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REVIEW

Evaluating the usefulness of continuous leaf turgor pressure measurements for the assessment of Persimmon tree water status

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Abstract Continuous plant water status monitoring is crucial in order to improve irrigation management. The non-invasive Yara ZIM-probe was assessed for detecting plant water stress in Persimmon trees (*Diospyros kaki* L.f.). The probe measures the pressure transfer function (P_p) through a patch of an intact leaf, which is inversely correlated with the turgor pressure. This technology was evaluated in two parallel experiments involving either distinct watering regimes or rootstocks with different drought tolerance [*Diospyros lotus* (L) and *Diospyros virginiana* (V)]. Concomitant measurements of midday stem water potential (Ψ_{stem}) and trunk diameter variations were taken throughout the experiments. P_p was highly correlated with Ψ_{stem}. Persimmon leaves exhibited the inversed P_p curve phenomena under water stress, which enabled the association of a particular range of Ψ_{stem} to each of the three leaf turgor states defined. Persimmon trees with no sign of initial or total inversion ensured Ψ_{stem} above −0.8 MPa, values considered of a well-watered Persimmon tree. Yara ZIM-probe readings as well as Ψ_{stem} and trunk diameter variation measurements pointed L as a more sensitive rootstock to drought than V. In conclusion, results showed that the Yara ZIM-probe can be used to continuously monitor water status in Persimmon trees although further research would be needed to ensure their feasibility for scheduling irrigation.

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Introduction

Water is becoming a limiting factor for crop production in much of the world (IPCC 2014). That is the case of the Mediterranean ecosystems where the scarce rainfall is not enough to cover the high crop water requirements during most of the season, and the water resources available are limited. Optimizing irrigation must be then a priority in order to ensure the sustainability of the agricultural systems.

Water-saving irrigation strategies such as the partial rootzone drying or regulated deficit irrigation (RDI) have been studied in depth in experimental and commercial orchards with successful results (Ruiz-Sanchez et al. 2010). A common conclusion in all the studies related to the implementation of water-saving irrigation strategies is that water stress monitoring is crucial in order to avoid an undesirable impact on yield. A series of plant-based water stress indicators can be found in the market to continuously monitor the plant water status throughout the season. Stem dendrometers, porometers, sap flow probes or the measurement of canopy temperature among others have been studied during the last decades in woody crops to automatically monitor the plant water status in an attempt to substitute the stem water potential measurement, which is the accepted method as reference despite being a destructive and time- and labor-consuming technique (Ballester et al. 2013a; Fernández and Cuevas 2010; Fernández 2014; Jones et al. 2009; Ortuño et al. 2010). The use of these methods in the field, however, is still a constraint for growers due to different reasons such as difficulty of installation, maintenance requirements and the need of processing a large amount of data (Fernández 2014).

Monitoring the leaf turgor pressure with a highly sensitive pressure sensor clamped to a patch of a leaf (Yara ZIM-probe, Zimmermann et al. 2008) has been reported as an easier to install and easier to use technique than the above-mentioned methods with a great potential to be used at field by growers (Fernández 2014).

The noninvasive Yara ZIM-probe is a magnetic-based probe that measures the pressure (P_p) transfer function through a patch of an intact leaf. This P_p has been shown to be inversely correlated with the turgor pressure (Zimmermann et al. 2008, 2009; Westhoff et al. 2009). The usefulness of the Yara ZIM-probe to detect plant water stress has been studied on several horticultural and fruit crops, providing evidence that it can detect changes in turgor pressure caused by variations in the microclimate or in the soil water availability (Westhoff et al. 2008; Zimmermman et al. 2009; Rüger et al. 2010, 2011; Ehrenberger et al. 2012; Fernández et al. 2011; Rodriguez-Dominguez et al. 2012). Moreover, some studies suggest that its use has the potential for efficiently select genotypes tolerant to water stress environments (Kant et al. 2014). Different approaches such as the assessment of the daily or nightly maximum P_p value, the turgor recovery phase during the afternoon or the reverse of the P_p curve, however, must be followed to determine the degree of stress reached by the plants depending on their physiological characteristics and their tolerance or sensitivity to drought stress, which makes necessary the assessment of this technology for each particular case.

Persimmon (*Diospyros kaki* L.f.) cultivation in Spain has steadily increased in the last decades from a cropped area of 2.000 ha in 2002, to an approximately 13.000 ha in 2014 (Perucho 2015). This notable increase in production is mainly due to the current replacement of citrus with Persimmon trees, particularly with the *cv*. 'Rojo Brillante,' which fruit reaches a higher value in the market than oranges, thanks to a postharvest treatment with high CO_2 concentrations that removes its astringency (Arnal and Río 2003). Studies performed in Valencia, Spain, with the *cv*. 'Rojo Brillante' showed that RDI strategies may lead growers to obtain water savings of 20 % without any reduction in yield, increasing then the water use efficiency (Buesa et al. 2013). Results also showed that fruit weight reduction in RDI trees caused a decrease in the fruit commercial value, pointing out that further research would be needed to define a successful RDI strategy for this crop. The Yara ZIM-probe technology could be a suitable tool to be used in this crop for irrigation scheduling in order to properly manage water stress and avoid any fruit size reduction that could affect the economic return obtained by farmers.

The objectives of the present study were: (1) to assess the feasibility of the Yara ZIM-probe for detecting plant water stress in Persimmon trees; (2) to explore the relationships between P_p and Ψ_{stem} for their possible use as a tool for irrigation scheduling in this crop; and (3) finally, to test the sensitivity of the Yara ZIM-probe in two rootstocks of differing drought tolerance.

Materials and methods

Plot and irrigation treatments

The experiment was performed during 2014 in a commercial orchard planted with Persimmon trees *cv*. 'Rojo Brillante' grafted onto two contrasting rootstocks in vigor, *Diospyros lotus* (L) and *Diospyros virginiana* (V) at a spacing of 5 m × 2.5 m. The plot was located in Liria (40°N, elevation 300 m), Valencia, Spain, where the climate is typically Mediterranean and the soil is sandy loam with 32 % by weight stones and an effective depth of 0.8 m. Soil density ranged from 1.35 to 1.45 t m^{-3} and was considered of low fertility (0.66 organic matter and 0.05 % total N).

Irrigation was applied with two drip lines leaving ten pressure compensated emitters (4 L h^{-1}) per tree. Water had an average electrical conductivity (EC) of 1.1 dS m^{-1} and an average Cl concentration of 122 mg L^{-1}. Irrigation was applied according to the estimated crop evapotranspiration ($ET_c = ET_o \times K_c$). Reference evapotranspiration, ET_o, (Allen et al. 1998) was obtained from a weather station located near the orchard, which also measured the solar radiation (Pyranometer CMP3, Kipp & Zonen, Delft, The Netherlands). Crop coefficient applied ranged from 0.2 in March to 0.9 at full canopy growth. As a part of an outgoing experiment, trees had been irrigated at 100 and 125 % ET_c.

The Yara ZIM-probes were tested on trees grafted on both rootstocks and irrigated at both rates. In a first experiment, trees grafted onto L and irrigated at 100 % ET_c (L-WW) during the whole experiment (total amount applied 332.5 mm) were compared with trees grafted onto the same rootstock (L-DS) in which irrigation was withheld during two periods from August 18th to August 23rd [day of the year (DOY) 230–235] and from August 29th to September 3rd (DOY 241–246). L-DS trees were irrigated as L-WW trees between the two drought cycles. A second experiment was then set up with trees irrigated at 125 % ET_c (total amount received 366.6 mm) in order to compare the behavior of trees grafted onto L (L-125-DS) and V (V-125-DS) rootstocks when subjected to drought cycles. In these trees, irrigation was withheld from August 25th to September 3rd (DOY 237–246).

The orchard was divided into three blocks of three rows each where the treatments were applied. All the treatments consisted of 21 trees (seven trees per row) with the five trees of the mid-row (perimeter trees were avoid) used for the measurements. The L-125-DS and V-125-DS treatments, in which four trees were used for the plant water status measurements, were carried out in the block of the middle while the L-WW and L-DS treatments in the remainder blocks.

Leaf turgor monitoring

The basic principle of the Yara ZIM-probe is described by Zimmermann et al. (2008) and the principle of the magnetic leaf patch clamp pressure probe by Westhoff et al. (2009). Briefly, the Yara ZIM-probe consists of two magnets that exert an external pressure to a patch of a leaf covering an area of 87 mm^2. One of the magnets contains a highly sensitive pressure sensor able to detect pressure variations up to 300 kPa. The sensor measures the difference in pressure between the magnets and the leaf turgor, named patch pressure (P_p), and therefore provides information about relative changes in leaf turgor at real time. The distance between the magnets can be regulated in order to set up the most suitable initial P_p, which ranges between 10 and 60 kPa.

All the Yara ZIM-probes were previously tested under laboratory conditions to ensure that ambient temperature (T_a) did not have any influence on their readings.

Selected trees from each treatment were equipped with two Yara ZIM-probes each (8–10 Yara ZIM-probes/treatment) on 13th and 14th of May, 2014. The Yara ZIM-probes were installed in mature leaves located in the east side of the canopies. In order to distinguish between relative changes in leaf turgor caused by water stress and those caused by microclimate variations (Zimmermann et al. 2013a), relative humidity (RH) and T_a sensors (Yara ZIM Plant Technology GmbH (Hennigsdorf, Germany) were also installed in the orchard. All probes (leaf turgor, T_a and RH) were connected by cable to transmitters which sent the data wirelessly every 5 min over a distance of up to 1500 m to a central controller (Yara ZIM Plant Technology GmbH Hennigsdorf, Germany). The controller contains a GPRS modem which is linked to an Internet server where data are stored and available for real-time inspection and download.

Other plant water status determinations

Measurements of Ψ_{stem} were carried out during the experiment to determine the plant water status in all the trees equipped with the Yara ZIM-probes. Measurements were performed at solar noon with a Scholander pressure chamber (PMS Instrument Company, mod. 600, OR, USA) using 2–4 mature leaves per tree previously bagged with aluminum foil for at least 1 h before the measurements to avoid transpiration (Turner 1981).

The four selected trees from L-125-DS and V-125-DS treatments (grafted onto the two contrasting rootstocks) were equipped with linear variable differential transformers (LVDT, Schlumberger mod. DF-2.5) to monitor trunk diameter variations during the drought stress cycles. Each sensor was fixed to the main trunk of the tree by a metal frame of Invar (a metal alloy with a minimal thermal expansion), located about 25 cm from the ground. All the transformers were previously calibrated in the laboratory by means of a precision micrometer (Verdtech SA, Spain). The trunk diameter variations were used to calculate the maximum daily trunk shrinkage (MDS) by obtaining the difference between the maximum (MXTD) and minimum (MNTD) diameter in a day. At the beginning of the experiment, trees grafted onto L and V had, respectively, an average trunk perimeter of 0.25 ± 0.004 and 0.23 ± 0.020 m. Data were automatically recorded every 30 s using a data logger (model CR10X) connected to an AM16/32 multiplexer programmed to report mean values every 30 min.

Data analysis

Data were analyzed using Statgraphics X64, Origin 2015 (Microcal Software Inc., Northampton, MA) and SigmaPlot 11.0. The relationship between P_p and the others water status indicators used during the measurement was explored by ANOVA and the least significant difference (LSD) procedure. Both methods take into account that values of $P < 0.05$ are considered to be statistically significant. Data shown are mean ± standard deviation.

Results

Meteorological conditions

Total ET_o and rainfall registered during the experiment (from April 1st to September 10th) were of 787 and 63 mm, respectively, which can be considered typical values for the area of study. Daily means of T_a ranged from 12.2 to 28.57 °C with a maximum temperature recorded in August of 40.5 °C. Daily means of RH ranged from 28.9 to 76.2 % with a minimum value reached in July (9.2 %).

Experiment 1: L-WW versus L-DS

Stem water potential measurements

The L-WW treatment in which water restrictions were not applied had Ψ_{stem} values around −0.60 MPa during the whole experiment (mean Ψ_{stem} of −0.62 ± 0.01 MPa;

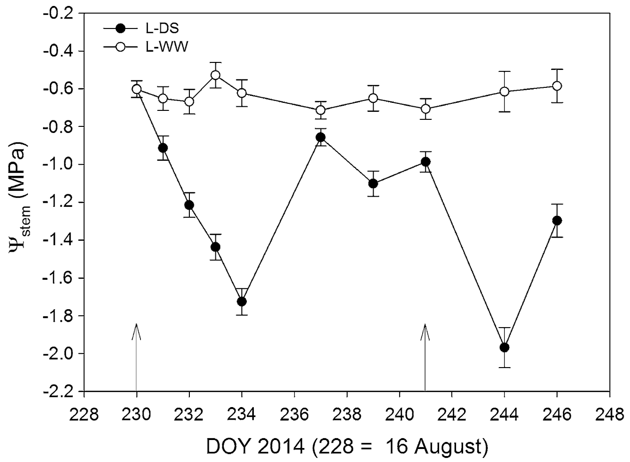

Fig. 1 Stem water potential (Ψ_{stem}) evolution in control (L-WW) and non-irrigated trees (L-DS) during the drought cycles. Each point is the average of 10–20 leaves (5 trees per treatment). *Vertical bars* represent the ±LSD intervals, and *arrows* indicate the starting of the drought cycles

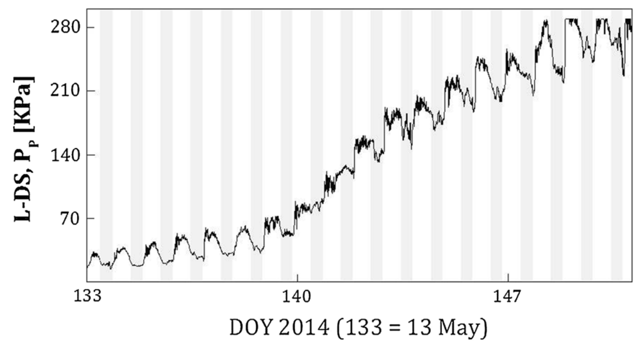

Fig. 2 Patch pressure (P_p) increase after clamping at the first stages of the leaf growth. Sensors were reclamped when P_p reached

Fig. 1). L-DS trees had similar Ψ_{stem} values to L-WW trees at the beginning of the experiment. Once water restrictions began, Ψ_{stem} dropped steadily to a minimum value of −1.73 and −1.93 MPa during the first and second drought cycles, respectively (Fig. 1).

Leaf turgor monitoring with the Yara ZIM-probes

A daily continuous increase in maximum (recorded at midday) and minimum (recorded at night) P_p was observed in all of the Yara ZIM-probe sensors at the beginning of the experiment just after clamping. Some probes showed a steadily P_p increase similar to the increase in air temperature recorded in May and stabilized after a couple of weeks. Other probes (about 35 %), however, exhibited a sharp increase in P_p reaching the maximum values detected by the sensor (250–300 kPa) in weeks (Fig. 2). These probes were reclamped again (several times in some occasions) until the P_p readings were more stable and treatments began (end of June).

Three different daily P_p curve shapes were obtained depending on the range of stress reached by the trees. Each of these shapes was associated to a leaf turgor state as reported in Ehrenberger et al. (2012); thus, state I was related to a daily P_p shape with peaking values at noon and minimum values recorded at night; state II was related to a half inverted curve with a sharp decrease of P_p at noon; and state III was related to a complete inversion of the P_p curve with minimum values recorded during the day and maximum values during the night. Figure 3 depicts the Ψ_{stem} and P_p evolution of a representative L-WW and L-DS tree during the experiment as well as the classification of the P_p shape curves in the above-mentioned states. The P_p curve in L-WW trees was all the time in state I, while L-DS trees showed a progressive change in the P_p curve shape from state I to state II and III as Ψ_{stem} decreased during the drought cycles. Similarly, the P_p curve shape in L-DS trees changed from state III to state II and I when irrigation was resumed as Ψ_{stem} recovered to similar values to the L-WW treatment. When data from all the Yara ZIM-probes of each treatment were analyzed, the P_p curve in L-WW trees was in the state I during the whole experiment. In L-DS trees, on the other hand, the P_p curve remained in the state I just 9.7 % of the time while it was 34.7 and 55.6 % of the time in the state II and III, respectively.

The assessment of the P_p curve shapes in both treatments during the experiment enabled the classification of each leaf turgor state within a range of Ψ_{stem}. Statistically significant differences in mean Ψ_{stem} were observed within trees from each leaf turgor state (Fig. 4). State I of leaf turgor was observed in trees with a Ψ_{stem} higher than −0.80 MPa. The intermediate state of leaf turgor (state II) was observed in trees with a Ψ_{stem} compressed between −0.69 and −1.33 MPa. Finally, the state III of leaf turgor was observed in trees with a Ψ_{stem} ranging from −1.02 to −2.40 MPa.

Experiment 2: L-125-DS versus V-125-DS

Stem water potential and trunk diameter measurements

Water restrictions applied in both treatments offered different results in terms of mean and maximum Ψ_{stem} values. During the drought cycle, L-125-DS treatment registered an average Ψ_{stem} of −0.97 ± 0.38 MPa with a minimum value of –1.80 MPa. In contrast, V-125-DS treatment had a higher mean Ψ_{stem} value of −0.80 ± 0.16 MPa and reached a minimum value of −1.14 MPa. Significant differences were found in Ψ_{stem} between trees grafted onto L and V rootstocks from 2 days of the beginning of the water restrictions (Fig. 5).

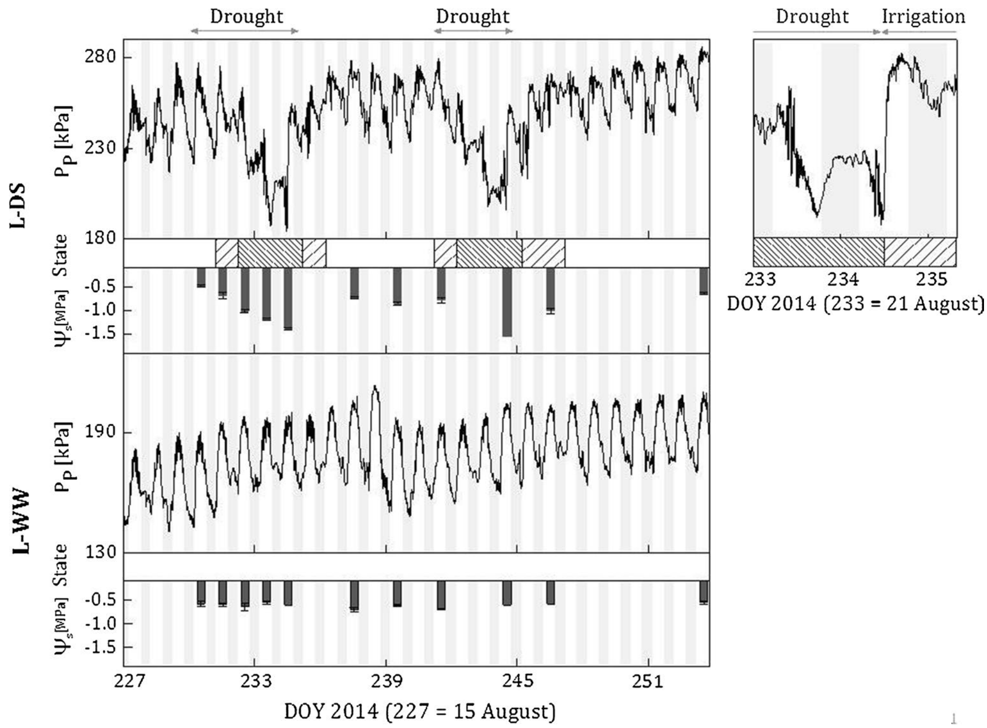

Fig. 3 Stem water potential (Ψ_{stem}, columns) and patch pressure (P_p, *solid line*) evolution in one control (L-WW) and one non-irrigated (L-DS) tree during the two drought cycles. Different P_p *curve* shapes associated with different plant water status are also identified for each treatment (state I *without lines*; state II with low-density *diagonal lines*; and state III high-density *diagonal lines*). Ψ_{stem} values are means; *vertical lines* indicate the standard errors, $n = 4$. *Shaded background columns* indicate the nocturnal hours. The *additional graph* highlights the fast recovery of the plant water status when the drought period finishes. The P_p *curve* shows the evolution from the state III to state II in several hours

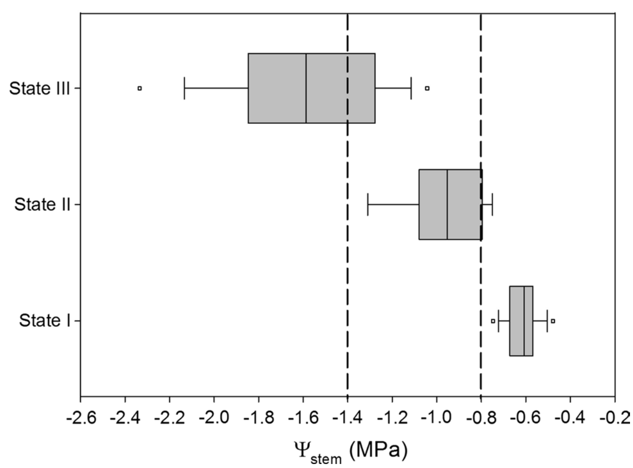

Fig. 4 Range of stem water potential (Ψ_{stem}) values obtained during the two drought cycles within each leaf turgor. Ψ_{stem} values are the average of five trees. *Horizontal bars* in *boxes* indicate the maximum and minimum values of Ψ_{stem} for each state. *Dotted border lines* define Ψ_{stem} thresholds for plant water status: adequate (>−0.8 kPa), mild to critical stress (−0.8 to −1.4 kPa) and moderate stress (<−1.4 kPa)

Trunk diameter variations were monitored during the same period. MDS was lower in V (179.0 ± 48.0 µm) than in L (215.4 ± 67.8 µm) although no significant differences were observed between the rootstocks until the end of the drought cycle when Ψ_{stem} reached values around −1.6 MPa in L trees (Fig. 5). The MXTD, on the other hand, was 42 % higher in V than in L rootstocks (Fig. 6), and it is important to highlight that during the drought period, V maintained a constant growth rate slope in contrast to L where trunk growth rates decreased.

Leaf turgor monitoring with the Yara ZIM-probes

The evolution of the P_p curve shape in the different leaf turgor states (I, II and III) was linked to the Ψ_{stem} measurements as did in experiment 1 (Fig. 7). The P_p curve in V-125-DS trees was most of the time in state I, while L-125-DS trees showed a gradual evolution from state I to state II and III. On average, L-125-DS was in state I, II and III 30, 30 and 60 % of the time, respectively. However, V-125-DS was 80 % of the time in state I and just 20 % in state II and III. Each leaf turgor state within each rootstock corresponded to a range of Ψ_{stem} (Fig. 8). L-125-DS reached lower values of Ψ_{stem} (−1.03 ± 0.18 and −1.41 ± 0.23 MPa) than V-125-DS (−0.91 ± 0.10 and −1.02 ± 0.29 MPa) for states II and III, respectively. However, state I in L-125-DS (−0.66 ± 0.10) was associated with higher Ψ_{stem} values than in V-125-DS (−0.74 ± 0.12).

Discussion

The results presented in this work point out the Yara ZIM-probes as a reliable tool for continuously monitoring plant water status in Persimmon trees. Notwithstanding the P_p evolution observed just after clamping (April–May), in

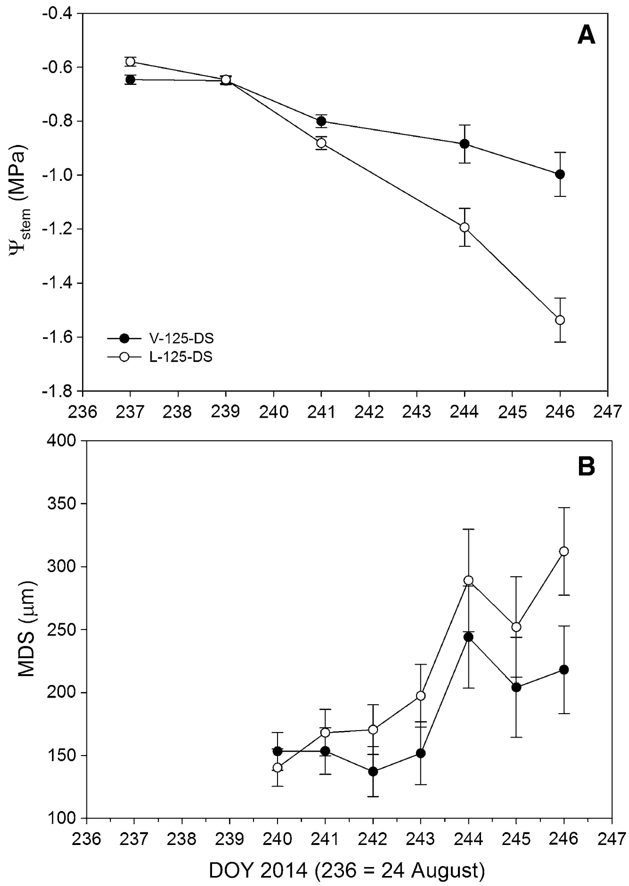

Fig. 5 Stem water potential (Ψ_{stem}) and maximum daily trunk shrinkage (MDS) evolution in trees grafted onto lotus (L-125-DS) and virginiana (V-125-DS) during the drought cycle. *Each point* in figure (**a**, **b**) is the average of 10–20 leaves (5 trees per treatment) and 4 trees, respectively. *Vertical bars* represent the ± LSD intervals

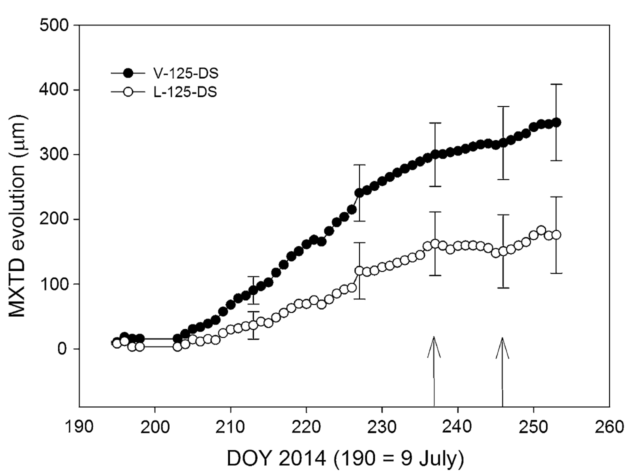

Fig. 6 Maximum daily trunk diameter (MXTD) monitored during the crop season. *Each point* is the average of four diameter trees. *Vertical bars* represent the ± LSD intervals, and *arrows* indicate the starting of the drought cycles

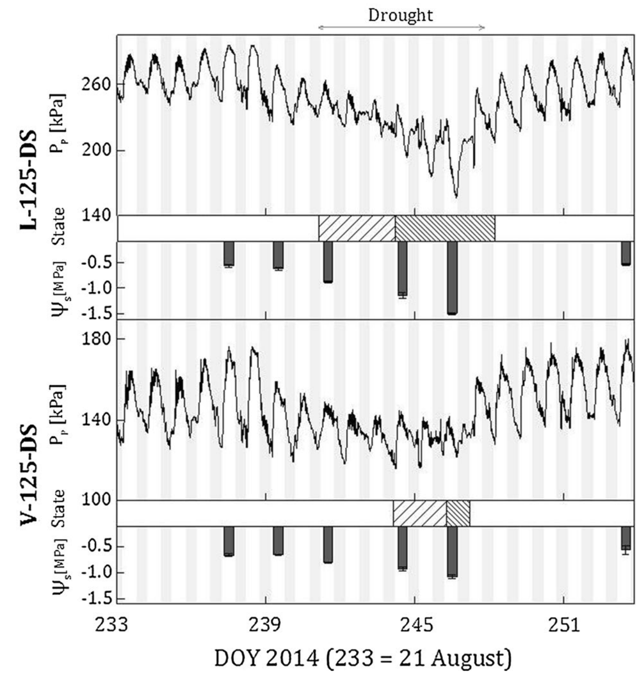

Fig. 7 Stem water potential (Ψ_{stem}, *columns*) and patch pressure (P_p, *solid line*) evolution in a plant grafted onto lotus (L-125-DS) and virginiana (V-125-DS) during the drought cycles applied. Different P_p *curve* shapes associated with different plant water status are also identified for each treatment (state I *without lines*; state II with low-density *diagonal lines*; and state III high-density *diagonal lines*). Ψ_{stem} values are means; *vertical lines* indicate the standard errors, $n = 4$. The *shaded background columns* indicate the nocturnal hours

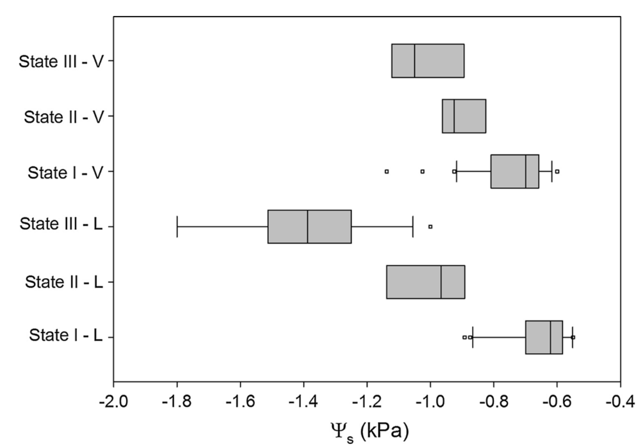

Fig. 8 Stem water potential (Ψ_{stem}) values within each state of leaf turgor in trees grafted on lotus (L) and virginiana (V) trees. *Horizontal bars* indicate the maximum and minimum values of Ψ_{stem} for each state

which daily and nightly P_p increased reaching the maximum pressure detected by the sensor in some of the probes (Fig. 2), leaf turgor monitoring with the Yara ZIM-probes enabled the detection of mild to severe water stress in

Table 1 Stem water potential (Ψ_{stem}) associated with each of the leaf turgor states observed in control (L-WW) and non-irrigated (L-DS) trees. Water status for the average, maximum and minimum Ψ_{stem} recorded within each state is also shown

State	Ψ_s (MPa)			Water status		
	Average	Maximum	Minimum	Average	Maximum	Minimum
I	−0.61 ± 0.08	−0.79	−0.47	Adequate	Adequate	Adequate
II	−0.98 ± 0.19	−1.33	−0.69	Mild stress	Moderate stress	Adequate
III	−1.58 ± 0.36	−2.40	−1.02	Moderate stress	Severe stress	Mild stress

The interpretation of the Ψ_{stem} values in relation to the degree of water stress is derived from previous experiments carried out in order to determine Persimmon trees responses to different irrigation regimes (Badal et al. 2010, 2013; Buesa et al. 2013)

L-DS, L-125-DS and V-125-DS trees as well as their recovery when irrigation was resumed.

The particular P_p evolution observed just after clamping in Persimmon trees has not been reported for other fruit tree crops. This effect could be related to the structure of Persimmon leaves which is more complex than in other crops due to their density and thickness. Moreover, the foliar limb is slightly wavy and the main and secondary nervation stands out on the abaxial surface (Giordani et al. 2015), which most likely hamper the proper continuity between magnets. More studies would be needed regarding this matter to untangle this unusual behavior of P_p and be able to monitor leaf turgor during the whole growing period of Persimmon trees.

Different approaches can be followed to detect plant water stress when analyzing data from the Yara ZIM-probes (Zimmermann et al. 2013b). The assessment of the maximum daily P_p seems to be a useful method for clementine trees, in which a half or complete inversion of the P_p curve does not often occur even under severe (Ψ_{stem} of up to −1.9 MPa) water-stressed conditions (Ballester et al. 2016). Contrary to this and more in the line of what has been reported for other crops like almond, eucalyptus, avocado (Zimmermann et al. 2013b) and olive trees (Fernández et al. 2011; Ehrenberger et al. 2012; Padilla-Díaz et al. 2015), the change observed in the P_p curve profile was shown as a useful method to detect drought stress in Persimmon trees. The change in the P_p curve profile from a normal curve peaking at midday to a half and eventually complete inversion of the curve as a consequence of the water replacement for air into the parenchyma tissue of cells leaves [see Ehrenberger et al. (2012) for more details] made possible to differentiate between three ranges of Ψ_{stem} linked to well-watered, moderate and severe water-stressed trees. The P_p curve profiles were classified in three states of leaf turgor as described in Ehrenberger et al. (2012). Thus, each state was linked to a range of Ψ_{stem} and consequently to a plant water status (Table 1). State I, in which L-WW trees remained during the whole study and L-DS trees just less than 10 % of the time during the drought cycles, was linked to Ψ_{stem} values above −0.8 MPa, considered of well-watered Persimmon trees (Badal et al. 2010). The Ψ_{stem} thresholds for the intermediate state of leaf turgor (−0.69 and −1.33 MPa) were overlapped with the upper limit of state I (−0.79 MPa) and the lower limit of state III (−1.02 MPa) (Table 1). State II would include then trees with mild to moderate water stress (George et al. 1995), whereas trees within the state III, with Ψ_{stem} values ranging from −1.02 to −2.40 MPa, would indicate trees with moderate to severe water stress. Additionally, irrigation effect and water status recovery were also detected by the Yara ZIM-probes immediately. When irrigation was resumed after a drought cycle, the daily P_p curves evolved from the inverse shape to the half inverse or even the normal shape directly (see this behavior highlighted in Fig. 3).

These results show that leaf turgor monitoring with the Yara ZIM-probes could possibly be used in Persimmon trees for irrigation scheduling. Irrigation management has been proven as a useful tool to reduce fruit drop in Persimmon trees cv. 'Rojo Brillante' (Badal et al. 2013). Water restrictions applied during spring or summer have been reported as effective strategies to decrease fruit drop and significantly increase water use efficiency in this crop (Buesa et al. 2013). Nevertheless, fruit growth in this particular cv. ('Rojo Brillante') is highly sensitive to deficit irrigation and a proper management of the water stress reached by the trees is crucial to do not impair fruit size and reduce farm profitability (Buesa et al. 2013). The use of the Yara ZIM-probes in orchards under deficit irrigation strategies could provide continuous information of plant water status for an adequate management of water stress. Based on Buesa et al. (2013), fruit drop could be reduced by maintaining trees within the state II of leaf turgor during either spring or summer for a couple of weeks and then leading them to state I by increasing water allocations. The unusual P_p readings observed after clamping should not be a problem when using the probes in RDI orchards provided that these were installed in the trees with enough time to stabilize before the period of water restrictions, which in spring RDI strategies is recommended from late May to mid-July. Further research on how crop load and other factors apart from water status influence leaf turgor would be valuable in order to design deficit irrigation strategies based on Yara ZIM-probe readings.

Compared with the results obtained by Fernández et al. (2011) in a similar study conducted in Seville on olive trees, states I, II and III of leaf turgor in Persimmon trees were related to higher values of Ψ_{stem}. These results could be expected since olive is a well-adapted crop to water-limited environments (Connor 2005), while Persimmon has been reported as a crop not highly sensitive to vapor pressure deficit and with poor stomatal regulation (Badal et al. 2010; Ballester et al. 2013b).

In this study, the sensitivity of the Yara ZIM-probe to detect drought stress was tested in the experiment 2 comparing trees grafted on contrasting rootstocks to drought tolerance. V rootstock is known to produce more vigorous plants (larger root system) than L, which ensure a better performance of trees when are planted in heavy and dry soils (Badenes et al. 2015). Both rootstocks are used in the area of study although 90 % of the production stands on trees grafted onto L. Results obtained from the Ψ_{stem} and trunk diameter variation measurements showed that trees grafted onto V remained in a better plant water status than those grafted onto L during the drought cycle. These differences in water status were also reflected in the leaf turgor measurements since trees grafted onto V remained more days in state I (well-watered conditions, 8 out of 10 days) than those grafted onto L (3 out of 10 days). The use of the Yara ZIM-probes to monitor leaf turgor in combination with other plant physiological assessments may provide then useful information to assess the response of rootstocks to drought stress in order to identify those more adequate for a range of scenarios with different water-limiting conditions.

Conclusions

The results obtained from this study show that continuous leaf turgor monitoring with the Yara ZIM-probes enabled the detection of water stress in Persimmon trees. Three states of leaf turgor were identified depending on the shape of the P_p curve (normal, half inverted and total inverted) obtained from the probes. State I (Ψ_{stem} above −0.8 MPa) was observed during the whole experiment in the well-watered trees and when water restrictions were not applied in the drought-stressed treatments. States II and III of leaf turgor were observed just during the drought cycles when trees reached Ψ_{stem} values considered of mild to severe water stress.

These results suggest, on one hand, that the Yara ZIM-probe could be a possible tool to be used in this crop for scheduling irrigation. Further research, however, is needed to address different aspects such as the unusual P_p evolution observed just after clamping or how P_p is influenced by the seasonal variability in tissue water relations, or crop load before attempting to recommend its use for irrigation scheduling purposes. Its use along with other physiological measurements, on the other hand, may be used to assess the tolerance of rootstocks to drought stress with the aim to identify those more adequate for semiarid environments.

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