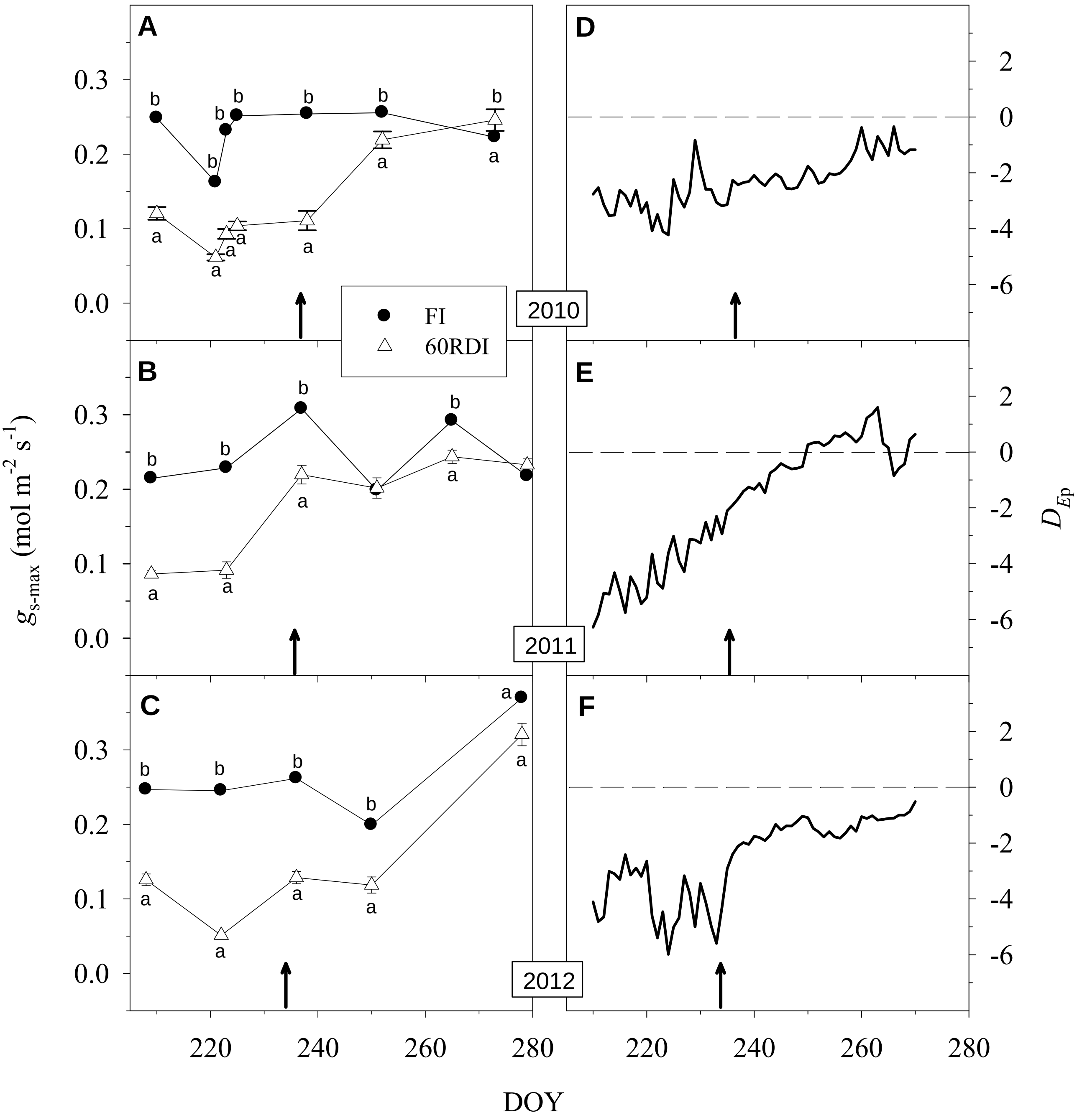
Fig. 7. Seasonal courses of midday stem water potential (Ψ_{stem}, avg ± SE, $n = 8$) measured in 2011 in FI, 60RDI and 30RDI trees of the Sanabria orchard (see Fig. 1 for details on treatments). Different letters indicate significant differences between treatments at $p < 0.05$. No letter means no effect (top graph). Horizontal colour bars below the graph represent the occurrence, along the season, of P_p curves showing State 1 (low water stress), State 2 (moderate stress) or State 3 (severe stress) (see Fig. 6 for details). P_p data were collected with three ZIM probes per treatment, one per tree, except in the 30RDI treatment, where two trees only were instrumented. For each irrigation treatment, periods between dashed lines indicates Ψ_{stem} values below -1.4 MPa, a threshold for water stress in olive trees with high crop load (Moriana et al., 2012).


A
B
C
FI
60DI
REW
D_{MXTD} (µm)
D_{Ep} (L tree^{-1} day^{-1})
1.2
1.0
0.8
0.6
0.4
0.2
200
100
0
-100
-200
-300
-400
6
4
2
0
-2
-4
-6
160
170
180
190
200
210
220
DOY 2006 (160 = June 9)

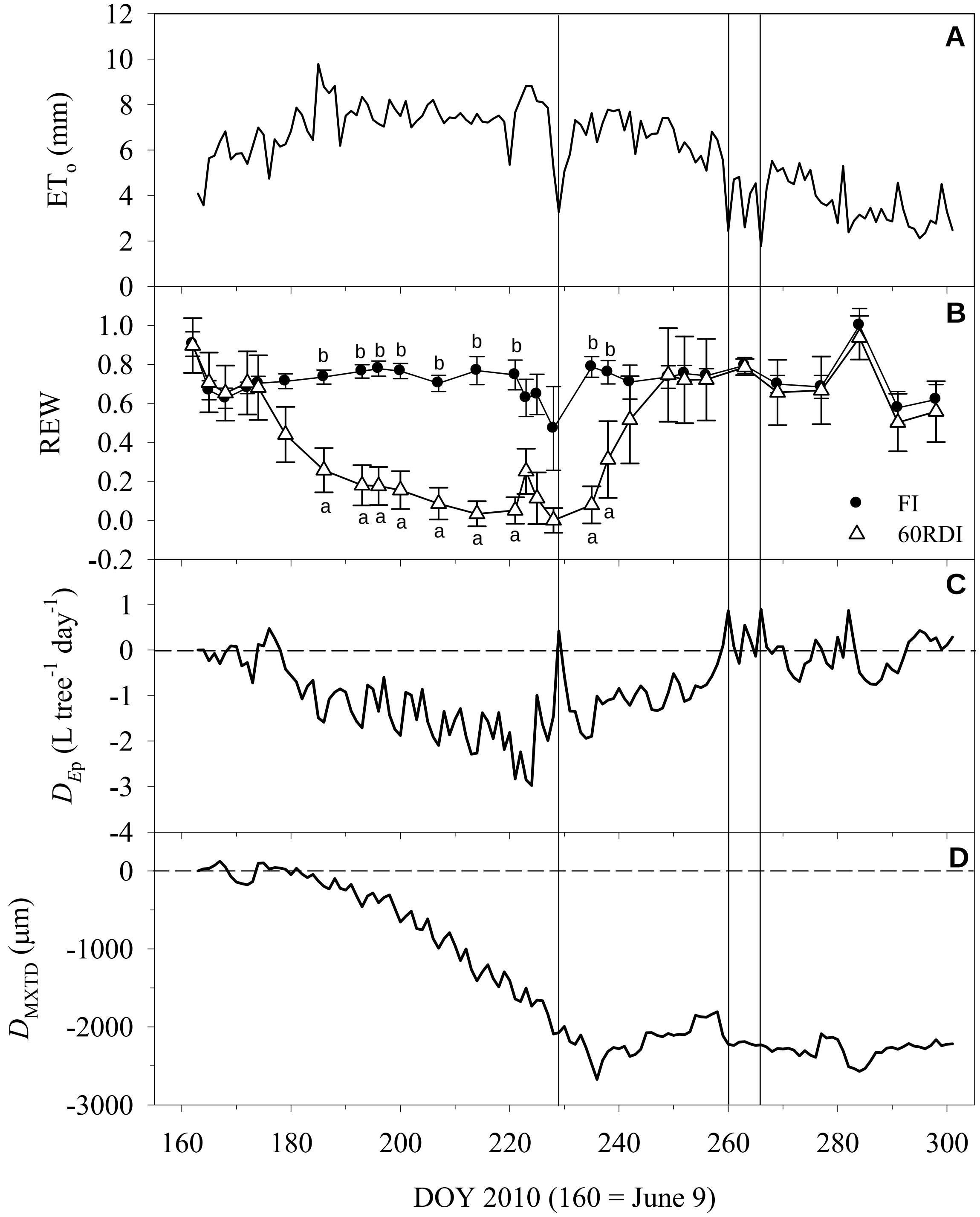


A
B
C
D
August 28
Field trees
August 30
Potted trees
Rainfed
LI
Pond
Ψ_1 (MPa)
g_s (mol m^{-2} s^{-1})
GMT
0
-1
-2
-3
-4
0.30
0.25
0.20
0.15
0.10
0.05
0.00
6
9
12
15
18
21
a
b

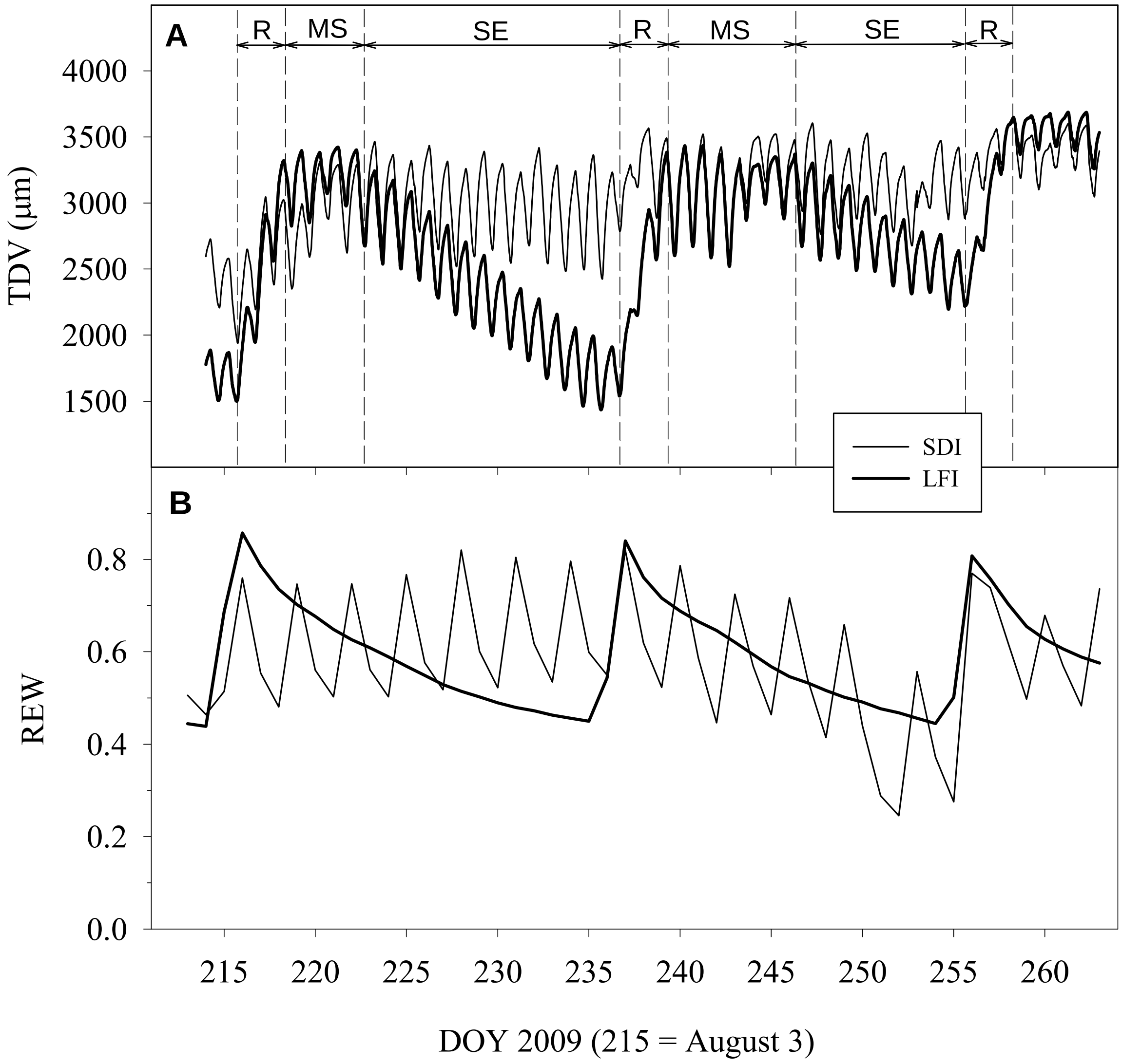
919

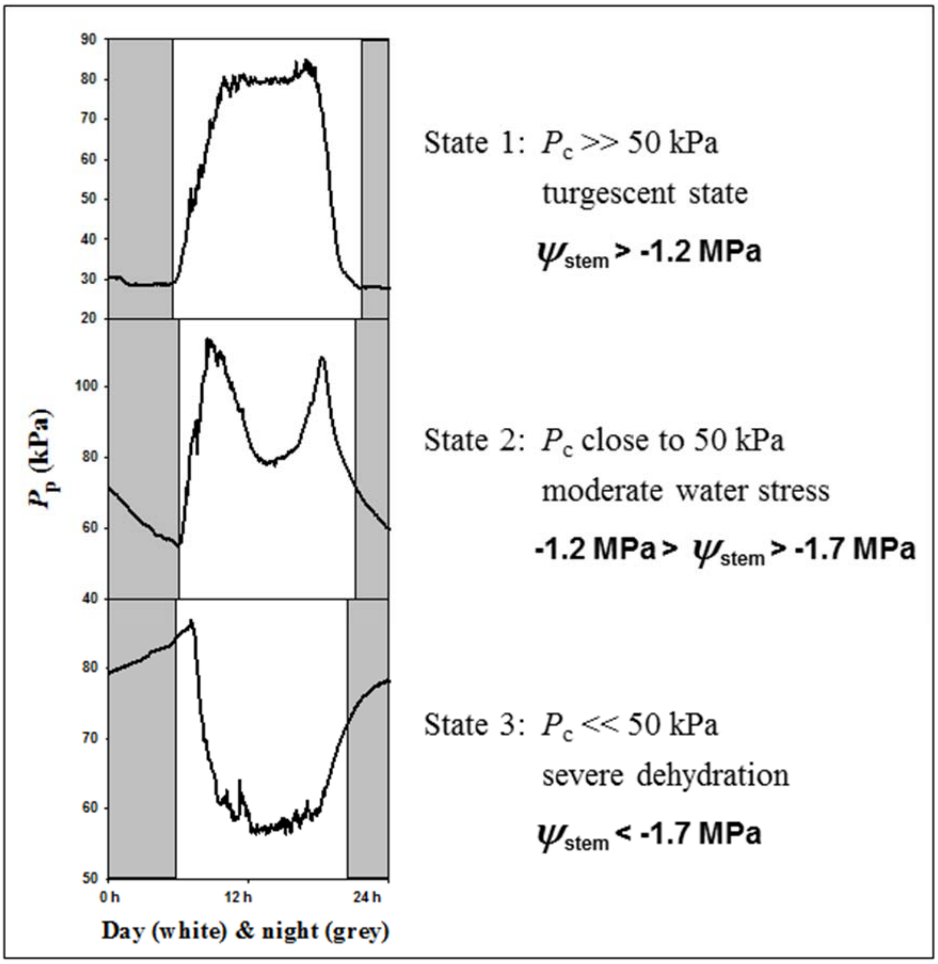


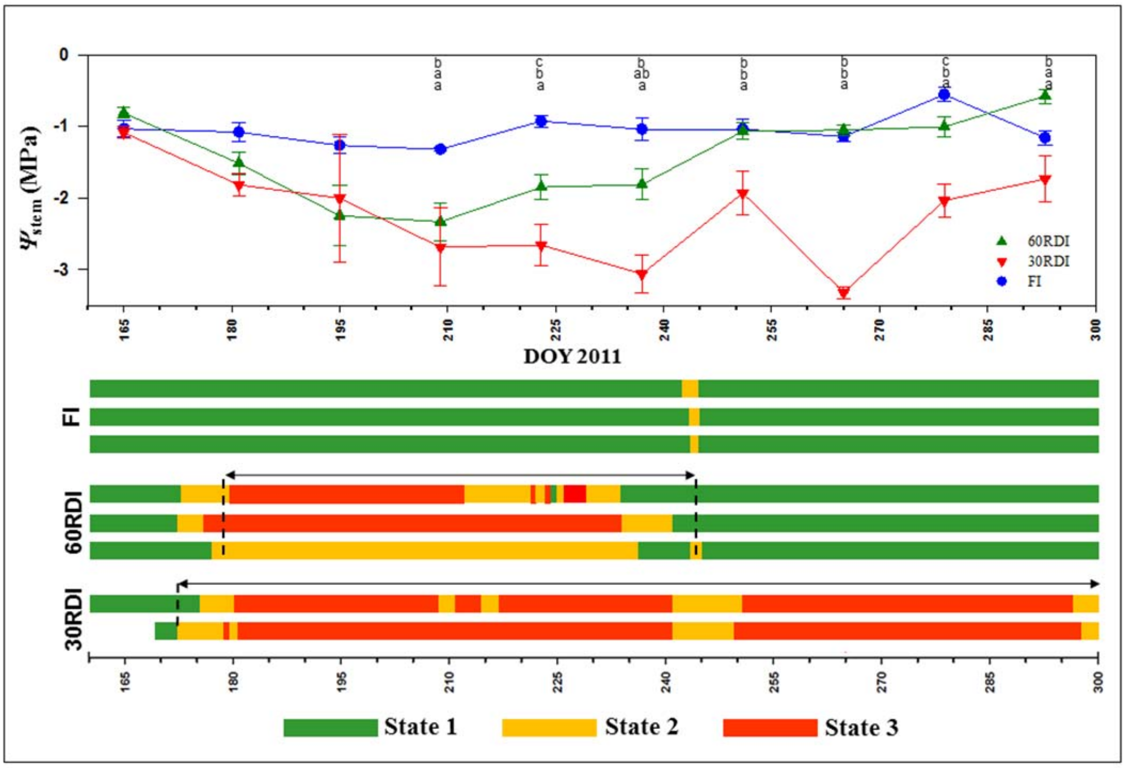
(For 2010 and 2011, DOY 220 = August 8; for 2012, DOY 220 = August 7)


A
B
C
D
ETo (mm)
REW
DEp (L tree-1 day-1)
DMXTD (µm)
DOY 2010 (160 = June 9)
FI
60RDI
b
a
0
2
4
6
8
10
12
-0.2
0.0
0.2
0.4
0.6
0.8
1.0
-4
-3
-2
-1
0
1
-3000
-2000
-1000
0
160
180
200
220
240
260
280
300

921


A
R
MS
SE
R
MS
SE
R
TDV (µm)
4000
3500
3000
2500
2000
1500
SDI
LFI
B
REW
0.8
0.6
0.4
0.2
0.0
215
220
225
230
235
240
245
250
255
260
DOY 2009 (215 = August 3)


90
80
70
60
50
40
30
20
100
80
60
40
80
70
60
50
P_p (kPa)
0 h
12 h
24 h
Day (white) & night (grey)
State 1: $P_c >> 50$ kPa
turgescent state
$\psi_{stem} > -1.2$ MPa
State 2: P_c close to 50 kPa
moderate water stress
$-1.2 \text{ MPa} > \psi_{stem} > -1.7$ MPa
State 3: $P_c << 50$ kPa
severe dehydration
$\psi_{stem} < -1.7$ MPa



Ψ_stem (MPa)
0
-1
-2
-3
b a a
c b a
b ab a
b b a
b b a
c b a
b a a
60RDI
30RDI
FI
165
180
195
210
225
240
255
270
285
300
DOY 2011
FI
60RDI
30RDI
State 1
State 2
State 3