

Quantifying between and within tree stem variations using dendrometers

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Abstract (250 words)

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 reliable irrigation control. This study quantifies the variability of key dendrometer parameters commonly proposed for irrigation management usage between and within trees. In addition, continuous microtensiometer measurements of trunk water potential (Ψ_{trunk}) and standard stem water potential measurements using a Scholander pressure chamber (Ψ_{stem}) were compared with dendrometer-derived growth and tree water deficit (TWD). The number of sensors required to achieve a 0.15 MPa (Ψ_{trunk}) standard error was then calculated. All tree water status proxies 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). Tolerating a bigger variability of 0.2 MPa, 5 dendrometers need to be used. Daily Ψ_{trunk} minimum and TWD_{max} were well correlated (R^2_m and $R^2_c = 0.73$), although this correlation was weaker and tree dependent for Ψ_{trunk} maximum and TWD_{min} ($R^2_m = 0.06$, $R^2_c = 0.32$). 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. Options to reduce the observed variability in dendrometers, especially during the night, should be studied.

Keywords: dendrometer position, microtensiometer, stem water potential, tree water deficit

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28 1. Introduction

29 Automated irrigation systems in orchards typically rely on soil moisture measurements to
30 determine the amount of water to be applied. However, many researchers have criticised this
31 control strategy (e.g. Wheeler et al., 2023, Waldburger et al., 2025a) because soil moisture
32 does not always reflect the actual water requirements of plants. Consequently, indicators of
33 plant stress may offer a more reliable basis for irrigation management. One promising
34 approach is the use of dendrometer sensors, which can detect plant water stress through
35 changes in stem size. This has been demonstrated by the successful use of dendrometers in
36 crops such as citrus, olives, and apples (e.g. Velez et al., 2007; Girón et al., 2016; Waldburger
37 et al., 2025b). Dendrometers are particularly appealing due to their relatively low cost, non-
38 invasive installation, and extensive validation across multiple species (e.g. Dietrich et al.,
39 2018).

40 Dendrometers enable the continuous, high-resolution measurement of stem size by
41 typically employing a linear potentiometer or similar sensor. Changes in stem size recorded
42 by these instruments represent not only increments in growth but also short-term daily
43 fluctuations in the tree's water status (Zweifel et al., 2016). These daily expansions and
44 contractions occur because water is temporarily stored and released within the relatively
45 elastic outer tissues of the stem—particularly the cambial zone and phloem—which respond
46 dynamically to variations in transpiration demand and internal water balance (Devine and
47 Harrington, 2011). Such fluctuations capture primarily the elastic response of the stem to
48 environmental changes and are commonly expressed as the maximum daily shrinkage (MDS;
49 Fig. 1), defined as the difference between the maximum and minimum stem radius recorded
50 within a given day (e.g. Naor and Cohen, 2003). Water status can also be reported by tree
51 water deficit (TWD) (e.g. Dietrich et al., 2018), calculated as the deviation from a baseline
52 growth obtained by extrapolating maximum stem size based on the maximum previously seen
53 size (e.g. Girón et al., 2016; Dietrich et al., 2018; Goldhamer and Fereres, 2001; Naor and

Cohen, 2003; Fernández and Cuevas, 2010; Moriana et al., 2010; Wheeler et al., 2023). TWD calculations assume non-significant growth under stress periods, as proposed by Zweifel et al. (2016), and can be at difference of MDS and tree growth (TG), calculated at multiple times of the day (e.g. Dietrich et al., 2018).

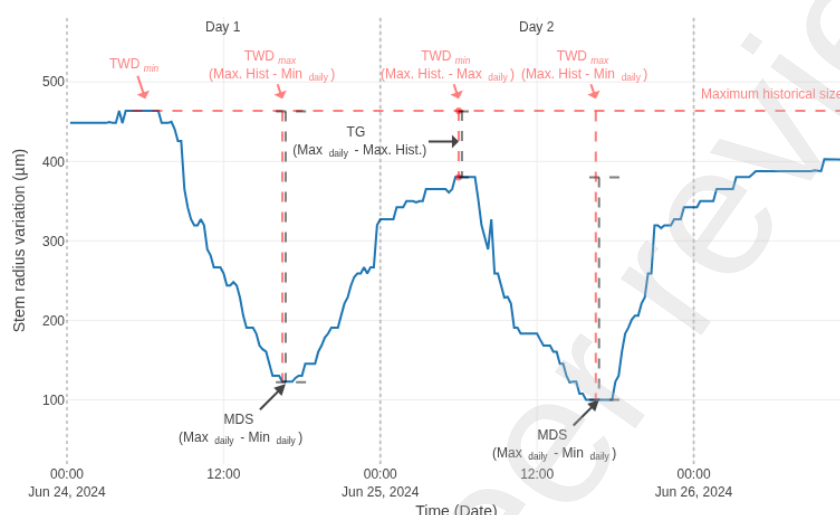


Fig. 1. Example of two days of stem radius change, highlighting maximum daily shrinkage (MDS), tree growth (TG), and tree water deficit (TWD), calculated as minimum (TWD_{min}) and maximum (TWD_{max}) values. Vertical dashed lines indicate the range of stem radius variation used to calculate each parameter, while the horizontal dashed line extrapolates the maximum historical size, as in previous studies (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 measurements 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 suggesting underestimation (Vacaro et al., 2025) or overestimation of 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. 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.

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. 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 (Ψ)

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. 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 Kalcsits (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 variations were recorded as voltage signals and logged using an Agriscope 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 $6.1 \mu\text{m}$. TG (Eq. 1) and MDS (Eq. 2) were calculated 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 ($\text{TWD}_{\min}$; Eq. 3), closely resembling TG and similarly weather independent, and at its maximum daily value in the middle of the afternoon ($\text{TWD}_{\max}$; 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 respectively, if available.

$$TG = SR_{\text{dailymax}} - SV_{\text{historicalmax}} \# (1)$$

$$MDS = SR_{\text{dailymax}} - SR_{\text{dailymin}} \# (2)$$

$$\text{TWD}_{\min} = SR_{\text{historicalmax}} - SR_{\text{dailymax}} \# (3)$$

$$\text{TWD}_{\max} = SR_{\text{historicalmax}} - SR_{\text{dailymin}} \# (4)$$

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 multiple tree daily dendrometer parameters and Ψ (Ψ_{stem} or Ψ_{trunk}) was then evaluated using R^2_m and R^2_c as is then possible to evaluate the general effect that does not consider the specific tree effect (R^2_m) and the addition of each tree effect (R^2_c). For this, the model presented in Eq. 5 was used, with the intercept being independent for each tree and the replicates nested within the tree.

$$Dendrometerparameter = \Psi + (1|Tree/Rep) \#(5)$$

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:

$$Parameter = Date + (1|Tree/Rep) \#(6)$$

The model included date as a category and fixed effect to account for temporal variation and a nested random-effects structure, with repeated measurements nested within individual trees 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, aiming to select a period of time free of any growing tendencies.

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, a linear mixed-effects model was fitted between Ψ_{trunk} and TWD_{min} . Since 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 was incorporated to account for repeated measurements, enabling the estimation of the effects of water status and environmental variables on TWD. 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 error for irrigation purposes.

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 as it doesn't include the daily weather effect, we hypothesised that TWD_{min} would have a stronger variation and it is additionally not equivalent to the today standard Ψ_{stem} midday measurement. 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. 7.

$$CVTWD_{max} = \frac{SETWP_{max}}{\left| \frac{dx}{dy} f(\Psi_{trunk}) \right| * \sum TWD_{max}} \quad \#(7)$$

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 the growing season. 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).

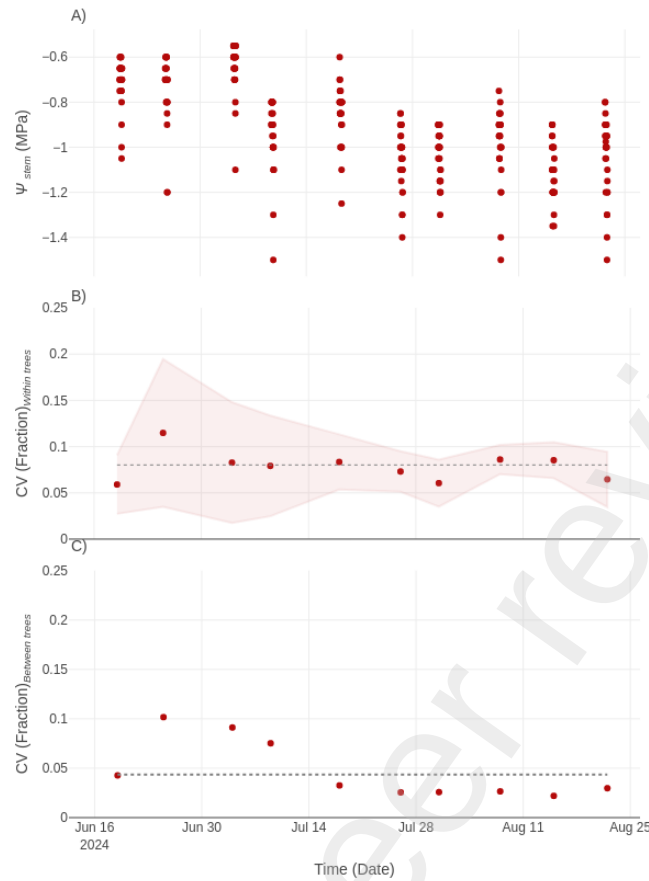


Fig. 2. (a): Individual measurements of Ψ_{stem} (MPa) for all trees and replicates at each sampling date. (b): Coefficient of variation (CV, fraction) of Ψ_{stem} calculated within trees across replicates on each date. Dotted points indicate the average value within trees, shaded area indicates $\pm$ 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).

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. 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 daily patterns (Fig. 3b). The maximum Ψ_{trunk} value per day correlated with the manually measured Ψ_{stem} with an adequate correlation ($R^2_m = 0.5$; $R^2_c = 0.58$), with a clear overestimation of Ψ_{stem} .

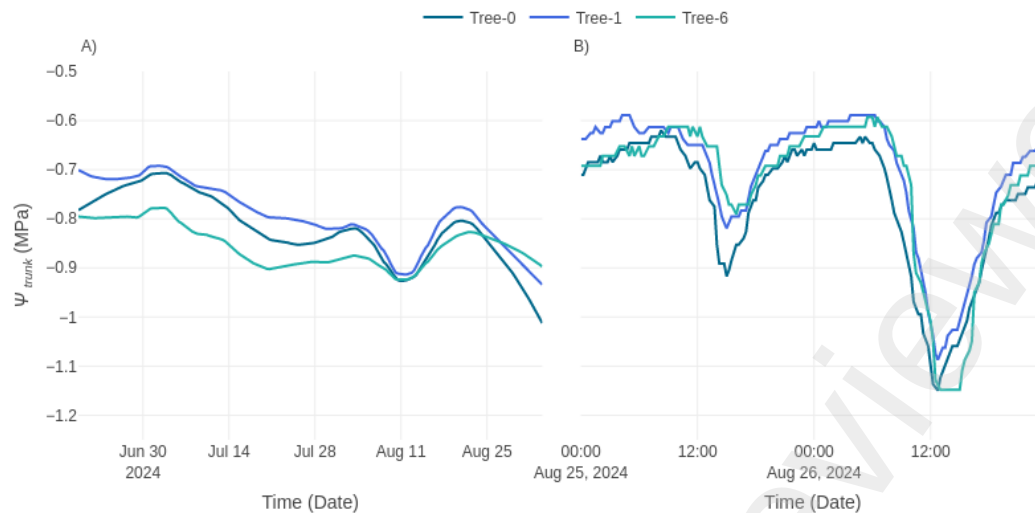


Fig. 3. Microtensiometer data (Ψ_{trunk}) showing a smoothed seasonal trend (LOESS, span = 0.3) obtained from three trees during the experiment. (b) Raw data focusing on two selected days (2025-08-25 to 2025-08-26).

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. 4 a and c). MDS displayed a high variability, with peak values frequently exceeding 400–600 μm 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 μm during the driest periods (Fig. 4b and 4d).

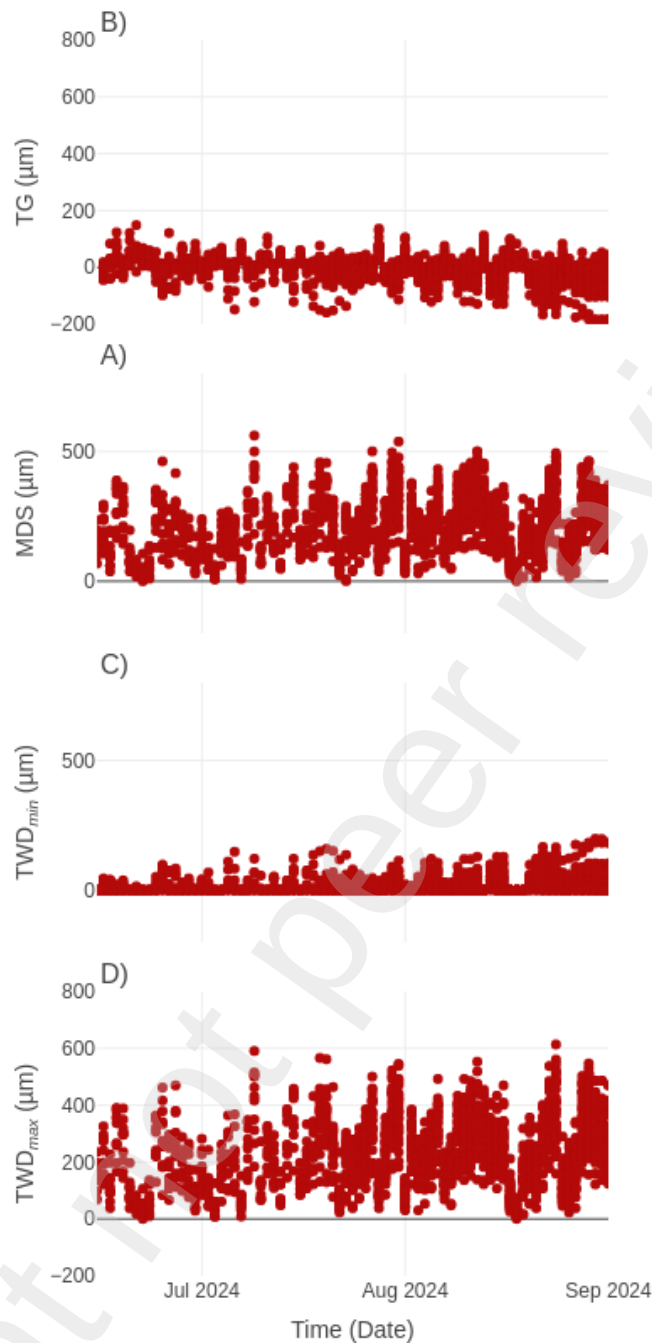


Fig. 4. Raw dendrometer-derived parameters recorded between July and September. (a) Tree growth (TG), (b) maximum daily shrinkage (MDS), (c) tree water deficit daily minimum (TWD_{min}), and (d) tree water deficit daily maximum (TWD_{max}). Each point represents an individual tree measurement.

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 (~36%), weather-dependent parameters were totally dominated by within-tree variability (~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} . Regarding the latest, mixed-effects modelling showed that only a negligible proportion of variance originated from differences between trees, whereas 10% and 1% of the overall between-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 supplementary figure 6). The position exhibiting the most consistent measurements across trees varied depending on the parameters analysed, as summarised in Table 1. Overall, TWD_{min} was the least-correlated parameter across trees.

Table 1. Average between-tree correlation 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	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	0.518	0.857	0.316	0.857

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. Linear regressions for this period confirmed this relationship: both Ψ_{trunk} and stem radius variations were highly correlated with VPD ($R^2 = 0.874$ and 0.95 , respectively) (Fig. 5b).

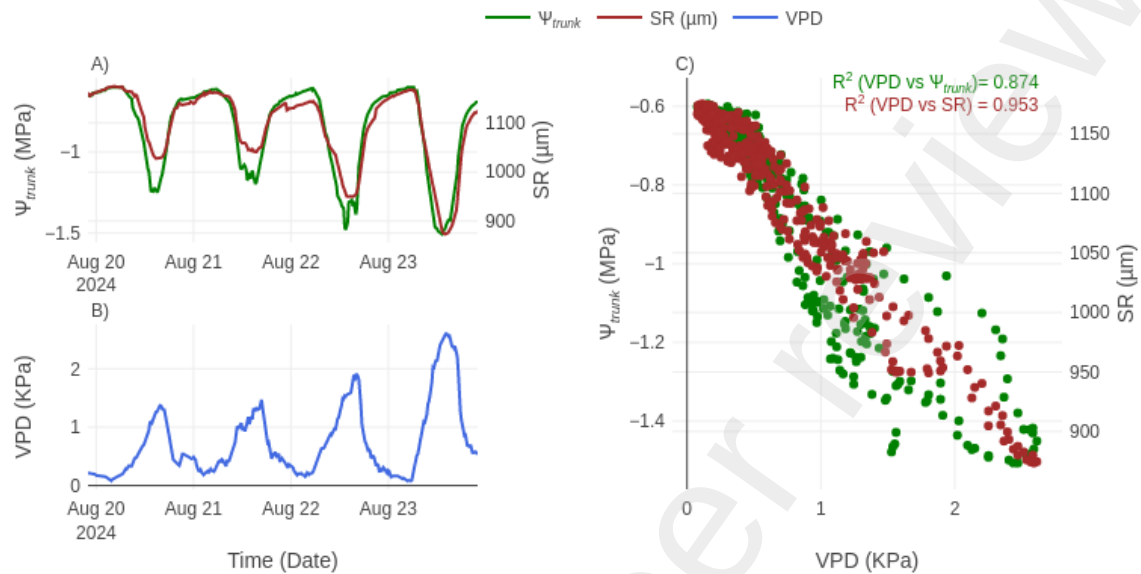


Fig. 5. (a) The stem radius variations (dark red) and trunk water potential (Ψ_{trunk} , dark green) and (b) the daily dynamics of vapour pressure deficit (VPD, blue) between 20–26 August 2024. (b) The relationships of VPD with stem radius variations and Ψ_{trunk} (green and red, respectively), including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

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 ($R^2_m = 0.05$, $R^2_c = 0.44$) when correlated directly with Ψ_{stem} . Incorporating maximum VPD values per day into the linear mixed-effects models markedly improved this relationship ($R^2_m = 0.33$, $R^2_c = 0.76$). 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 ($R^2_m = 0.06$, $R^2_c = 0.37$) (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 observed variability across trees ($R^2_m = 0.73$, $R^2_c = 0.76$, Fig. 6, b). The addition of VPD as a fixed factor did not have a significant effect on TWD, regardless of the selected time of day.

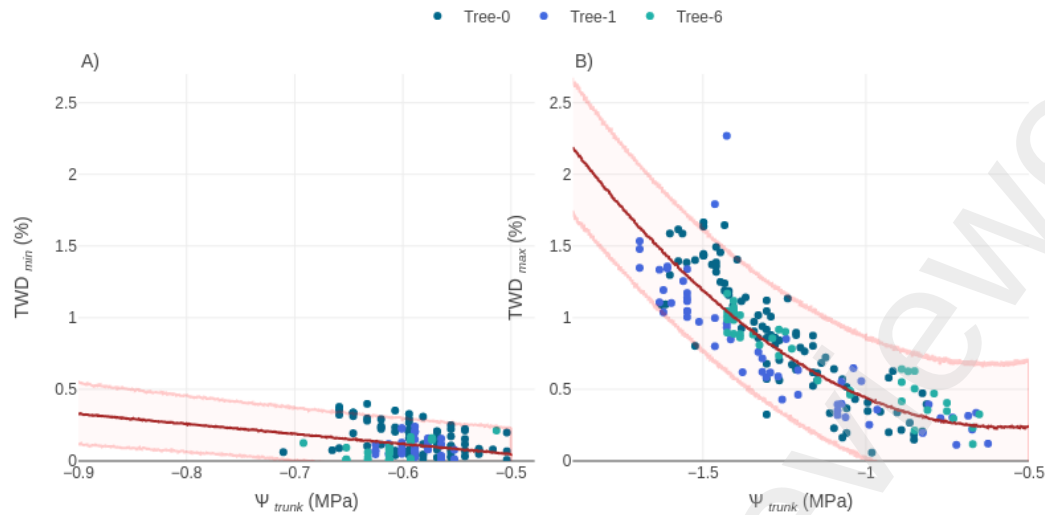


Fig. 6. Relationships between tree water deficit (TWD) and Ψ_{trunk} measured at its minimum (a) and maximum value (b). Each point represents an individual tree measurement, where colours denote different trees. The solid red lines show the fitted regression models (linear for TWD_{min} , quadratic TWD_{max}),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

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} ($n =$ four 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 supplementary 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 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} .

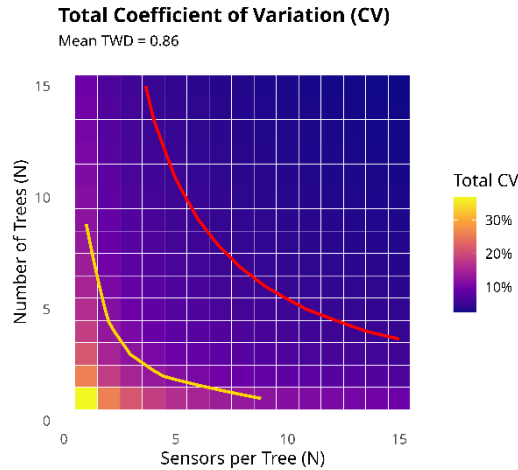


Fig. 7. Total coefficient of variation (CV) in tree water deficit max (TWD_{max}) as a function of sampling design. The x-axis represents the number of sensors per tree, and the y-axis represents the number of trees sampled. The colour scale indicates the total CV (%) in the estimated mean TWD_{max} , 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}).

4. Discussion

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 ($R^2_m = 0.50$ / $R^2_c = 0.58$). 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 underestimate the water stress expressed by Ψ_{stem} . This contrasts with the findings by Conesa et al. (2023) and Vaccaro et al. (2025), who reported an overestimation of water stress. 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 are cap to the maximum historical size. This aligns with the hypothesis that TWD_{min} is mainly indicative of rehydration, depending on 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.

4.3 Relationships between parameters

As Ortuño et al. (2010) summarised and as presented in this study, Ψ_{stem} correlate better per tree (R^2_c) than as a general effect (R^2_m) 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 effect that may have diminished such relationships was short periods of additional increases in stem radius of around 100 μm after a rain event (data not shown). This was followed by slow stem radius decreases that lasted for approximately two days, which we attributed to the drying of the bark, as only little water stress was observed during these periods. This may have also affected the Ψ_{trunk} measurements too as this effect was not evident in the relationship 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, thus far, is not commonly found in the literature, was limited by a lack of stress in our experiment. Higher water stress could increase the range of nocturnal Ψ_{trunk} , helping to better understand 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} were 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. 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} and can therefore be used to determine an optimal number of sensors. However, because TWD_{max} is mainly driven by VPD, it remains strongly influenced by environmental conditions rather than plant water status. 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 would 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 be used as an indicator of stress.

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 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. Bringing dendrometer derivative parameters variability in line with Ψ_{stem} variability would necessitate increased replication, either through a greater number of sampled trees or multiple sensors per tree. Nevertheless, allowing for an uncertainty of 0.15 MPa in Ψ_{trunk} prediction when using dendrometers, nine sensors could be used, whereas five sensors would still allow for an acceptable 0.2 MPa error in Ψ_{trunk} .

Stem radius measurements were additionally influenced by rainfall causing hydration of the bark, which may have affected the correlation of ψ_{stem} and ψ_{trunk} . Given the strong correspondence between ψ_{trunk} and TWD_{max} , we hypothesise that microtensiometers capture the same water status dynamics at the same stem location as dendrometers, which include bark conditions.

6. Data availability

Data for the experiment, together with other previously published work data on apple ecophysiology, are available on www.zenodo.org under the following DOI: 10.5281/zenodo.1838389

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