

Quantifying between and within tree stem variations using dendrometers

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ABSTRACT

Dendrometers have been widely studied for irrigation management in apple orchards, yet the high variability of dendrometer-derived parameters among trees remains a challenge for irrigation control. This study evaluated the variability of key dendrometer-derived parameters across eight trees and four stem positions per tree, with particular focus on their applicability for irrigation optimisation. Continuous measurement of trunk water potential (Ψ_{trunk}) obtained with microtensiometers and conventional stem water potential measurements (Ψ_{stem}) obtained using a Scholander pressure chamber were compared with dendrometer-derived growth and tree water deficit (TWD) parameters. The number of sensors required to achieve a 0.15 MPa (Ψ_{trunk}) standard error was then calculated. All measured variables showed higher variability than Ψ_{stem} . Dendrometer parameters showed greater variability within trees than between trees, indicating substantial heterogeneity across stem positions. When using TWD_{max} as Ψ_{trunk} predictor, nine sensors were required to achieve 0.15 MPa standard error (coefficient of variation = 0.123). Five dendrometers were needed to accommodate a larger variance of 0.2 MPa. Daily Ψ_{trunk} minimum and TWD_{max} were well correlated (R_m^2 and $R_c^2 = 0.73$), although this correlation was weaker and tree dependent for Ψ_{trunk} maximum and TWD_{min} ($R_m^2 = 0.06$, $R_c^2 = 0.32$). This reflects their shared measurement location conditions and supports the suitability of dendrometers for monitoring tree water status, especially in the middle of the day. Overall under the here presented experiment conditions, dendrometers represent a practical, economical, and reliable tool for operational water stress assessment, and options to reduce observed variability should be studied.

1. Introduction

Sensor-based automated irrigation systems in orchards typically rely on soil moisture measurements to determine the amount of water to be applied. However, many researchers have criticised this control strategy (e.g., Wheeler et al., 2023; Waldburger et al., 2025a) because soil moisture does not always reflect the actual water requirements of plants. Consequently, indicators of plant stress may offer a more reliable basis for irrigation management. One promising approach is the use of dendrometer sensors, which can detect plant water stress through changes in stem size. This has been demonstrated by the successful use of dendrometers in crops such as citrus, olives, and apples (e.g., Velez et al., 2007; Girón et al., 2016; Waldburger et al., 2025b). Among the different dendrometer technologies available (point dendrometers, band dendrometers, LVDTs, etc.), point dendrometers are particularly appealing due to their relatively low cost, high measurement resolution, non-invasive installation, and extensive validation across *Multiple species* (e.g., Dietrich et al., 2018).

Dendrometers enable the continuous, high-resolution measurement of stem size by typically employing a linear potentiometer or similar sensor. Changes in stem size recorded by these instruments represent not only increments in growth but also short-term daily fluctuations in the tree's water status (Zweifel et al., 2016). These daily expansions and contractions occur because water is temporarily stored and released within the relatively elastic outer tissues of the stem—particularly the cambial zone and phloem—which respond dynamically to variations in transpiration demand and internal water balance (Devine and Harrington, 2011). Such fluctuations capture primarily the elastic response of the stem to environmental changes and are commonly expressed as the maximum daily shrinkage (MDS; Fig. 1), defined as the difference between the maximum and minimum stem radius recorded within a given day (e.g., Naor and Cohen, 2003). Water status can also be reported by tree water deficit (TWD) (e.g., Dietrich et al., 2018), calculated as the deviation from a baseline growth obtained by extrapolating maximum stem size based on the maximum previously seen size (e.g., Girón et al., 2016; Dietrich et al., 2018; Goldhamer and Fereres,

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2001; Naor and Cohen, 2003; Fernández and Cuevas, 2010; Moriana et al., 2010; Wheeler et al., 2023). Tree water deficit (TWD) represents the absolute stem water deficit relative to the maximum historical stem radius. A TWD value of zero indicates complete hydration of the stem tissues, whereas positive TWD values indicate increasing depletion of water stored in the elastic stem tissues (Dietrich et al., 2018). TWD calculations assume non-significant growth under stress periods, as proposed by Zweifel et al. (2016), and can be the difference between MDS and tree growth (TG), calculated at multiple times of the day (e.g., Dietrich et al., 2018).

Since the stem structure of a tree is not entirely homogeneous, and slight differences can occur even within small sections of the stem, the position of the dendrometer, whether installed at varying stem heights or on branches, can substantially influence the variability of the recorded parameters. Such local variability can arise from intrinsic physiological characteristics, including differences in cell size, tissue composition, or local growth rates, as well as from external influences (e.g., Zhang et al., 2024; Houston et al., 2016).

The influence of dendrometer position was investigated by Zweifel and Häslér (2001), who worked with mature subalpine Norway spruce (*Picea abies* L.). These authors showed that the largest daily fluctuations in stem radius occurred in the upper stem within the crown. This pattern was attributed to higher transpiration rates and greater water demand in the canopy. Conversely, the smallest fluctuations were found at the stem base, where water storage capacity and elastic tissues may buffer short-term changes, resulting in more stable stem radius measurements. Comparable patterns have been reported in agricultural systems. For instance, Corell et al. (2014) investigated dendrometer placement on mature olive trees by comparing measurements taken on the main stem versus branches in an irrigation trial. The authors found that MDS varied significantly in stressed trees depending on the dendrometer position, whereas TG did not show significant variation across positions.

Substantial between-tree variability in dendrometer measurements has been reported as one of the major challenges associated with this sensor. This issue has been widely documented in the literature (e.g., Naor and Cohen, 2003; Biondi and Rossi, 2015; Özçelik, 2025). Depending on the parameter derived from dendrometers, tree-to-tree variation can reach up to 60%, normally quantified as a function of the coefficient of variation (CV, e.g., Naor and Cohen, 2003; Fernández and Cuevas, 2010). The high variability observed in dendrometer data raises important questions about how precisely these measurements can be applied to irrigation management and what strategies might help mitigate this variability. By contrast, such a high level of variability is not typically observed with the Scholander pressure chamber—the most

widely used instrument for assessing plant water status. Nevertheless, some degree of within-tree heterogeneity has also been documented with Scholander pressure when directly measuring water potential (Ψ). In olive hedgerow orchards, Hueso et al. (2023) reported a vertical decline in Ψ_{stem} of approximately 0.10 MPa m^{-1} between 0.6 m and 1.3 m above ground level, and a more pronounced decline of 0.33 MPa m^{-1} between 1.3 m and 1.9 m. The correlation between these two— Ψ_{stem} versus dendrometer-derived parameters—has been reported to not always be consistent, ranging from weak to strong ($0.4 \leq R^2 \leq 0.8$), making it challenging to rely on Ψ_{stem} as a universal calibration tool (e.g., Blanco and Kalcsits, 2023; Wheeler et al., 2023).

To enable automatic direct measurement of plant Ψ_{trunk} , psychrometry has been widely used (e.g., Cermak et al., 2015). Recently, a new microtensiometer has been introduced, consisting of a small sensor capsule directly implanted into the woody tissue of the trunk to a depth of at least 9 mm (e.g., Blanco and Kalcsits, 2021; Vacaro et al., 2025). Several studies have demonstrated its applicability across a range of crops and environmental conditions, reporting that precision and accuracy vary with species- and site-specific factors, with some authors suggesting higher values of Ψ_{trunk} (Vacaro et al., 2025) or lower values of Ψ_{trunk} than compared with Ψ_{stem} (Blanco and Kalcsits, 2023; Villalobos et al., 2024).

Despite numerous studies linking dendrometer parameters with other measurement tools for calibration purposes, to our knowledge, no research has systematically examined the within-tree variability of dendrometer readings taken at different positions along the same stem, supported by continuous Ψ_{trunk} measurements. This gap limits our understanding of how point sensor placement affects the accuracy of water stress monitoring in trees. We hypothesised that dendrometer-derived parameters would differ in their sensitivity to sensor position and tree-to-tree variability. Specifically, we expected that middle of the day derivate parameters would provide more consistent measurements across stem positions and exhibit a stronger relationship with continuously measured Ψ_{trunk} than nocturnal derivate parameters.

The aim of this study is to quantify the variability of dendrometer-derived parameters measured at four positions on the same apple tree stem and to assess their suitability for irrigation optimisation. We also compare these measurements with Ψ_{stem} values and Ψ_{trunk} at different times of day. This comparison is intended to clarify how such variability should be further reduced to enable more reliable monitoring protocols for practical irrigation management.

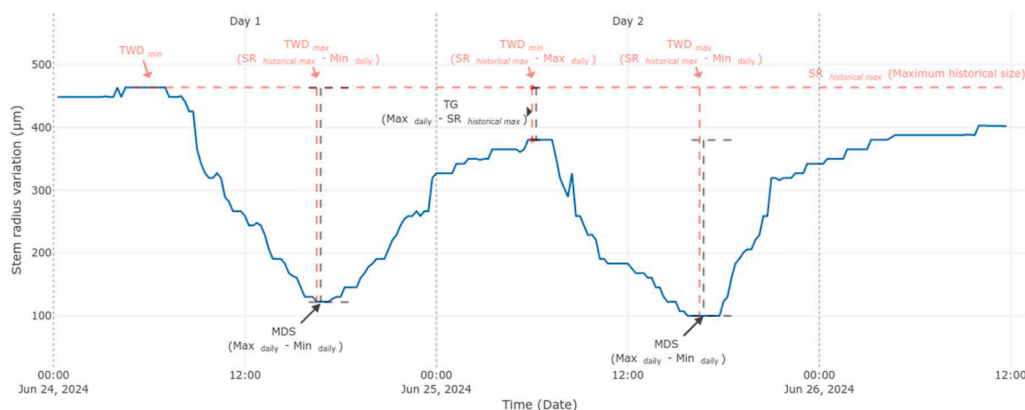


Fig. 1. Schematic representation of the dendrometer-derived parameters calculated from continuous stem radius measurements. The blue line represents stem radius variation over time. The red dashed line indicates the maximum historical stem radius ($SR_{historical\ max}$), which serves as the reference for calculating tree water deficit (TWD). Tree growth (TG) is defined as the increase in the daily maximum stem radius ($SR_{daily\ max}$) relative to the previous historical maximum. Maximum daily shrinkage (MDS) is calculated as the difference between the daily maximum ($SR_{daily\ max}$) and minimum ($SR_{daily\ min}$) stem radius. TWD_{min} corresponds to the difference between the historical maximum stem radius and the daily maximum stem radius, whereas TWD_{max} corresponds to the difference between the historical maximum stem radius and the daily minimum stem radius, calculated as minimum (TWD_{min}) and maximum (TWD_{max}) values.

2. Materials and methods

2.1. Site

The study was conducted at Strickhof, a practical competence centre for sustainable food systems (47°26'44.9" N, 8°40'46.3" E), located approximately 519 m above sea level in Eschikon, Canton Zürich, Switzerland. The site experiences a mean annual temperature of approximately 10 °C and receives around 1020 mm of precipitation per year. Data for this study were collected between 4 June and 20 September 2024. During this period, the total precipitation was 397.5 mm, while the mean temperature was approximately 19 °C, with a recorded maximum of 33.6 °C.

2.2. Experimental setup

The research was conducted on eight individual apple trees of the Gala (*Malus domestica* 'Gala Galaxy') variety, all located within a single plot and planted in 2016 on rootstock M9 T337. The plot had a tree density of 3175 trees per hectare, with individual tree spacing of 0.9 m and row spacing of 3.5 m. Average stem diameter was 45 mm, with an average leaf area of 13 m² per tree, which was measured by halometric relationships (e.g., Baïram et al., 2017). The soil was covered with plastic sheeting to prevent direct precipitation from infiltrating the root zone, thereby maximizing the water stress on the trees. No irrigation was provided during the experiment, other than naturally available water sources. The orchard follows traditional commercial management.

2.3. Measurements with dendrometers, microtensiometers, and pressure chamber

With the aim of evaluating the variability in dendrometer-derived parameters, two parameters were measured: water potential (Ψ) and stem radius.

2.3.1. Water potential

As a reference for tree water status, stem water potential (Ψ_{stem}) was monitored using a Scholander pressure chamber (Scholander et al., 1965; Model M-600, Geary Stress, Albany, USA) following standard methodology (e.g., Waldburger et al., 2025b). Weekly measurements were performed between 12:00 and 13:00 on four healthy, fully shaded leaves on eight trees. Each leaf was enclosed in an aluminium-coated plastic bag for at least 30 min and excised along with its petiole. A 30-min equilibration period was selected based on previous experiments conducted on the same trees, which showed no differences in the measurements when compared longer equilibration periods (45 and 60 min, data not shown). The petiole was cut with a sharp blade shortly before measurement. In the pressure chamber, compressed air was gradually applied until the xylem sap appeared at the cut end, and the required pressure, displayed in bars, was recorded.

To complement these measurements, trunk water potential (Ψ_{trunk}) was recorded every 20 min using microtensiometers (FloraPulse, Davis, CA, USA) in three single trees. Sensors were installed on the north-facing side of the stem on a flat surface 0.5 m above the graft union, following Blanco and Kalcits (2024). These were connected to LoRaWAN data loggers, which sent each measurement directly to our private data server.

2.3.2. Stem radius

For each tree ($n = 8$), four dendrometer sensors were installed to monitor the stem radius at 15-min intervals. The sensors were custom-built by Agroscope using linear potentiometers (Model SLPT 25 mm, Opkon, Istanbul, Turkey) mounted on an aluminium frame, allowing movement along a single horizontal plane.

Stem radius (SR) variations were recorded as voltage signals and logged using an Agroscope data logger (Agribase 2.327, Agroscope,

Mauguio, France). Data were transmitted via a 916 MHz radio frequency and uploaded through a modem to an online server, where the signals were linearly converted to values in micrometres (μm) with a resolution of 6.1 μm . The initial stem circumference of each tree was considered in the calculations. TG (Eq. (1)) and MDS (Eq. (2)) were recorded as shown in Fig. 1. TWD was then calculated at two different time points following the methodology of Dietrich et al. (2018): at the daily minimum value in the early morning (TWD_{min} ; Eq. (3)), closely resembling TG and similarly weather independent, and at its maximum daily value in the middle of the afternoon (TWD_{max} ; Eq. (4)), which should closely correlate to MDS and therefore highly weather dependent. This was done with the aim of pairing TWD values with the minimum and maximum daily values of Ψ measurements, if available. In Eqs. (1)–4, $\text{SR}_{daily\ max}$ is the maximum stem radius recorded during a given day, $\text{SR}_{daily\ min}$ is the minimum stem radius recorded during the same day, and $\text{SR}_{historical\ max}$ is the maximum stem radius recorded since the beginning of the measurement period. $\text{SR}_{historical\ max}$ represents the corresponding maximum stem size used as the reference for calculating TG.

$$TG = \text{SR}_{daily\ max} - \text{SR}_{historical\ max} \quad (1)$$

$$MDS = \text{SR}_{daily\ max} - \text{SR}_{daily\ min} \quad (2)$$

$$\text{TWD}_{min} = \text{SR}_{historical\ max} - \text{SR}_{daily\ max} \quad (3)$$

$$\text{TWD}_{max} = \text{SR}_{historical\ max} - \text{SR}_{daily\ min} \quad (4)$$

2.4. Statistic analysis

2.4.1. Ψ_{stem} and Ψ_{trunk}

Ψ_{stem} was correlated with the continuous measurements of Ψ_{trunk} minimum value, as both should correlate with higher levels of daily stress. Preliminary correlations of Ψ_{stem} with the closest time-related Ψ_{trunk} measurements resulted in weaker correlations (data not shown). For this, the average of each tree Ψ_{stem} was correlated with its respective Ψ_{trunk} value. The relationship between the daily dendrometer parameters and Ψ (Ψ_{stem} or Ψ_{trunk}) of multiple trees was then evaluated using was then evaluated using R_m^2 and R_c^2 . R_m^2 (marginal R^2) represents the proportion of variance explained by the fixed effects only, whereas R_c^2 (conditional R^2) represents the proportion of variance explained by both the fixed and random effects of the mixed model (Nakagawa et al., 2017). This allowed for evaluating the general effect (R_m^2) that did not consider the specific tree effect, and the effect of each tree (R_c^2) is then added. For this, the model presented in Eq. (5) was used, with the intercept being independent for each "Tree" and the replicates "Rep", nested within the tree.

$$\text{Dendrometerparameter} = \psi + (1 \vee \text{Tree} / \text{Rep}) \quad (5)$$

2.4.2. Variations within and between trees

Variation within and between trees for Ψ_{stem} , Ψ_{trunk} and dendrometer derived parameters was quantified using their coefficient of variation (CV) to initially obtain an approximation and a graphical visualisation; CV is calculated by dividing the standard deviation by the mean. Within-tree CV was calculated using single dendrometer values, while CV between trees was calculated using the mean for each tree. CV was chosen because it provides a standardised measure of relative variability, allowing direct comparison of dispersion across different parameters and measurement scales. To corroborate such analysis, the data were further analysed using generalised linear mixed-effects models implemented in the glmmTMB package in R (Brooks, 2017), with the model in Eq. (6):

$$\text{Parameter} = \text{Date} + (1 \vee \text{Tree} / \text{Rep}) \quad (6)$$

The model included "Date" as a category and fixed effect to account for temporal variation and a nested random-effects structure, with repeated measurements, "Rep", nested within individual "Tree" to

account for within-tree and replicate variability. This approach allowed us to partition variation between temporal effects and hierarchical sources, providing robust estimates of variance partition while properly accounting for the non-independence of repeated measurements.

We then investigated the between-tree correlation of each position along the trees in the multiple studied parameters. To highlight the correlation of MDS and TWD to vapour pressure deficit (VPD), we demonstrated its correlation for 7 consecutive days using the average value of all available microtensiometers and dendrometers—that is, a period of time of any growing tendencies are removed.

2.4.3. Modelling TWD as a function of Ψ_{stem} and Ψ_{trunk}

To investigate the relationship between TWD, Ψ_{stem} , and Ψ_{trunk} at different times of the day, linear mixed-effects model was fitted between, initially between Ψ_{stem} and both TWD, as shown in equation 7 (data not shown). We then focus in the relationship between TWD and Ψ_{trunk} using only the trees who were equipped with both sensors: microtensiometers and dendrometers, using the model in Eq. 7. As TWD_{max} is predominantly influenced by environmental conditions, the additional impact of VPD was also tested in the model, which was replicated for both Ψ_{stem} and Ψ_{trunk} .

In all models, a random intercept for each tree is incorporated to account for repeated measurements, enabling the estimation of the effects of water status and environmental variables on TWD. In the case of TWD_{max} , a quadratic equation was fitted. For easier visualisation and normalisation due to different tree sizes, TWD was additionally expressed in percentage units with respect to the maximum historical size.

2.4.4. Estimation of sensor requirements based on TWD prediction

Based on the previously calculated CV, we estimated the number of sensors required to achieve a CV similar to that obtained by Ψ_{stem} measurements. To illustrate this in the context of irrigation management, we calculated the number of sensors needed to reach an equivalent standard error (SE) of 0.15 MPa, which we estimated to be an acceptable operational error for irrigation purposes based in own previous experiments. Such difference was visible in our previous experiments within a treatment after two or three days (Waldburger et al., 2025a; Waldburger et al., 2025b). Therefore the selection of a CV of similar magnitude may allow us to distinguish between future experiments at a similar temporal resolution, depending of the experimental and environmental conditions.

To express this threshold with respect to TWD, we used TWD_{max} , as although an estimation of TWD_{min} would be more useful for the detection of water availability, we hypothesised that TWD_{min} would have a stronger variation. Such a threshold was expressed as the CV of TWD_{max} , which is inversely proportional to the slope of the previously obtained linear model based on Ψ_{trunk} . For simplicity, the corresponding coefficient of variation for TWD_{max} was then calculated for the average TWD_{max} and the average slope. This provides an estimate of the required detectable change in TWD_{max} corresponding to the chosen Ψ_{trunk} SE, as presented in Eq. (8) where CV TWD_{max} is the coefficient of variation of TWD_{max} , SE TWD_{max} is the selected standard error of Ψ_{trunk} , and $\left(\frac{dx}{dy}f(\Psi_{trunk})\right)$ is the absolute slope of the fitted regression relating TWD_{max} to Ψ_{trunk} , and TWD_{max} is the mean maximum daily tree water deficit.

$$CVTWD_{max} = \frac{SETWP_{max}}{\left|\frac{dx}{dy}f(\Psi_{trunk})\right| * \sum TWD_{max}} \quad (8)$$

All statistical analyses were carried out using R (version 4.4.3) and considering a significance level of 0.05.

3. Results

3.1. Scholander pressure chamber (Ψ_{stem})

As illustrated in Fig. 2a, stem water potential measured at noon (Ψ_{stem}) exhibited a consistent temporal pattern of decreasing values throughout a wet growing season (Supp. Fig 1). Ψ_{stem} values ranged from approximately -0.5 MPa to -1.6 MPa across all sampling dates, without substantial water stress during the monitoring period. The within-tree CV was low, generally below 0.10, with only modest increases observed in late June (Fig. 2b). The between-tree variability was small (0.05), indicating a uniform water potential response between trees within the experimental (Fig. 2c).

3.2. Microtensiometers (Ψ_{trunk})

Continuous monitoring of trunk water potential (Ψ_{trunk}) using microtensiometers showed the expected daily fluctuation corresponding to daytime water depletion and night-time recovery. Overall, the mean Ψ_{trunk} across trees values ranged between approximately -0.5 MPa and -1.8 MPa, indicating no water stress conditions during the measurement period (Beikircher et al., 2013). Similar to Ψ_{stem} , from late June to August, a gradual decline in Ψ_{trunk} was observed in the smoothed seasonal trends in daily values (Fig. 3a), with similar patterns observed within individual days. The maximum Ψ_{trunk} value per day correlated with the manually measured Ψ_{stem} with an adequate correlation ($R_m^2 = 0.5$; $R_c^2 = 0.58$), with higher values than Ψ_{stem} .

3.3. Dendrometer parameters

TG and TWD at its minimum daily value (TWD_{min}) steadily decreased and increased from early July into late summer, respectively (Fig. 4a and c, Supp. Fig 2 and 4.). MDS displayed a high variability, with peak values frequently exceeding 400 – 600 μ m during mid-summer, especially in July and August, while TWD at its maximum daily value (TWD_{max}) exhibited patterns similar to MDS, with high variability, reaching values above 600 – 800 μ m during the driest periods (Fig. 4b and 4d, Supp. Fig 3 and 5).

3.3.1. Variations within and between trees

Across all parameters—TG, MDS, TWD_{min} , and TWD_{max} —within-tree (sensor-to-sensor) variability dominated the overall variation (see Supplementary Figures 2–5). Within-tree variability was particularly pronounced for TG and TWD_{min} , with observed empirical CV of 0.86 and 0.73, respectively. MDS and TWD_{max} showed lower but still substantial empirical CV (0.36 and 0.33, respectively). Mixed-effects results indicated that whereas growth and water content dominated parameters mostly showed within-tree variability ($\sim 36\%$), weather-dependent parameters were totally dominated by within-tree variability ($\sim 53\%$).

The between-tree variability calculated from the average of four sensors per tree was consistently low, especially for MDS and TWD_{max} . TG and TWD_{min} showed higher variability between-tree variability (0.5 and 0.36, respectively) than MDS and TWD_{max} . Specifically, TWD_{max} mixed-effects modelling showed that only a negligible proportion of variance originated from differences among trees, whereas 10% and 1% of the overall tree variability were explained by the between-tree variability in TG and TWD_{min} , respectively.

3.3.2. Sensor position within the tree

To investigate whether a specific position had higher consistency, the average correlation of all pairs of trees was calculated at each specific position. Sensors were mounted as identically as possible on all trees; however, exact distances could not be maintained due to variations in stem structure, which made it challenging to install the sensors at identical points on every tree (see Supp. Fig. 6). The position exhibiting the most consistent measurements across trees varied depending on

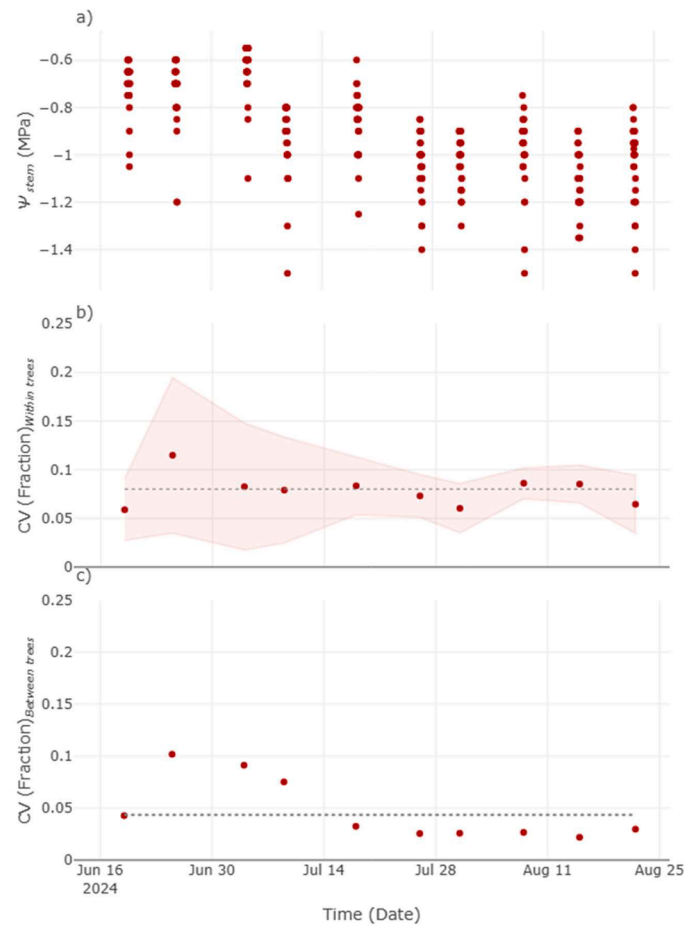


Fig. 2. (a): Individual measurements of Ψ_{stem} (MPa) for all trees and replicates at each sampling date. (b): Coefficient of variation (CV, fraction) of Ψ_{stem} calculated within trees across replicates on each date. Dotted points indicate the average value within trees, shaded area indicates $\pm$ standard deviation (SD), and the dotted line shows the overall average CV within trees. (c): Coefficient of variation (CV) of the mean Ψ_{stem} between trees on each date, with the same graphical conventions (dotted points: average between trees, dotted line = overall average CV between trees).

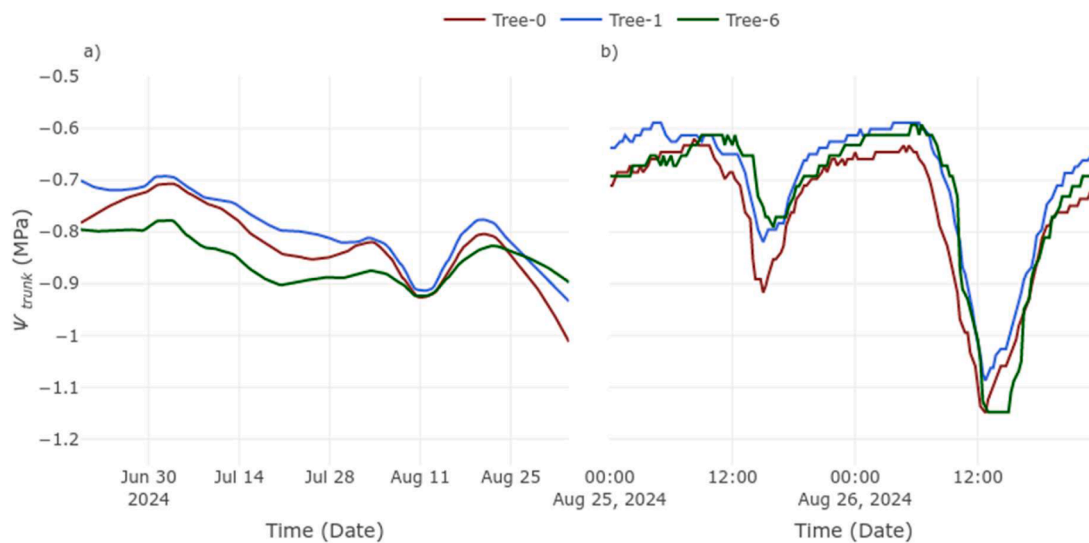


Fig. 3. Microtensiometer data (Ψ_{trunk}) showing a smoothed seasonal trend (LOESS, span = 0.3) obtained from three trees during the experiment. (b) Raw data focusing on two selected days (2024-08-25 to 2024-08-26).

the parameters analysed, as summarised in Table 1. Overall, TWD_{min} was the least-correlated parameter across trees.

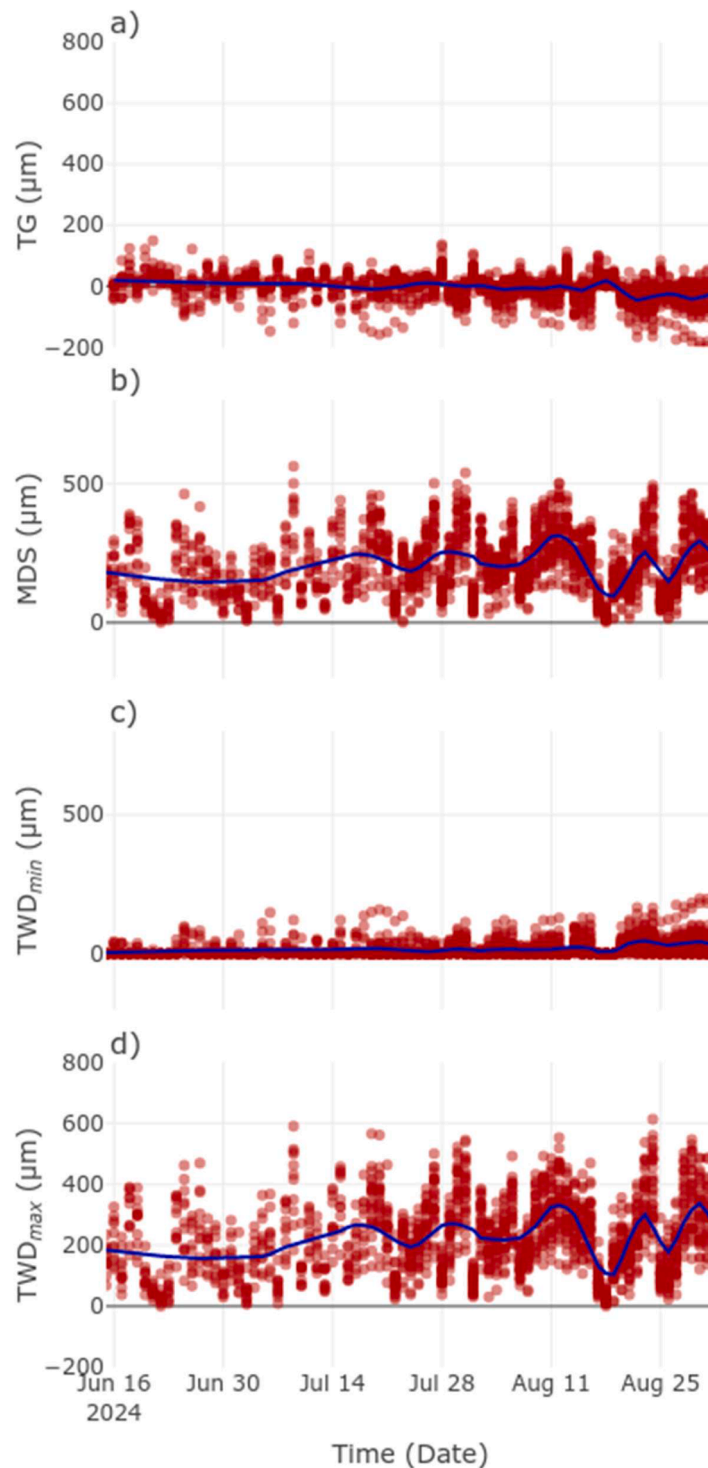


Fig. 4. Raw dendrometer-derived parameters recorded between July and September. (a) Tree growth (TG), (b) maximum daily shrinkage (MDS), (c) tree water deficit daily minimum (TWD_{min}), and (d) tree water deficit daily maximum (TWD_{max}). Each point represents an individual tree measurement, meanwhile the continuous line correspond to the smoothed trend (LOESS, span = 0.15).

3.4. Parameter interactions

3.4.1. VPD, Ψ_{trunk} and stem radius

The values of VPD, Ψ_{trunk} , and stem radius variations closely tracked one another throughout the experiment. Fig. 5 illustrates a 7-day period (20–26 August), with all variables showing synchronous cycles (Fig. 5a). Increasing VPD was strongly associated with decreases in the average Ψ_{trunk} and reductions in the average stem radius. Both Ψ_{trunk} and stem

radius variations were highly correlated with VPD ($R^2 = 0.874$ and 0.95 , respectively) (Fig. 5b).

3.4.2. Relationships between Ψ and dendrometer-derived parameters

The relationships between the dendrometer-derived parameters and Ψ_{stem} were generally weak. MDS showed a weak correlation ($R_m^2 = 0.05$, $R_c^2 = 0.44$) when correlated directly with Ψ_{stem} . Incorporating maximum VPD values per day into the linear mixed-effects models markedly

Table 1

Average between-tree correlation (R^2) at the different sensor positions for tree growth rate (TG), maximum daily shrinkage (MDS), and min and max tree water deficit (TWD).

Position	TG	MDS	TWD _{min}	TWD _{max}
1 (lowest, min 30 cm from the floor)	0.575	0.895	0.254	0.874
2	0.496	0.908	0.282	0.869
3	0.574	0.859	0.408	0.851
4 (highest, max 80 cm from the floor)	0.518	0.857	0.316	0.857

improved this relationship ($R_m^2 = 0.33$, $R_c^2 = 0.76$). Similar results were achieved when correlating TWD_{max} or TWD_{min} to Ψ_{stem} .

In the case of Ψ_{trunk} correlation with TWD_{min} parameter, a weak linear correlation was found ($R_m^2 = 0.06$, $R_c^2 = 0.37$, Supp. Table 1) (Fig. 6a), with trees that had more negative water potentials exhibiting higher trunk shrinkage during the night. TWD_{max} increased sharply as Ψ_{trunk} declined below -1.0 MPa. The fitted model (Fig. 6, b - red line) closely captured the wobserved variability across trees ($R_m^2 = 0.73$, $R_c^2 =$

0.76, Supp. Table 1. Fig. 6, b). The addition of maximum VPD as a fixed factor did not have a significant effect on TWD, regardless of the selected time of day.

3.4.3. Ψ measurements

Daily measurements of Ψ_{stem} and Ψ_{trunk} revealed higher variability in Ψ_{trunk} values. Within the same dates, significant differences in the values of Ψ_{stem} and Ψ_{trunk} were found between trees ($p < 0.05$), whereas no significant differences were detected within trees for Ψ_{stem} ($n = 4$ samples per tree). On average, Ψ_{trunk} showed lower values (more water stress) than Ψ_{stem} . A clear positive correlation between Ψ_{stem} values and their respective time-bounded Ψ_{trunk} values was identified using a linear mixed-effects model, which improved when using the minimum daily Ψ_{trunk} values with a R_m^2 of 0.5 and R_c^2 of 0.59 (See Supp. Fig. 7).

3.5. Number of sensors needed for the estimation of Ψ_{trunk} using TWD_{max}

To calculate the number of sensors needed to achieve a standard error of 0.15 MPa, the values of Ψ_{trunk} and TWD_{max} were used. This

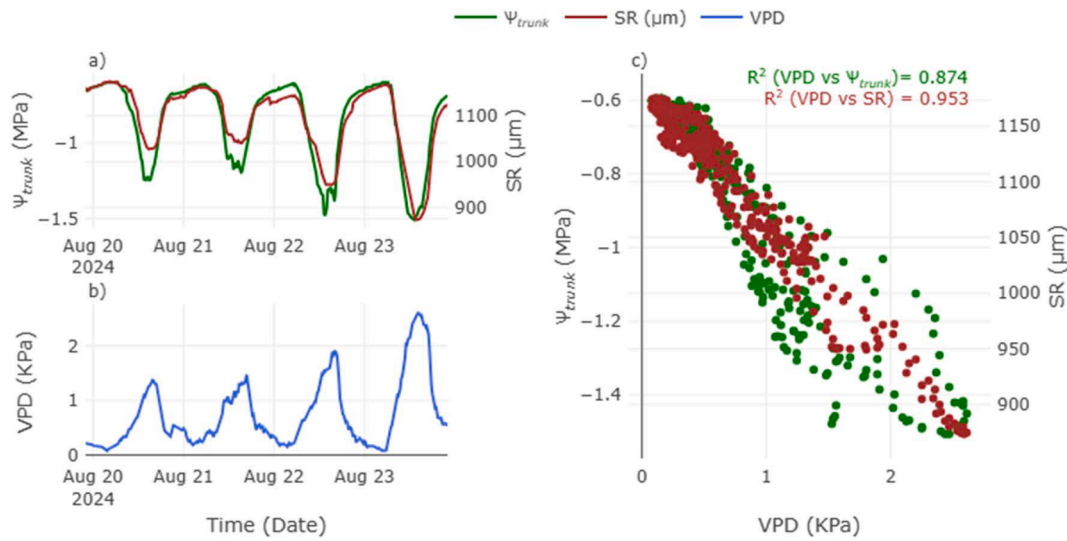


Fig. 5. (a) The stem radius variations (SR, dark red) and trunk water potential (Ψ_{trunk} , dark green) and (b) the daily dynamics of vapour pressure deficit (VPD, blue) between 20 and 26 August 2024. (c) The relationships of VPD with stem radius variations (SR) and Ψ_{trunk} (green and red, respectively), including linear regressions and their corresponding coefficients of determination (R^2).

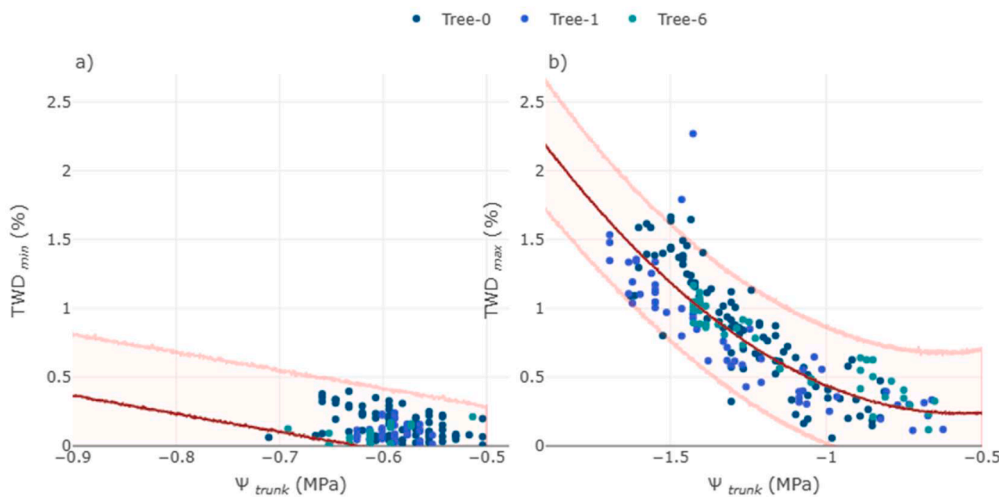


Fig. 6. Relationships between tree water deficit (TWD) and Ψ_{trunk} measured at its minimum (a) and maximum value (b). Each point represents an individual tree measurement, where colours denote different trees. The solid red lines show the fitted regression models (linear for TWD_{min}, quadratic TWD_{max}), and the shaded areas indicate 95% confidence intervals.

analysis, based on the variance partitioning of TWD_{max} , revealed a strong dependence of total measurement uncertainty on both the number of trees monitored and the number of sensors per tree (Fig. 7). The golden contour line in Fig. 7 represents the target CV in TWD_{max} (≈ 0.12) required to maintain an equivalent standard error of 0.15 MPa in Ψ_{trunk} . The red contour line corresponds to a stricter precision threshold of 0.05 CV, similar to Ψ_{stem} .

4. Discussion

This study evaluated the variability of key dendrometer metrics across eight trees and four stem positions per tree and assessed their suitability for irrigation optimisation by comparing them with continuous Ψ_{trunk} measurements obtained using microtensiometers and conventional Ψ_{stem} measurements obtained using a Scholander pressure chamber.

Overall, dendrometer-derived parameters exhibited greater variability than Ψ_{stem} , with within-tree variability exceeding between-tree variability. Despite this, strong relationships were observed between selected dendrometer metrics, particularly maximum tree water deficit (TWD_{max}), and Ψ_{trunk} , supporting the potential of dendrometers for monitoring tree water status. The findings also highlight the importance of sensor placement and optimisation strategies to improve measurement reliability.

The discussion is organised into four sections: (i) the relationship between Ψ_{stem} and Ψ_{trunk} ; (ii) the sources and implications of variability in dendrometer measurements; (iii) the relationships between dendrometer-derived parameters and tree water status indicators; and (iv) sensor optimisation and the practical implications for irrigation management in apple orchards.

4.1. Relationship between Ψ_{stem} and Ψ_{trunk}

No water stress was observed throughout the experiment, with an adequate relationship between the two measurements, Ψ_{stem} and Ψ_{trunk} without or with the inclusion of the independent tree effect ($R_m^2 = 0.50$ / $R_c^2 = 0.58$). This is consistent with the precision reported by Vaccaro et al. (2025). However, other researchers have reported stronger correlations between these parameters ($R^2 > 0.8$ by Blanco and Kalcsits, 2023; $R^2 = 0.86$ by Conesa et al., 2023). The lower correlation in the present study could be partly explained by differences in the timing of peak

water stress: the most negative Ψ_{trunk} values typically occurred around 16:00, whereas Ψ_{stem} measurements are conventionally taken at midday (12:00). Despite the lower correlation, our study showed the same bias as reported by Blanco and Kalcsits (2023), who demonstrated that the Ψ_{trunk} values tended to be lower than the water stress expressed by Ψ_{stem} . This contrasts with the findings by Conesa et al. (2023) and Vaccaro et al. (2025), who reported higher Ψ_{trunk} than Ψ_{stem} values. This lack of accuracy could also be explained by sensor calibration parameters, which previous authors have linked to installation factors, including the use of mating paste (Vaccaro et al., 2025).

4.2. Variability in dendrometer data

The analysis of the average correlations across sensor positions (Table 1) revealed that measurement consistency varied independently of the specific position. Although sensors were installed following a standardised configuration, structural differences between trees, such as stem curvature and bark irregularities, made it impossible to maintain identical sensor positions. Nevertheless, good correlations were found for MDS and TWD_{max} , suggesting representative measurements across trees when these were mainly dominated by weather conditions.

Our finding suggests that TG and TWD_{min} are more sensitive to individual tree conditions, which may include growth-related and nocturnal refilling or structural differences at the measurement point, than to between tree variation. Moreover, calculating TWD_{min} from TG had a negative effect due to the loss of information, as TWD_{min} values were capped to the maximum historical size. This aligns with the hypothesis that TWD_{min} is mainly indicative of rehydration, depending on the soil water conditions that may not be well-synchronised across individuals (Zweifel et al., 2016). Therefore, it is significantly harder to accurately assess TWD_{min} than MDS and TWD_{max} , as such variables are mostly dominated by weather-dependent effects.

Variance analysis revealed that contrary to TG and TWD_{min} , most of the variability in MDS and TWD_{max} occurred within individual trees rather than between trees. Similar results were reported by Zweifel et al. (2021), who documented pronounced radial and axial heterogeneity across the entire stem. This supports the robustness of MDS as an indicator of daily water transpiration at the stand level under non-stress conditions, as exemplified by the close relationship between MDS and VPD (Fig. 5). By contrast, the higher CV within trees for TG and TWD_{min} suggest that micro-scale tissue properties and internal tree anatomy may be important sources of variation to be considered when determining the extent of daily stem variations, as mentioned above. The normalization of such parameters may have a positive effect when studying trees of different species or ages, as proposed by Peters et al. (2025).

4.3. Relationships between parameters

As Ortuño et al. (2010) summarised and as presented in this study, Ψ_{stem} correlate better per tree (R_c^2) than as a general effect (R_m^2) with the multiple dendrometer-derived parameters. This confirms the known per-tree calibration for the prediction of Ψ_{stem} when directly using dendrometer-derived parameters as a tool for irrigation prediction. Nevertheless, an additional factor that may have weakened these relationships was the transient increase in stem radius, of approximately 100 μm , observed immediately after rainfall events (data not shown), followed by a gradual decrease over the subsequent two days. Although this mechanism was not directly investigated in the present study, these observations are consistent with temporary bark hydration rather than changes in tree water status. Consequently, dendrometer measurements may reflect not only internal stem water dynamics but also transient increases in bark water content, which may partly explain the additional variability observed in the relationship with Ψ_{trunk} . As this mechanism was not directly assessed, it should be regarded as a plausible explanation rather than a confirmed process. This may have also affected the Ψ_{trunk} measurements too as this effect was not evident in the relationship

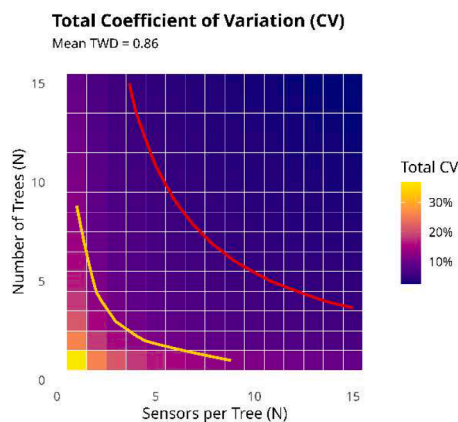


Fig. 7. Total coefficient of variation (CV) in tree water deficit max (TWD_{max}) as a function of sampling design. The x-axis represents the number of sensors per tree, and the y-axis represents the number of trees sampled. The colour scale indicates the total CV (%) in the estimated mean TWD_{max} , combining within-tree, between-tree, and measurement noise variability components. The red contour line marks the 5% CV threshold, and the gold contour line represents the target CV required to achieve an equivalent uncertainty of ± 0.15 MPa in trunk water potential (Ψ_{trunk}).

between dendrometer-derived parameters and Ψ_{trunk} . This implies that even a small amount of rain can increase the thickness of the bark, affecting not only dendrometer measurements but also the measurement of microtensiometers. This aligns with observations by Zweifel et al. (2016), who emphasised that Ψ_{stem} primarily reflects the status of conductive xylem tissues, capturing the dynamic balance between transpiration demand and hydraulic supply, whereas dendrometer parameters can reflect changes in elastic tissues, such as the cortex, phloem, and bark, whose fluctuations depend strongly on their previous hydration status.

In our study, the correlation between Ψ_{trunk} and TWD_{min} ($R^2_c = 0.37$), which has rarely been reported in the literature, was relatively weak. Besides the limited range of water stress observed during the experiment, this may also reflect the physiological decoupling between xylem water potential and radial stem changes under high water-status conditions. TWD_{min} is influenced not only by xylem water potential but also by stem tissue elasticity, hydraulic capacitance and nocturnal refilling processes (Zweifel et al., 2016). These mechanisms can buffer changes in stem water potential and reduce the linear relationship between Ψ_{trunk} and TWD_{min} under non-stress conditions. Higher water stress could increase the range of nocturnal Ψ_{trunk} , providing a better support for the correlation between Ψ_{trunk} and TWD_{min} , particularly as it is known that such correlation increases exponentially beyond -2 MPa (Beikircher, 2013; Ziegler, 2024; Girona et al., 2025). As mentioned above, the strong correlation between Ψ_{trunk} and TWD_{max} ($R^2_c = 0.71$) reflects the fact that both measurements capture the effect of daily weather conditions (VPD) on water status at essentially the same location on the stem, reducing spatial divergence and improving correspondence. Thus far, most of the reported correlations between microtensiometers and dendrometer-derived parameters have been associated with MDS. For instance, Blanco and Kalcsits (2023) reported that MDS and Ψ_{trunk} was strongly related at the onset of deficit irrigation ($R^2 = 0.63$), but this relationship weakened when the entire season was evaluated ($R^2 = 0.44$). The same authors obtained similar results ($R^2 = 0.42$) in a second experiment (Blanco and Kalcsits, 2024).

4.4. Sensor optimisation and practical implications

In the present study, a 0.15 MPa uncertainty in Ψ_{trunk} corresponded to a 0.123 CV, attainable with a combination of 9 sensors distributed within and between trees. For example, for commercial purposes, a simpler setup using five trees equipped with one sensor each can maintain an overall uncertainty of 0.2 MPa in Ψ_{trunk} (CV = 0.16). Although deploying multiple sensors per tree may not be feasible in commercial settings, such an approach can be valuable to reduce within-tree variability and to provide better insights into the sources and magnitude of physiological variation among trees, especially for non-weather dependent dendrometer derivate parameters. Based on our results, such an option would help to reduce variability within trees, which would require further validation, especially as band dendrometers have not demonstrated such capacities (e.g., Corell et al., 2014).

Our experiment demonstrated that TWD_{max} is strongly explained by Ψ_{trunk} under the environmental conditions evaluated and can therefore be used to determine an optimal number of sensors. However, because TWD_{max} is strongly influenced by VPD, it reflects not only tree water status but also atmospheric demand and should therefore not be interpreted as a direct proxy of tree water status. Nonetheless, despite this limitation, TWD_{max} remains one of the most robust and widely used dendrometer-derived indicators for detecting plant water stress, particularly under conditions of limited water availability. To develop a more reliable model, TWD_{min} could also be considered, as it may better reflect water availability independently of short-term environmental fluctuations. Such an approach may improve the ability to capture both the full daily cycle of tree hydraulics and night-time stem refilling, although a higher number of sensors may be required. However, as suggested in our previous work (Waldburger et al., 2025a), the lack of

correlation between TWD_{max} and VPD occurring during periods of water stress could potentially be used as an indicator of stress. Nevertheless, as the present study was conducted under limited or no substantial water stress, these implications should be interpreted with caution, and further studies under deficit-irrigation and more severe water-stress conditions are needed to confirm the applicability of these findings.

The continuous measurements provided by the microtensiometers allowed for a broader and more detailed assessment of their correlation with relative stem radius changes and VPD, which was not achievable with the intermittent measurements obtained from the Scholander chamber. Nevertheless, the current generation of microtensiometers, particularly the model used in this study, is not yet suitable for widespread commercial deployment. Their installation requires invasive procedures that cause permanent damage to the tree, the sensors have a limited operational lifespan, and their costs remain high compared with dendrometers (Di Biase et al., 2025). Moreover, the strong correlation between microtensiometer measurements and dendrometer data supports dendrometers as a reliable tool for monitoring tree water stress, whereas microtensiometers may be more appropriate as research instruments than as practical options for routine on-farm irrigation management.

To enhance comparability, the implementation of standardised sensor installation protocols, particularly regarding sensor height above ground and the potential use of multiple sensors per tree, could substantially reduce measurement inconsistencies, further advancing water usage efficiency in the context of irrigation.

5. Conclusion

In the present study, all variables showed a higher variability than Ψ_{stem} , independent of whether these were triggered by growth or nocturnal refilling (TG, TWD_{min} , Ψ_{trunk}) or by environmental conditions, particularly via VPD (MDS, TWD_{max} , Ψ_{trunk}). For all the studied dendrometer-derived parameters, within-tree variability was always greater than between-tree variability. MDS and TWD_{max} showed consistent responses across different sensor positions between individual trees, whereas TWD_{min} varied substantially, reflecting differences in growth or night-time recovery between trees. Achieving variability levels comparable to those observed for Ψ_{stem} would require increased replication, either by sampling a larger number of trees or by deploying multiple sensors per tree. Nevertheless, allowing for an uncertainty of 0.15 MPa in Ψ_{trunk} , nine sensors could be used, whereas five sensors would still allow for an acceptable 0.2 MPa error in Ψ_{trunk} .

Stem radius measurements may have been additionally influenced by rainfall-induced bark hydration, which may have affected the relationships with both Ψ_{stem} and Ψ_{trunk} . Nevertheless, the strong correspondence observed between Ψ_{trunk} and TWD_{max} suggests that both microtensiometers and dendrometers capture the same underlying stem water-status dynamics at the measurement location. The dendrometers also respond to small changes in bark hydration, which introduces an additional source of variability following rainfall or other trunk-wetting events.

CRedit authorship contribution statement

Thainna Waldburger: Writing – review & editing, Investigation, Formal analysis, Data curation, Conceptualization. **Thomas Anken:** Writing – review & editing, Project administration, Conceptualization. **Camilo Chiang:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Data curation.

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.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.agrformet.2026.111552](https://doi.org/10.1016/j.agrformet.2026.111552).

Data availability

Data is publicly available in zenodo.org.

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