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Long-term validation of continuous measurements of trunk water potential and trunk diameter indicate different diurnal patterns for pear under water limitations

Victor Blanco [a,b], Lee Kalcsits [a,b,*]

[a] *Tree Fruit Research and Extension Center, Washington State University, Wenatchee, WA 98801, USA*
[b] *Department of Horticulture, Washington State University, Pullman, WA 99164, USA*

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ABSTRACT

Microtensiometers are plant-based sensors than can continuously measure trunk water potential (Ψ_{trunk}). This new water status indicator, Ψ_{trunk}, was compared with the midday stem water potential (Ψ_{stem}) measured with a pressure chamber, the current standard for assessing water status in trees, leaf water potential, and maximum daily shrinkage (MDS) in adult 'D'Anjou' pear trees (*Pyrus communis* L.) irrigated following two strategies, (1) a control treatment (CTL) irrigated at 100% of crop evapotranspiration and, (2) regulated deficit irrigation (RDI). Ψ_{trunk}, Ψ_{stem} and MDS were directly influenced by soil water content and atmospheric demand. MDS was able to detect water stress in DI trees the earliest. However, variability was high and it was not sensitive enough to detect significant differences between irrigation treatments at the end of the season. MDS had a maximum value of 300 µm (Ψ_{stem} =−1.4 MPa). On the other hand, variation for midday Ψ_{stem} and Ψ_{trunk} was low and both indicators were able to distinguish between irrigation strategies. Midday Ψ_{stem} and Ψ_{trunk} had a strong linear relationship similar to the identity line ($R^2 = 0.88$). However, when Ψ_{stem} and Ψ_{trunk} were compared in the afternoon, Ψ_{trunk} reported by microtensiometers was − 0.7 MPa lower than Ψ_{stem} measured by a pressure chamber. The daily relationship between trunk diameter variations and Ψ_{trunk} measured with the microtensiometers followed five different stages. Changes in trunk diameter were delayed relative to changes in Ψ_{trunk}. The seasonal relationship between the MDS and Ψ_{trunk} was strongly related at the start of deficit irrigation ($R^2 = 0.63$), but when the complete season was considered, this relationship was weaker ($R^2 = 0.44$). Moreover, the low coefficient of variation and high sensitivity of the midday Ψ_{trunk} measured with the microtensiometers supports the suitability of using them in automated irrigation systems to monitor tree water status in spite of their high dependence on environmental conditions. This is one of the first studies that validates the use of microtensiometers to continuously monitor tree water status in fruit trees across two consecutive seasons under differing irrigation treatments.

1. Introduction

Plant biosensors integrate soil water availability and atmospheric water demand across phenological stages (Jones, 2008; Fernández, 2017; Fernandes-Silva et al., 2019; Noun et al., 2022). Plant-based sensors are preferred over soil moisture or atmosphere-based measures or models. Stem water potential has been extensively identified as a sensitive measure to assess tree water status (McCutchan and Shackel, 1992; Naor, 2000; Suter et al., 2019) over other indicators. However, despite being a standard measure, it has always been a time-consuming, non-automated method, which has limited its use (Bellvert et al., 2016; Boini et al., 2019; Conesa et al., 2019). Stem water potential directly assesses water tension within the trunk by quantifying the pressure required to push sap through the petiole of a leaf that has stopped its transpiration, by enclosing it in a plastic bag that is surrounded by aluminum foil, and is in equilibrium with the trunk. Stem water potential has been traditionally measured with a pressure chamber and is a temporally discrete and destructive measurement (Scholander et al., 1965). For these reasons, there is interest in developing continuous plant-based indicators that are as effective at measuring tree water

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[*] Correspondence to: Tree Fruit Physiology, Endowed Chair of Tree Fruit Environmental Physiology and Management, Washington State University, Department of Horticulture, WSU Tree Fruit Research and Extension Center, 1100 North Western Ave, Wenatchee, WA 98801, USA.
E-mail address: lee.kalcsits@wsu.edu (L. Kalcsits).

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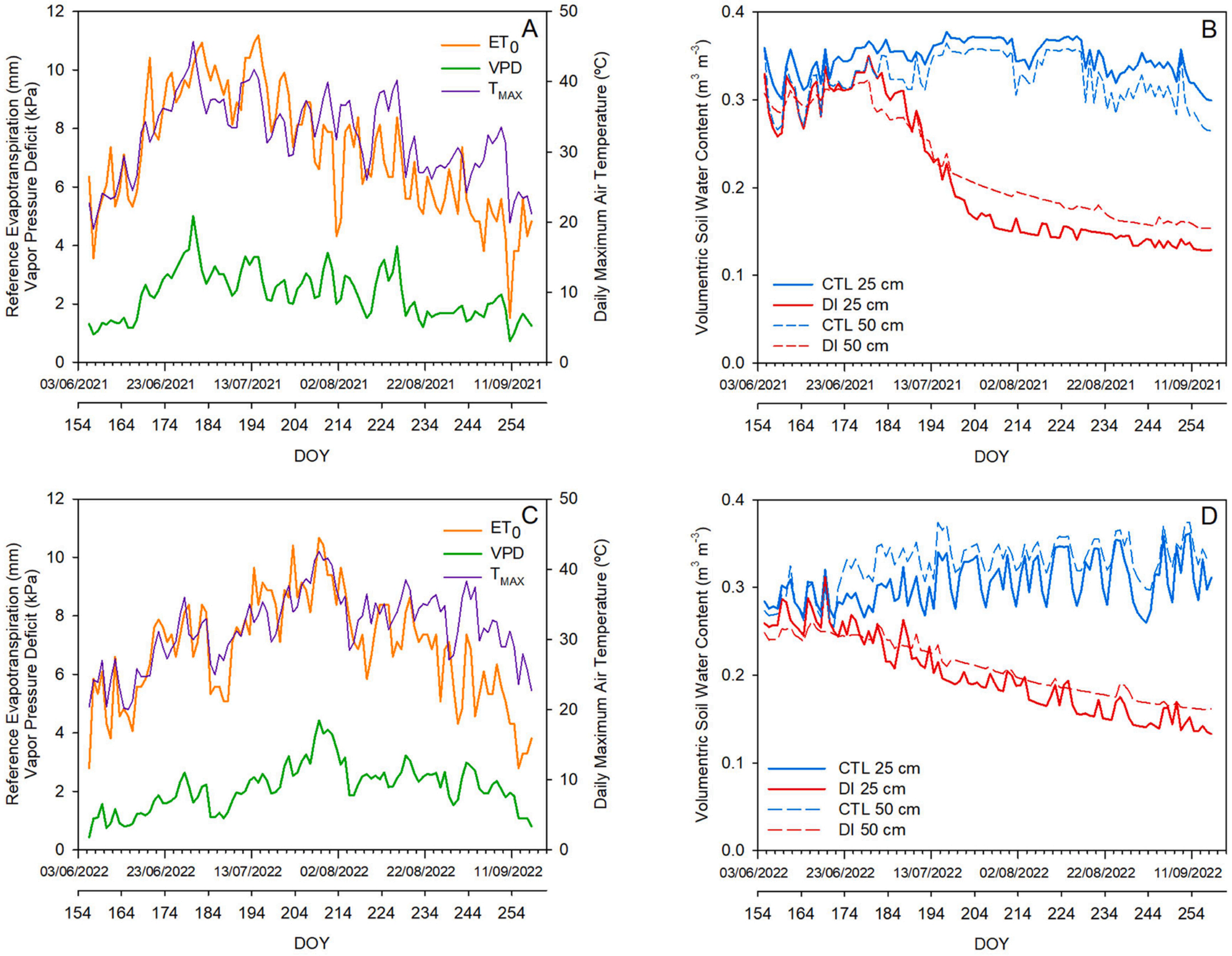

Fig. 1. Evapotranspiration (ET_0), vapor pressure deficit (VPD), and maximum daily temperatures (T_{max}) (A and C) and volumetric soil water content (m^3 m^{-3}) at 25 and 50 cm depth (B and D) for 2021 and 2022.

status, can be automated, subjected to remote control, and be part of an autonomous irrigation system (Steppe et al., 2008). These approaches and sensors include those that monitor trunk diameter variations, sap flow (Pereira et al., 2007; Conejero et al., 2007; Green et al., 2009), leaf turgor pressure (Rüger et al., 2010; Zimmermann et al., 2013; Padilla-Díaz et al., 2018), canopy temperature (Costa et al., 2019; Gonzalez-Dugo et al., 2019), and stem water content (McDonald et al., 2002; He et al., 2021). These approaches are either a function of downstream effects from changes in stem water potential or suffer from high variability for measurements.

Trunk diameter variations and indices derived from diurnal patterns have also been widely studied and reported to reflect tree water status (Ortuño et al., 2010). These measurements are based on changes in the water content of extensible tissues of the trunk which cause variations in trunk diameter (Vieira et al., 2022). Trunk diameter measurements are recommended over fruit diameter for irrigation decisions. Maximum daily shrinkage (MDS) is among the most frequently derived indices and is calculated as the difference between the maximum and minimum diameter on the same day. This is a sensitive indicator for detecting early water stress in mature fruit trees (Mirás-Avalos et al., 2017). However, in some cases, when the stem water potential decreases below a specific threshold value, MDS values do not continue to increase and even a reduction in the MDS values have been reported under severe water stress conditions (Girón et al., 2016; Blanco et al., 2018).

A common approach for validation is to compare sensor data with stem water potential measured with the pressure chamber. Microtensiometers directly measure trunk water potential in situ using microelectromechanical pressure sensors that are embedded into the trunk of the tree (Pagay et al., 2014). This produces continuous water potential measurements which might help improve irrigation strategies based on tree water status (García-Tejera et al., 2021). The daily pattern of trunk water potential recorded by microtensiometers has been positively associated with stem water potential measured with a pressure chamber (Blanco and Kalcsits, 2021). In vines, Pagay (2022) also reported the diurnal patterns of trunk water potential from microtensiometers. However, both of these studies made comparisons across a short period of time. While recently there is an increasing interest in assessing the microtensiometers as a tool for irrigation management (Lakso et al., 2022; Gonzalez et al., 2022), there are few studies that examine trunk water potential measured by microtensiometers across whole seasons and compare its measurements with data acquired from established methods like a pressure chamber or trunk dendrometers. To our knowledge, this is the first study in which the trunk water potential is compared with the trunk diameter variations. The aim of this study was to make long-term comparisons of stem water potential values measured with either microtensiometers or with a pressure chamber and to compare stem water potential with MDS for detecting early water stress in pear trees under controlled water limitations.

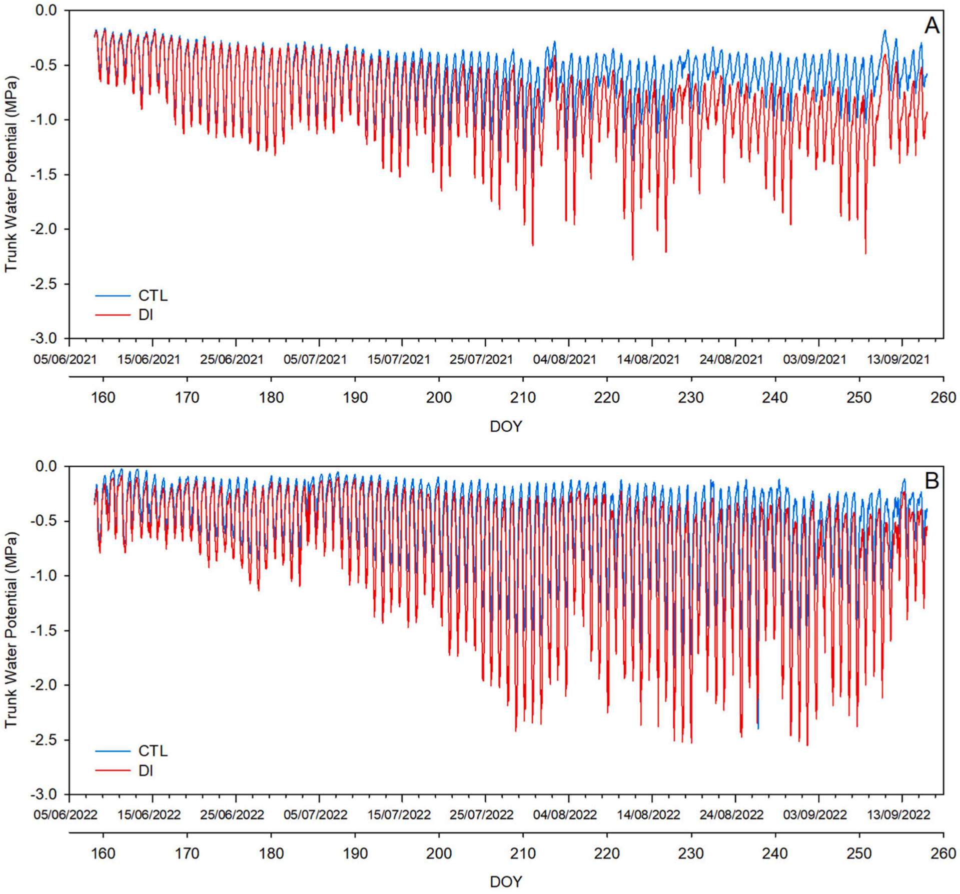

Fig. 2. Hourly trunk water potential (Ψ_{trunk}) continuously measured with microtensiometers for deficit irrigated (DI) or fully irrigated (CTL) trees from June 8 to September 15 in 2021 (A) and 2022 (B) (N = 6).

2. Materials and methods

2.1. Experimental site

The experiment was conducted in 2021 and 2022 at the Washington State University experimental orchard located in Rock Island (Washington State, USA, 47° 19′ N, 120° 04′ W). The experimental plot (0.81 ha) was 'D'Anjou' pear (*Pyrus communis* L.) orchard grafted on OHxF.87 rootstock and trained on a central leader system at a tree density of 833 trees per hectare (2.67 ×4.5 m), planted in 2007. The soil was a shallow sandy loam and trees were drip irrigated by a system consisting of a single drip line per tree row and five emitters per tree of 2 L h^{-1} discharge rate. Horticultural practices (e.g. fertilization, pruning, and weed control) were the same for all trees in the block and followed commercial regular practices. Full bloom was in April, and harvest was in late August - early September for both years.

2.2. Irrigation treatments

Two irrigation treatments were imposed: 1. A control treatment (CTL), irrigated at 100% of crop evapotranspiration (ET_C) to ensure non-limiting soil water conditions during the complete season. 2. A regulated deficit irrigation treatment (DI), irrigated at 100% of ET_C from full bloom to early stage of cell expansion, April 1st to June 27th in 2021 and April 1st to June 24th in 2022, and 50% of ET_C until the end of the season (October). ET_C was calculated weekly according to Allen et al. (1998) from the product of the reference evapotranspiration (ET_0), the crop-specific coefficient for adult pear trees varying from 0.3 to 0.9 depending on the phenological stage and percentage of ground covered (Marsal et al., 2012), and the evaporation reduction coefficient (Fereres et al., 1982). Treatments were arranged in a completely randomized block design with three replicates per treatment with six trees in each replicate. Two trees per replicate were selected for their uniformity (average ground cover of 41% and mean trunk diameter of 10.5 ± 0.23 cm) for measurements.

2.3. Weather and soil monitoring

Hourly meteorological data were recorded by an AgWeatherNet station located at the experimental orchard (http://www.weather.wsu.edu; "Sunrise station"). The variables measured were air temperature, relative humidity, wind speed, precipitation, and solar radiation. Daily ET_0 was calculated according to the FAO-56 Penman–Monteith equation (Allen et al., 1998) and air vapor pressure deficit (VPD) from air temperature and relative humidity. Moreover, in order to consider the microclimate conditions within the pear orchard, two temperature and relative humidity sensors (ATMOS-14, METER Group Inc., Pullman, WA, USA) were also installed in the orchard. Soil volumetric water content was measured at 0.25 and 0.50 m depth with two capacitance/frequency domain sensors (TEROS 11, Meter Group, Pullman, WA, USA) per replicate. The soil sensors were installed under the canopy and placed 0.25 m from the drip emitter.

2.4. Trunk, stem and leaf water potential

Ψ_{trunk} was recorded every 20 min in six trees per treatment, two per replicate, using microtensiometers connected to a solar powered data logger (FloraPulse, Davis, CA, USA). The microtensiometers were embedded into the trunk of the selected trees each year of study on the North side of the trunk away from direct sunlight. The

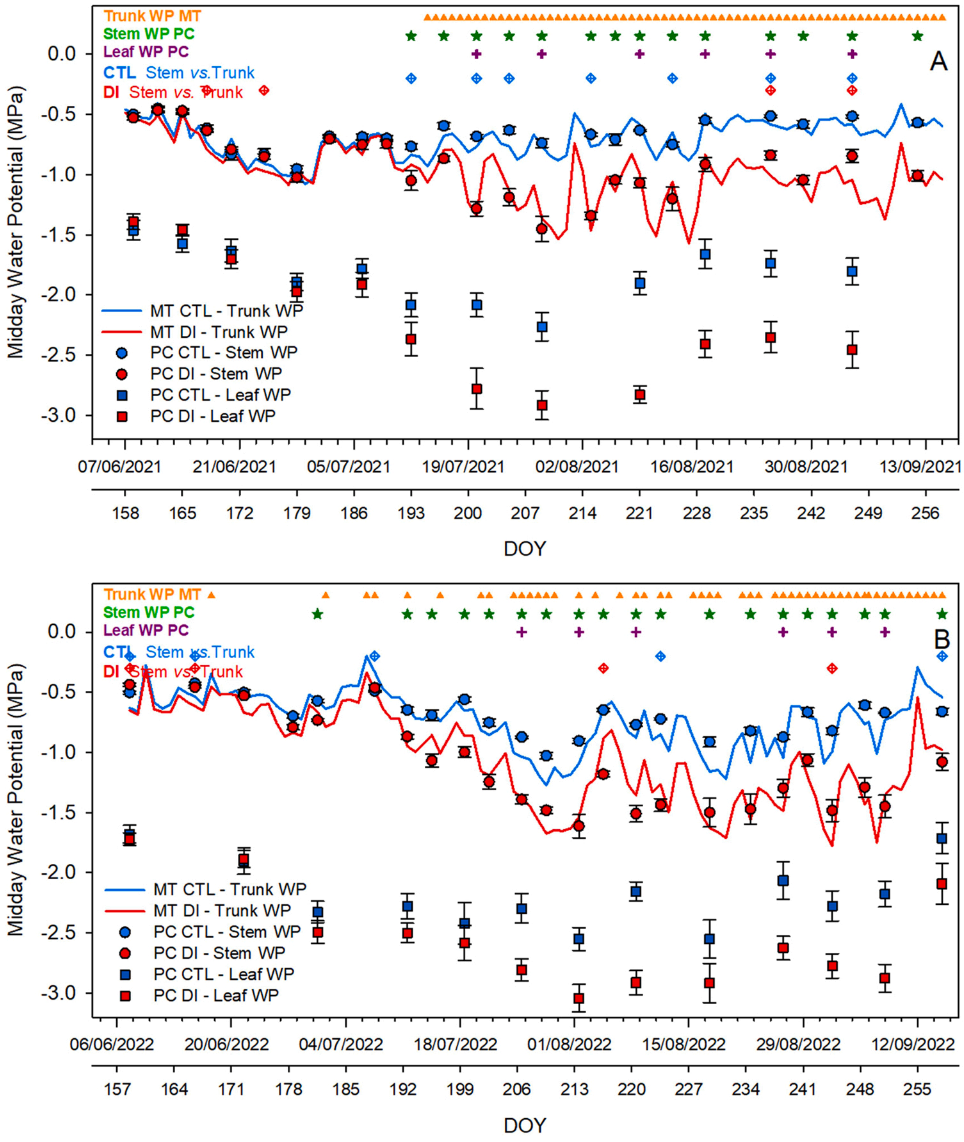

Fig. 3. Daily midday trunk water potential (trunk WP) measured by the microtensiometers (MT), midday stem water potential (stem WP) measured with the pressure chamber (PC) and midday leaf water potential (leaf WP) measured with the pressure chamber (PC) in 2021 (A) and 2022 (B) (N = 6). Orange triangle, green asterisk, and purple cross denote significant differences in Ψ_{trunk} measured using a microtensiometer (Trunk WP MT), Ψ_{stem} measured using a pressure chamber (stem WP PC), and Ψ_{leaf} (leaf WP), respectively between CTL and DI trees, according to an ANOVA test ($P < 0.05$). Blue and red diamonds denote significant differences between trunk and stem water potential for the CTL and DI trees respectively (Stem vs Trunk) according to ANOVA ($P < 0.05$). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

microtensiometers were not reinstalled, nor left working in the same tree for two seasons, each season new sensors were used in the same trees. The daily range of the Ψ_{trunk} was calculated as the daily difference in Ψ_{trunk} between the maximum and minimum value recorded by the microtensiometers.

Ψ_{stem} was manually measured with the Scholander pressure chamber (Model 615D, PMS Instrument Company, Albany, OR, USA) at solar midday every 4–7 days in six healthy, mature, and shaded leaves located close to the trunk per treatment. Leaves were wrapped with black polyethylene plastic and covered with aluminum foil for at least 2 h prior to the measurements (McCutchan and Shackel, 1992). Moreover, Ψ_{stem} was measured in 2022 every 14 days with the pressure chamber in the afternoon (15:30–16:30 h, solar time) for the same trees where microtensiometers were installed to validate the relationship between the Ψ_{stem} and Ψ_{trunk}. Midday leaf water potential (Ψ_{leaf}) was measured every 14 days in six fully-expanded, mature leaves from branches in the lower half of the canopy per treatment in the same trees where microtensiometers were installed with the same Scholander pressure chamber.

2.5. *Trunk diameter fluctuations*

Trunk diameter was monitored in 8 trees, 4 trees per treatment, every 10 min using linear voltage differential pressure transducer dendrometers (LVDT, model DE-1 T, Implexx Sense, Melbourne, Australia) installed on the northern side of the trunks, 30 cm above the point where the microtensiometers were installed. Sensors had a 0.001 mm resolution. Maximum daily shrinkage (MDS) was calculated as the daily difference in diameter between the maximum and the minimum (Goldhamer and Fereres, 2001).

2.6. *Statistical analysis*

Relationships between plant water status indicators and meteorological variables were explored through linear and non-linear regression analyses performed with SigmaPlot 12.5 (Systat Software Inc., San Jose, CA, USA). The sensitivity (S) of water stress indicators were calculated according to Goldhamer and Fereres (2001) for Ψ_{stem} measured with the pressure chamber and Ψ_{trunk} measured with the microtensiometers at midday, the daily mean and range of Ψ_{trunk}, and the MDS. S was calculated by dividing Signal Intensity (SI), calculated as the ratio between CTL and DI, by the coefficient of variation (CV). Data were analyzed by using analysis of variance (ANOVA) with a significance level of $p < 0.05$ (IBM SPSS Statistics, SPSS Inc., 24.0 Statistical package, Chicago, IL, USA). Linear regression analysis was performed with

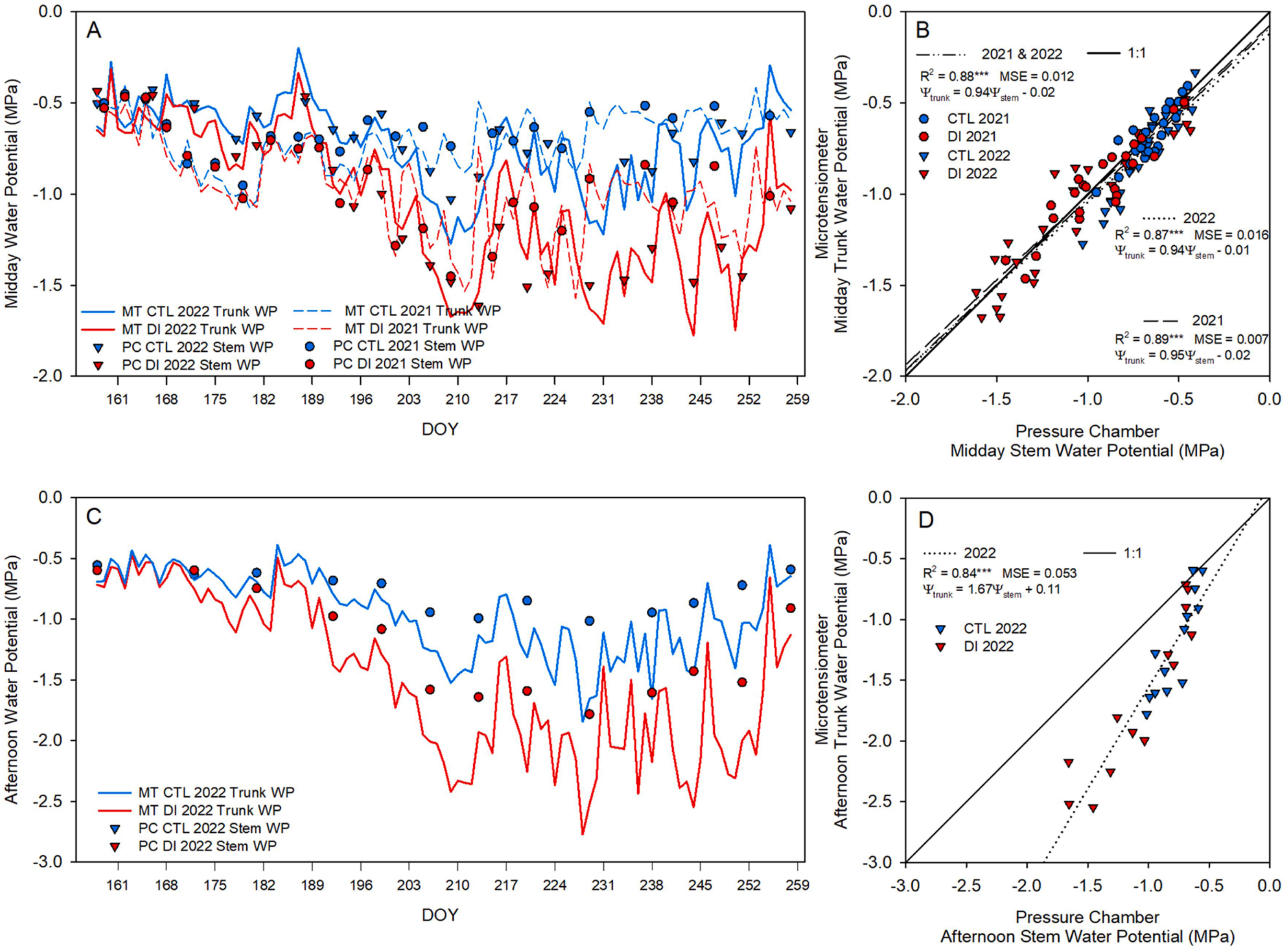

Fig. 4. Top: Daily midday stem water potential measured with the microtensiometers (MT) and the pressure chamber (PC) for both years 2021 and 2022 (A) and the linear relationship between them for each season and both seasons together (B). Bottom: Daily stem water potential measured in the afternoon (15:30–16:30 h) with the MT and the PC during the 2022 season (C) and the linear relationship between them (D).

SigmaPlot 12.5 (Systat Software Inc., San Jose, CA, USA).

3. Results

3.1. Weather and soil water status

The daily maximum air temperature ranged from 20 °C in early June and mid-September and 45 °C in early July in 2021 and late July in 2022 (Fig. 1). 67 and 64 days out of the 105 days had maximum air temperature that exceeded 30 °C in 2021 and 2022, respectively. The minimum air temperature varied between 10 and 25 °C. The daily ET_0 and the VPD was highly variable during the season, reaching maximum daily average values slightly higher in 2021 (11.5 mm and 5.0 kPa, DOY 180) than in 2022 (11 mm and 4.5 kPa, DOY 209). Daily maximum photosynthetic photon flux density (PPFD) was similar for both years peaking in late June at approximately 1900 μmol m^{-2} s^{-1}, and decreasing below 1400 μmol m^{-2} s^{-1} by September.

Volumetric soil water content in the CTL treatment from 0.25 to 0.50 m depth ranged between 0.27 and 0.37 m^3 m^{-3} during both years of study. In the DI treatment, soil water content strongly decreased once deficit irrigation started, it was similar to the CTL in June (0.30 m^3 m^{-3}) and then decreased to values similar to 0.15 m^3 m^{-3} at the end of the experiment for both years (Fig. 1). The rate of decrease was faster in 2021 than 2022 where volumetric soil water content fell below 0.15 m^3 m^{-3} by the end of July in 2021 and by the middle of August in 2022.

3.2. Trunk and stem water potential. Microtensiometers and pressure chamber

Ψ_{trunk} continuously measured using microtensiometers clearly showed differences between irrigation treatments in both years of the study (Fig. 2). Daily minimum Ψ_{trunk} was often reached during the afternoon when atmospheric demand was the highest. Once deficit irrigation started, daily minimum Ψ_{trunk} of DI trees were lower than those of the CTL trees. However, the daily maximum values observed at sunrise were similar for both treatments. When the evaporative demand increased, 30 days after the start of deficit irrigation, both the maximum and the minimum Ψ_{trunk} of the DI trees were significantly lower than those from the CTL trees. In 2022, both CTL and DI trees had higher variability and range of daily measurements than in 2021, with minimum values in midsummer of 2021 for DI trees of − 2.0 MPa and in 2022 of − 2.5 MPa. Daily mean Ψ_{trunk} was lower for DI trees in 2021 than in 2022. Following this pattern, Ψ_{trunk} was below − 1.0 MPa for 25 days in 2021 and 14 days in 2022 for DI trees. However, there were more extreme negative Ψ_{trunk} observed in 2022. Daily minimum Ψ_{trunk} values were below − 2.0 MPa for 5 days in 2021 and for 31 days in 2022 (Fig. 2).

Ψ_{trunk} measured with the microtensiometers at midday closely followed Ψ_{stem} and Ψ_{leaf} values measured with a pressure chamber at midday (Fig. 3). Midday Ψ_{stem} for CTL trees under no soil water limitations were between − 0.5 and − 0.8 MPa, with the lowest value of

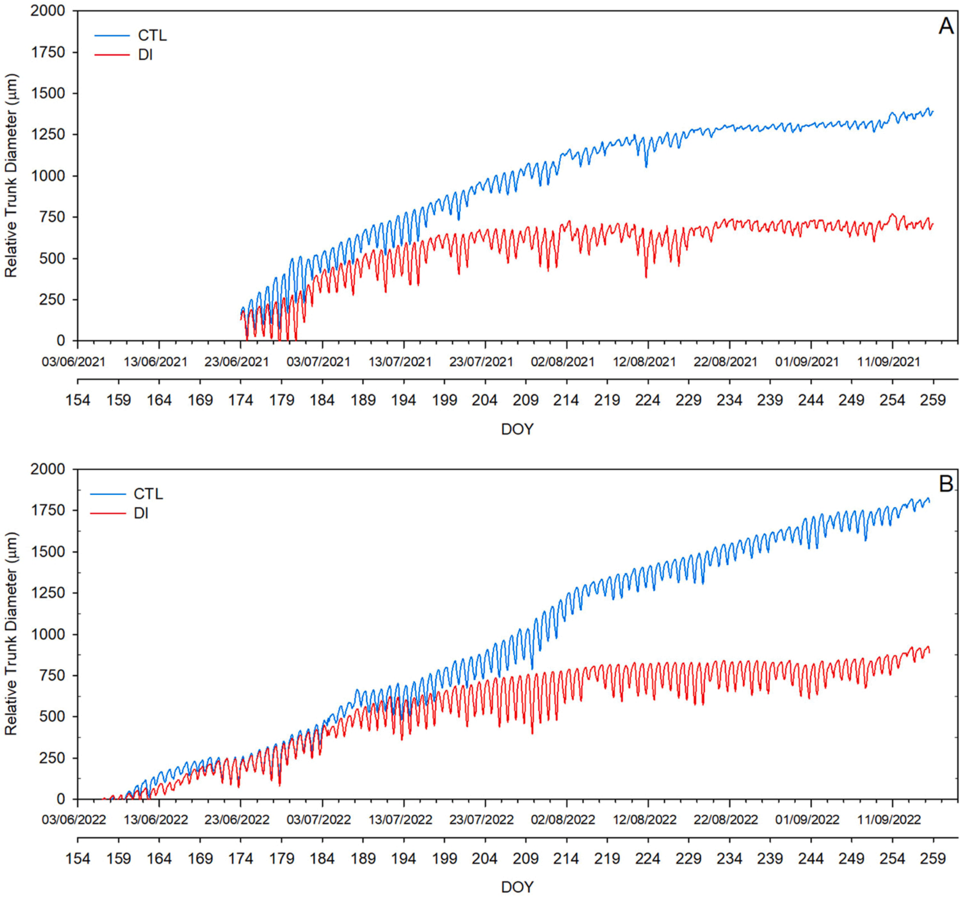

Fig. 5. Mean hourly relative trunk diameter (µm) in 2021 (A) and 2022 (B) for deficit irrigated (DI) and control (CTL) irrigated trees (N = 4).

− 1.0 MPa recorded in 2022 (DOY 209) by the pressure chamber and − 1.2 MPa by the microtensiometers. For DI trees, the lowest value of midday Ψ_{stem} measured with the pressure chamber and Ψ_{trunk} measured with the microtensiometers was − 1.5 MPa and was recorded from late July to mid August for both years. However, afterward, midday Ψ_{stem} and Ψ_{trunk} slowly increased to − 1.0 MPa, in 2021 while in 2022, similar values were observed several times until the end of the experiment. Ψ_{stem} and Ψ_{trunk} were sensitive water stress indicators and consistently differentiated between the two irrigation strategies imposed throughout the experiment. Ψ_{stem} measured by a pressure chamber was able to significantly distinguish differences between irrigation treatments two and one day earlier than the Ψ_{trunk} measured by the microtensiometers in 2021 and 2022, respectively. On the other hand, Ψ_{leaf} was not as sensitive as Ψ_{stem} and Ψ_{trunk}. Although they all followed a similar trend, Ψ_{leaf} showed more variability and was not able to detect early water stress in DI trees once the deficit was applied.

In 2022, Ψ_{stem} from the pressure chamber was compared with Ψ_{trunk} from the microtensiometers during the afternoon. Differences between both indicators were greater in mid-afternoon, particularly for DI trees. Ψ_{trunk} values were approximately 34% lower than Ψ_{stem} values. These differences between both indicators were not observed at midday (Fig. 4). There was a strong relationship between both at midday in both years of study (R^2 =0.88) and were similar to the identity line (1:1; x = y) for the range of midday Ψ_{stem} between − 0.3 and − 1.7 MPa. On the other hand, the relationship between both indicators in the afternoon was also strong but were different from the identity line, with more negative values for the Ψ_{trunk} values recorded by the microtensiometers (Fig. 4).

When midday Ψ_{stem} and Ψ_{trunk} were compared, there were differences for 7 and 5 days out of 24 for CTL trees in 2021 and 2022, respectively. Despite having significant differences, the variation between the mean values for each indicator was not higher than 0.5 MPa with more negative values of Ψ_{trunk} recorded by microtensiometers (Fig. 3).

3.3. Trunk diameter

As expected, trunk diameter growth and daily fluctuations were different between treatments. Trunk diameter increased for CTL trees by 94% and 78% compared to DI trees in 2021 and 2022, respectively. However, all the trees, regardless of their irrigation treatment, had greater growth in 2022 than in 2021 (Fig. 5). Moreover, the MDS in the late summer of 2021 (DOY 234 onwards) was low for both treatments compared to the MDS observed during the same period in 2022. Significant differences in maximum daily shrinkage (MDS) rapidly emerged between treatments when deficit irrigation was imposed in both years. Maximum MDS values (311 µm) were recorded in late June in 2021 for both CTL and DI trees when both treatments were irrigated to fulfill their water requirements during the week with the maximum ET_0 and VPD of the season. On the other hand, maximum MDS values in 2022 were recorded in late July by DI trees, approximately one month later than the water restrictions on those trees were imposed (Fig. 6). In 2021, maximum MDS for CTL trees occurred at the start of the experiment and then decreased during the season until daily MDS reached approximately 100 µm. MDS for DI trees followed a similar pattern but with almost double MDS than CTL trees from mid-July to mid-August (DOY 194 – 222). In 2022, MDS was more variable for both treatments, and significant differences occurred until the end of the experiment. MDS was three times greater for DI trees compared to CTL trees for several days in late August (DOY 235–242). MDS was then compared with the

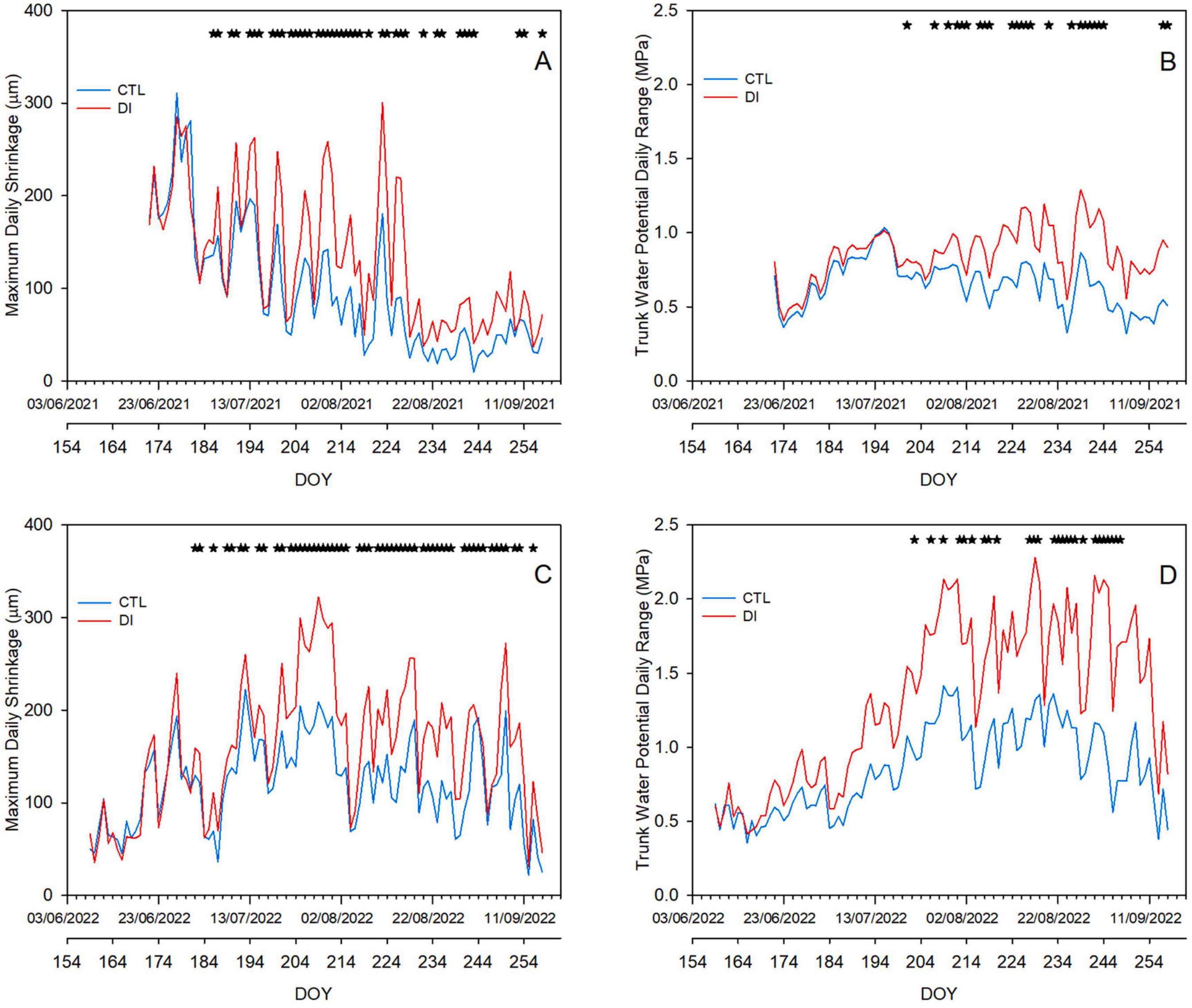

Fig. 6. Mean maximum daily shrinkage of CTL and DI trees (N = 4) in 2021 (A) and 2022 (C) and daily trunk water potential range (N = 6) for the same period in 2021 (B) and 2022 (D). Black asterisks denote significant differences between CTL and DI trees according to ANOVA ($P < 0.05$).

daily range of Ψ_{trunk} recorded by the microtensiometers in order to assess which method was better able to detect early water stress. The daily range for Ψ_{trunk} varied between years and was not able to detect early water stress compared to MDS. In 2021, Ψ_{trunk} daily ranged from 0.3 to 1.0 MPa for CTL trees and 0.3–1.3 MPa for DI trees and in 2022, ranged from 0.4 to 1.4 MPa for CTL trees and 0.4–2.2 MPa for DI trees.

3.4. Relationship between trunk water potential and trunk diameter fluctuations

MDS, Ψ_{stem}, and Ψ_{trunk} were strongly related to VPD and air temperature for CTL trees. VPD_{md} and T_{max} were particularly closely related with coefficients of determination that varied between 0.58 and 0.88 (Table S1; Fig. 7). In general, MDS responded more to environmental variables that aggregated values for a whole day or reflected maximum daily values. In contrast, midday stem and trunk water potential were more related with midday environmental variables, particularly Ψ_{trunk}. These different relationships can be observed when both indicators are compared with the ET_0. Ψ_{stem} vs ET_0 had the lowest coefficients of variation in 2022 (R^2 =0.34 and 0.37 for Ψ_{trunk} and Ψ_{stem}, respectively) while the MDS had coefficients of determination similar to those calculated with T_{mean} or VPD_{max} (R^2 =0.53).

Fig. 7 shows the regression analysis between the MDS and the midday Ψ_{stem} measured with the pressure chamber (Fig. 7A) and with the Ψ_{trunk} measured with the microtensiometers (Fig. 7B) using pooled data. When both relationships were compared, a polynomial regression fit the data with the Ψ_{stem}, while a linear regression was the best fit for the Ψ_{trunk}. However, when only the midday Ψ_{trunk} during the month prior and after the start of deficit irrigation was considered, a second-order regression best fit the data ($R^2 = 0.63$; Fig. 7C). The relationship between VPD_{md} and MDS or midday Ψ_{trunk} in the CTL trees was considered (Fig. 7D), a strong correlation was observed for both variables measuring water relations.

Signal intensity was similar for all variables and higher for the entire deficit period than for the 14 days immediately following the start of the deficit irrigation (Table 1). Coefficient of variation was the highest for MDS and was greater in 2022 for the first 14 days of deficit irrigation. However, when the entire deficit period was considered, CV was higher in 2021. Since the coefficient of variation was the highest for MDS, the sensitivity was, subsequently, the lowest for all measured variables. The daily range Ψ_{trunk} was the most sensitive index for the early water stress detection.

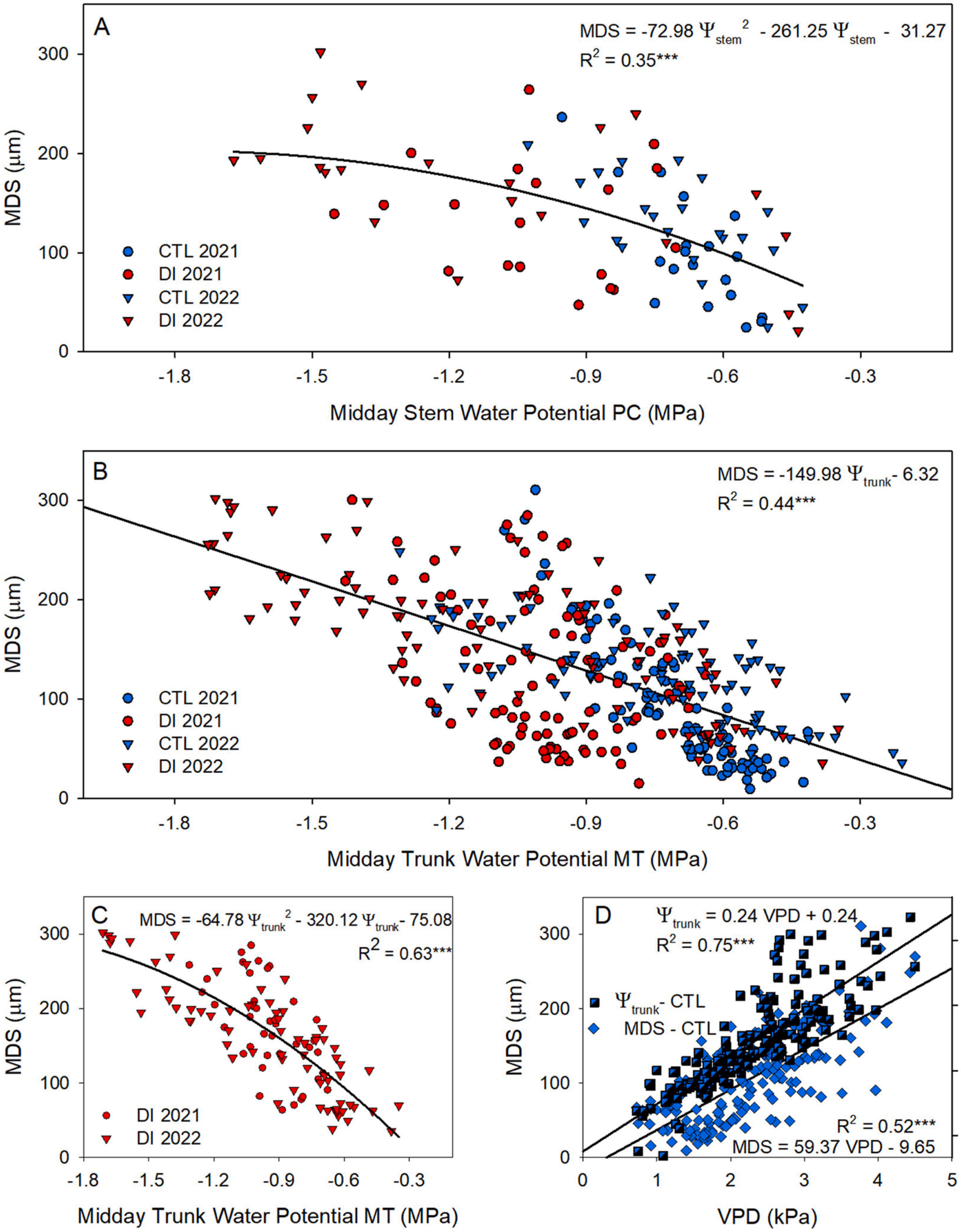

Fig. 7. The relationship between mean maximum daily shrinkage (MDS) and midday stem water potential (Ψ_{stem}) measured with a pressure chamber, PC, (A) and trunk water potential (Ψ_{trunk}) measured with the microtensiometers,MT, (B) for CTL and DI trees in 2021 and 2022. The relationship between MDS and midday Ψ_{trunk} MT of DI trees for 30 days before and after the start of deficit irrigation (C). The relationship between the midday daily vapor pressure deficit (VPD) and the MDS or midday Ψ_{trunk} MT of CTL trees for 2021 and 2022.

Daily maximum and minimum Ψ_{trunk} were reached 2–2.5 h earlier than the maximum and minimum trunk diameters were recorded, respectively. However, there was a four-hour delay between the time when Ψ_{trunk} completely recovered and when trunk diameter stopped increasing (Fig. 8). When both patterns were compared, five stages were identified. Stage I was the final recovery of trunk diameter at night after Ψ_{trunk} has been already recovered, the tree was rehydrated, and transpiration was negligible. Stage II describes the period when maximum Ψ_{trunk} occurred at sunrise and when the trunk reached its maximum diameter. Stage III corresponded to the beginning of the trunk shrinkage until the minimum value of the Ψ_{trunk} occurs. Stage IV is the period between the occurrence of minimum daily Ψ_{trunk} and trunk diameter when Ψ_{trunk} slowly recovered but trunk diameter continued to decrease. Stage V corresponded to the final stage when both indicators

Table 1

Sensitivity analysis of the midday stem water potential (Ψ_{stem} md) measured with the pressure chamber (PC) and the midday trunk water potential (Ψ_{trunk} md) the microtensiometers (MT) for the same days, for the complete period (MT*), the daily range of Ψ_{trunk} measured by MT and the maximum daily trunk shrinkage (MDS) for the first 14 days after the start of deficit irrigation and for the entire deficit period (2021 and 2022).

	14 days									
	Ψ_{stem} md PC		**Ψ_{trunk} md MT**		**Ψ_{trunk} md MT***		**Ψ_{trunk} Range**		**MDS**	
	2021	**2022**	**2021**	**2022**	**2021**	**2022**	**2021**	**2022**	**2021**	**2022**
SI	1.14	1.12	1.05	1.28	1.04	1.28	1.09	1.30	1.10	1.18
CV	0.14	0.15	0.03	0.12	0.04	0.11	0.03	0.06	0.16	0.23
S	8.41	7.46	33.60	10.69	29.54	11.61	32.78	20.71	6.86	5.08
	DI period									
	Ψ_{stem} md PC		**Ψ_{trunk} md MT**		**Ψ_{trunk} md MT***		**Ψ_{trunk} Range**		**MDS**	
	2021	**2022**	**2021**	**2022**	**2021**	**2022**	**2021**	**2022**	**2021**	**2022**
SI	1.59	1.64	1.53	1.47	1.54	1.49	1.40	1.58	1.62	1.40
CV	0.19	0.19	0.21	0.15	0.20	0.15	0.20	0.15	0.34	0.20
S	8.27	8.58	7.33	10.81	7.83	9.75	7.13	10.37	4.79	7.02

SI: Signal intensity (SI = DI CTL-1); CV: Coefficient of variation; S: sensitivity (S = SI CV-1)

rapidly recovered and ended once Ψ_{trunk} again reached its daily maximum value. Although the behaviour of both indicators was strongly related during stages III and V of decrease and recovery, respectively, they were not as strongly related during stages I, II and IV because of slower changes in trunk diameter compared to Ψ_{trunk}.

4. Discussion

The strong relationship between Ψ_{trunk} reported from microtensiometers and Ψ_{stem} measured using a pressure chamber shows how microtensiometers can be used to continuously monitor tree water status. However, the relationship between the two indicators was less similar when measurements were taken in the afternoon. These results follow those previously reported (Blanco and Kalcsits, 2021) and the relationship between both methods was similar for both years (Fig. 4). Moreover, both indicators, midday Ψ_{stem} and Ψ_{trunk}, significantly identify the two irrigation strategies assayed (Fig. 3). Significant differences between treatments appeared earlier for Ψ_{stem} and Ψ_{trunk} than Ψ_{leaf} which supports previous studies reporting the efficacy of Ψ_{stem} to assess water relations in woody species (Naor, 2000; Santesteban et al., 2019). CTL trees almost always had midday Ψ_{stem} values higher than − 1 MPa and were similar to those reported for fully irrigated pear trees in other studies (Venturi et al., 2021; Marsal et al., 2002a, 2002b).

Ψ_{trunk} observed from microtensiometers steadily decreased after midday for both treatments, but particularly for DI trees (Fig. 1). In our experiment, Ψ_{stem} measured with the pressure chamber in the afternoon was slightly more negative than that measured at midday, however, for Ψ_{trunk}, between midday and 16:00 h, it decreased more than 0.7 MPa in DI trees. These differences between both indicators raise the question whether Ψ_{trunk} measured with the microtensiometers, although reliably reflects tree water status at midday, underestimates the water stress during the afternoon. We hypothesize that this behaviour is related with the strong relationship found between Ψ_{trunk} and VPD (reference equations are included in the supplementary material), so decreases in VPD during the afternoon cause Ψ_{trunk} drops. Consequently, the calculation of water stress indicators such as the water stress integral (Myers, 1988) might result affected if Ψ_{trunk} is used instead of Ψ_{stem}. Pagay (2022) reported that under environmental conditions with high evaporative demand, the relationship between both indicators weakened. In our study, daily maximum VPD reached as high as 5.5 kPa was usually observed at the same time when minimum Ψ_{trunk} was observed for microtensiometers while midday VPD was never greater than 4.5 kPa.

These differences could also be related to the fact that Ψ_{trunk} is measured in the main trunk of the tree so considers the whole tree canopy, so it should be more dependent on the average PPFD conditions, while Ψ_{stem} is measured in a leave that is in equilibrium with one specific branch, and that branch is composed by many leaves exposed to different levels of radiation during the day. Other factors such as artifacts generated for either method and environmental conditions may lead to differences between treatments. Changes in the xylem and phloem flow throughout the season and the effect of the crop load have been reported to affect Ψ_{stem} in temperate woody plants (Morandi et al., 2010; Ray and Savage, 2021) and these factors might also affect the sensitivity of Ψ_{trunk}, as well as the location within the trunk where the microtensiometers are installed, the high. For the pressure chamber, Stanley et al. (1983) reported that leaf age can influence Ψ_{stem}. Therefore, leaves at the beginning or end of the season might equilibrate differently with the stem compared to mature leaves. More research is needed to understand the underlying reasons contributing to differences between both indicators.

Like other plant-based sensors that need to be embedded in the trunk of the tree, such as electromagnetic sensors (Stott et al., 2020), the precision of microtensiometers highly depends on the installation process and the proper contact between the sensor and the xylem. Regarding Ψ_{stem}, even for established methods, Levin (2019) indicated that one of the main sources of variability when using a pressure chamber can be the operator. However, several authors have reported low coefficients of variability for Ψ_{stem} measured with a pressure chamber in fruit trees and vines (Goldhamer and Fereres, 2001; Ortuño et al., 2006; De la Rosa et al., 2016; Blanco et al., 2018; Berríos et al., 2022). In this study, even on days when significant differences between Ψ_{stem} and Ψ_{trunk} were observed, both indicators were able to distinguish between irrigation treatments.

In addition to comparing Ψ_{trunk} with Ψ_{stem}, these parallel measurements were compared with diurnal trunk diameter fluctuations. Like Ψ_{trunk} measured with a microtensiometer, dendrometers continuously measure plant responses and produce indices that can be used for irrigation decisions. However, dendrometers can have limitations (Noun et al., 2022). Indices derived from the trunk diameter fluctuations, including MDS, have been successfully used in fruit trees and vines to detect and quantify water deficit (Ortuño et al., 2009; Liu et al., 2011; Abdelfatah et al., 2013). MDS is considered a key water status indicator and has been used alone for irrigation scheduling in peach trees (Conejero et al., 2007). However, Marsal et al. (2002a), (2002b) and Intrigliolo and Castel (2006) reported the ability of MDS to assess tree water status was affected by trunk seasonal changes during the season. Here, MDS had a high signal intensity and differences between irrigation treatments emerged earlier than for midday Ψ_{trunk} by 9 and 2 days in 2021 and 2022, respectively. However, MDS was unable to resolve differences between treatments at the end of the 2021 season (Fig. 6) because of decreasing MDS as the season progressed for both years and treatments. Similarly, Conesa et al. (2018) reported that MDS was unsuitable for predicting water stress in vines after veraison. Although the MDS detected water stress earlier, MDS did not increase in the same

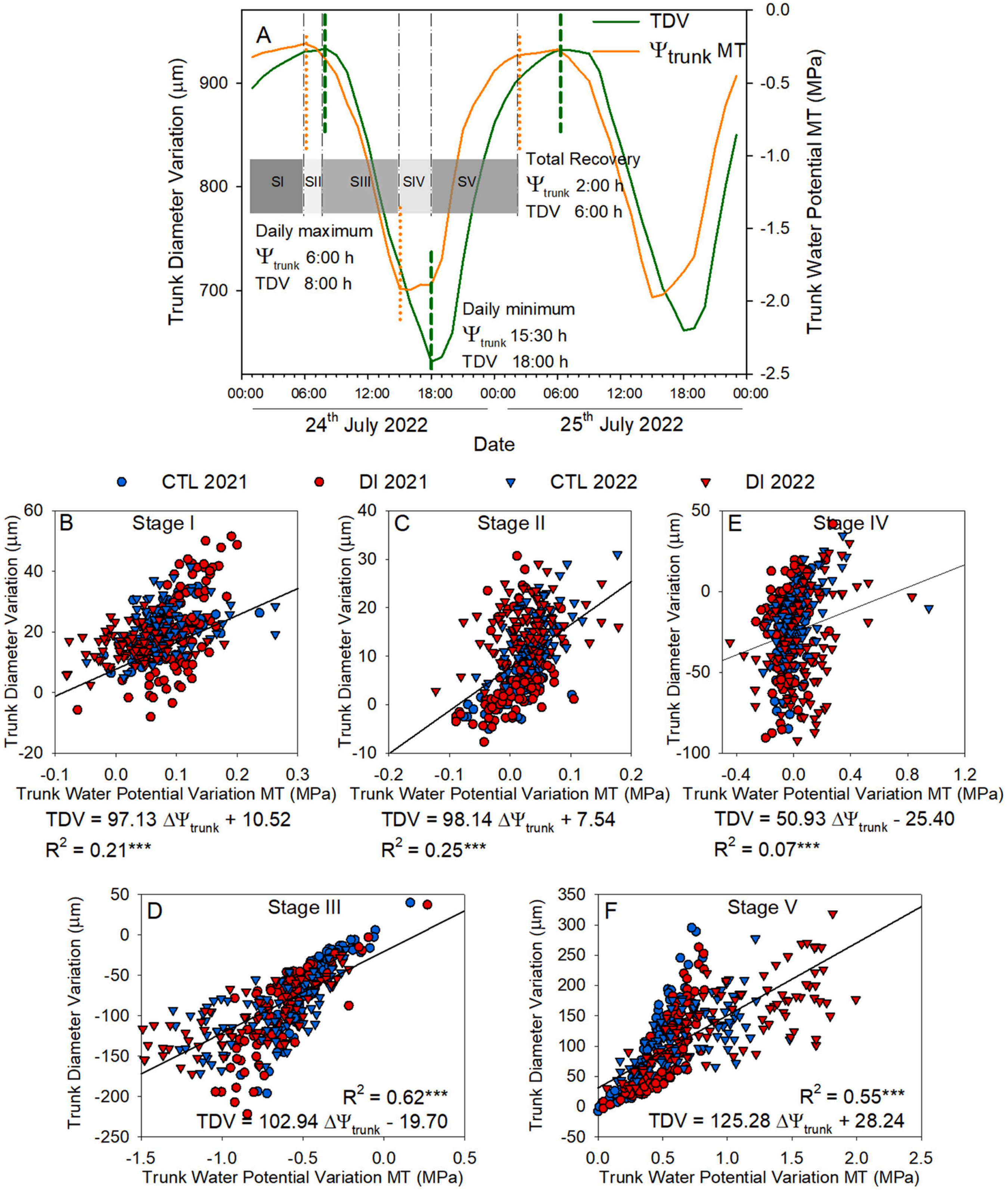

Fig. 8. Daily evolution of trunk diameter and trunk water potential (Ψ_{trunk}) on July 24 and 25, 2022 (A). Daily maximum, minimum, and recovery of trunk diameter and Ψ_{trunk} are indicated. Linear relationships between the variation of both indicators are indicated by five stages: Stage I (SI; B), Stage II (SII; C), Stage III (SIII; D), Stage IV (SIV; E) and Stage V (SV; F) for both treatments (CTL and DI) and both seasons (2021 and 2022).

proportion when Ψ_{stem} was lower than − 1.4 MPa and/or Ψ_{trunk} was lower than − 1.2 MPa (Fig. 7). Similar observations for the relationship of both water status indicators have been described in almond, cherry, grapes, nectarine and olive trees (Puerto et al., 2013; Blanco et al., 2018; Montoro et al., 2012; De la Rosa et al., 2016; Girón et al., 2016). When only the DI trees in the 30 days before and after the start of water limitations were considered, the relationship between MDS and Ψ_{trunk} was stronger. Although MDS has been traditionally compared with Ψ_{stem}, we also calculated the daily range Ψ_{trunk} to best compare both indicators. The daily range of Ψ_{trunk} did not detect significant differences between the irrigation treatments earlier than the MDS, the midday Ψ_{stem} or the midday Ψ_{trunk}.

Here, both trunk diameter variation and Ψ_{trunk} had a similar pattern compared to those described for Norway spruce by Herzog et al. (1995) for sap flow and trunk diameter with five characteristic stages. Our results also align with Malheiro et al. (2020) who reported that trunk diameter changes were delayed compared to sap flow which was responsive to changes in transpiration in ’Touriga-Nacional’ grapevines. Consequently, our results demonstrated that the dendrometry could be more related to the potential energy of the water available in the trunk of the tree which is responsive to changes occurring in the xylem (Herzog et al., 1995). Therefore, trunk diameter continued to decrease (stage IV) when Ψ_{trunk} reached its minimum value in the afternoon. On the other hand, during stage I when the xylem potential was the highest of the day, trunk diameter continued to increase. Furthermore, we observed that water stress affected trunk diameter swelling during the evening and night (stage V) and trunk diameter shrinkage (stage III). Under the same environmental conditions, DI trees had lower Ψ_{trunk} but similar trunk diameter growth than CTL trees (Fig. 8F). These patterns may imply that DI trees to fully recover their trunk diameter needed higher water potential gradients than CTL trees, so for the same gradient of water potential during the night (recovery stages), DI trees will have less trunk swelling which implies less water available for transpiration, as trunk internal water storage contributes with up to 28% of the total water used by a deciduous tree in a day (Oliva Carrasco et al., 2015). Coincidentally, our results were similar to those that reported a strong relationship between environmental conditions (particularly VPD, Table 1) and both MDS and Ψ_{stem} (Goldhamer et al., 1999; De Swaef et al., 2009; Ortuño et al., 2009; Egea et al., 2009; Galindo et al., 2013; Corell et al., 2016; Shackel et al., 2021).

Direct measurements of plant stress have the potential for application of precision irrigation strategies. In addition to Ψ_{stem} and MDS, there are other water status indicators that as Ψ_{trunk}, have the potential for being used for irrigation automation such as canopy temperature, sap flow, leaf turgor pressure, and trunk water content. Mira-García et al. (2022) reported threshold values for irrigation scheduling of lime trees under different cropping systems based on thermal indices. However, these thermal indices were not able to anticipate water stress detection better than soil sensors. Fan et al. (2022) stated that sap flow was useful to assess the water status of Asian pear trees but it had high variability and was not as sensitive to the changes in soil and the atmosphere water status in the early season as plant water potential. Scalisi et al. (2019) observed a strong relationship between the leaf turgor and Ψ_{leaf} of nectarine trees. However, values needed to be transformed into a second derivative to calculate leaf pressure change rate to compare it with midday Ψ_{stem}. Furthermore, these sensors can damage the organ where they were installed and may need frequent adjustment or reinstallation. Stott et al. (2020) monitored the changes in the trunk dielectric permittivity of peach trees by embedding different soil sensors into the trunk of the trees with promising results despite the high variability among them and Araújo et al. (2021) recommended individual calibration of the sensors. Alizadeh et al. (2021) introduced relative trunk water content sensor able to monitor changes in the tree water status. These sensors had a robust relationship with trunk diameter but, unlike microtensiometers, were delayed by three hours compared to diurnal variations in trunk diameter. Ψ_{trunk} recorded by microtensiometers responded quicker than variations in trunk diameter and do not require individual calibration like some sap flow and trunk water content sensors. Microtensiometers directly measure Ψ_{trunk} which resulted strongly related to midday Ψ_{stem} and do not need to be transformed into a different index like thermal indices or leaf turgor. However, Ψ_{trunk} measured by the microtensiometers was highly dependent on environmental conditions (VPD), consistently showed more negative minimum values during the afternoon than Ψ_{stem}, and did not detect water stress earlier than Ψ_{stem}.

5. Conclusion

The strong relationship with midday Ψ_{stem} measured with the pressure chamber, the environmental variables affecting water supply to and demand by the plant, high sensitivity, low variability, and the ability to continuously monitor tree water status increases the potential for Ψ_{trunk} measured by the microtensiometers to be used for automated irrigation under deficit or fully irrigated conditions. Long-term validation and consistent delineation of water stress treatments for pear show the low variability and sensitivity needed for industry adoption. Although this study does not resolve the underlying causes for differences in diurnal patterns between Ψ_{trunk} and Ψ_{stem}, we identify the relationship between the changes in trunk water status and trunk diameter. Continuous measurement of trunk water potential may contribute to the development of meaningful diurnal patterns and processes that might occur at different phases of short or long-term water stress.

CRediT authorship contribution statement

Both authors, Victor Blanco (V.B.) and Lee Kalcsits (L.K.) have read and agreed to the published version of the manuscript. Conceptualization and design, V.B. and L.K.; Methodology, V.B. and L.K.; Investigation, V.B. and L.K.; Formal analysis, V.B. and L.K.; Resources, V.B. and L.K.; Data curation and visualization, V.B. and L.K.; Writing—original draft preparation, V.B. and L.K.; Writing—review and editing, V.B. and L.K.; Project administration and funding acquisition, V.B. and L.K.;

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agwat.2023.108257.

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