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Trunk-diameter relative resistance to shrinking: an intrinsically derived plant water stress index, demonstrated in *Ficus Carica* cv. Black Mission.

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Abstract

The accuracy of irrigation timing and the definition of the amount of water to apply depend on the precise assessment of plant water status within the soil–plant–atmosphere continuum. Among the widely reported indicators, trunk diameter–based metrics provide continuous and sensitive plant-based monitoring that can detect the onset of water stress at very early stages and thus improve precision irrigation and controlled deficit irrigation management. Nonetheless, these indicators still suffer from high variability and strong climatic dependence, as well as species- and growth stage–specific behavior. In the present study, intermittent water-deficit periods with varying intensities (Control, Mild, Moderate, and Severe) were applied to fig trees to generate a wide range of stem water potential (–0.5 to –2.5 MPa) and trunk diameter shrinkage values (100 to 900 μm), together with reference and crop evapotranspiration measurements. A third-degree polynomial trend was fitted to the relationship between trunk diameter shrinkage and accumulated reference evapotranspiration during the morning period to derive a new intrinsic and self-informative water stress indicator. The results confirmed the potential of trunk diameter variation to reflect internal hydraulic adjustments in the plant and supported the development of a new intrinsic water-stress indicator called diameter relative resistance to shrinking (DRS). This indicator is self-informative (no need for a well-watered reference plant), easy to interpret (ranges between 0 and 1), and better correlated with stem water potential (lower NRMSE) than the commonly used maximum daily shrinkage. The proposed indicator shows strong potential for supporting precise and adaptive irrigation scheduling under deficit irrigation conditions. However, further studies are required to evaluate the extent to which DRS depends on species- and cultivar-specific hydraulic traits.

Keywords: Stem diameter variations, Plant water relations, Dendrometer, Maximum daily shrinkage, Stem water potential, plant hydraulic capacitance.

Highlights

- Morning trunk diameter shrinkage (DS) reflects internal stem capacitance buffering.
- A new water-status indicator, quantifies diameter resistance to shrinkage (DRS).
- DRS represents hydraulic buffering to demand-driven contraction.
- DRS correlates with stem water potential and outperforms MDS.
- DRS is self-informant without reference plants.

Introduction

Irrigated agriculture plays a key role in hydraulic ecosystems, influencing water distribution, land use, ecological balance, and socio-economic stability and growth. To manage this impact effectively, it is essential to encourage shared responsibility and participatory approaches (Bagheri et al. 2020; Islam et al. 2023), as well as, to provide precise monitoring indicators, practical water conservation tools, and interactive decision support systems (Zhang et al. 2021). At the farm level, the scientific community has carried out a large number of experimental studies on a wide range of plant types and species, aiming to understand the hydraulic relationships in the soil-plant-atmosphere continuum “SPAC” and thus, providing water stress indicators (Hsiao 1973; Cuevas et al. 2010; Fernandez et al. 2020; Carella et al. 2024) to schedule irrigation and improve water productivity precisely.

Although any element of the SPAC can provide helpful information, the plant remains the most representative one by having its root system exploring the vadose zone and its aerial part immersed among the climatic factors affecting its biological clock and driving the rates of photosynthesis and evapotranspiration. Among the well-known plant eco-physiological variables, the stem water potential and the leaf relative water content are usually reported as standard reference indicators for plant water stress (Marino et al. 2018; Parkash and Singh 2020); they hold a stretch relationship with the soil water availability and show a direct impact on stomatal conductance, cell growth and division, organs’ differentiation and yield production. Nonetheless, the hitches (invasive sampling, labor-intensity, reading time, potential hazard and automation challenges) of their standard determination methods have always promoted the development of proxy indicators and measuring instruments. For instance, the application of thermodynamic principles and energy balance approaches helped monitoring the evolution of the plant sap flow (Garnier 1985; Kumar 2022). The use of electro-mechanical (LVDT: linear variable displacement transducer) and electromagnetic instruments (LPCP: leaf patch clamp pressure) (Zimmermann et al. 2008) facilitated recording the circadian variations of the stem diameter and of the leaf turgor pressure respectively. Recently, the implementation of optical sensing techniques gave birth to a new non-invasive leaf-mounted sensor to monitor the plant water status (Brunetti et al. 2022). However, all the plant based indicators are sensitive to its age, the sensed organ (leaf, fruit, root, stem or trunk), the measuring position (vertical height, cardinal directions and depth inside the plant canopy), and the measuring instrument (pressure chamber, sap flow, LVDT, LPCP, LWM (Brunetti et al. 2022), etc.).

Among the previously cited indicators, those based on the trunk diameter variations (TDVs) stand out as some of the most sensitive. The TDVs are the result of instantaneous hydraulic adjustment between root water-uptake and sap flow on the one side and water loss by evapotranspiration on the other side. Early in the twentieth century, Hendrickson and Veihmeyer F.J. (1941), highlighted diurnal variations in tree trunk diameter (TDV) as a non-invasive and very sensitive indicator of plant water status, with clear potential for guiding precise irrigation scheduling. However, limitations in knowledge and measurement technology at that time delayed its application for several decades. It was not until the work of Goldhamer and Fereres (2001) that the concept was operationalized, when they proposed the use of the signal intensity (SI) of maximum daily shrinkage (MDS) in

trunk diameter as a robust index to reduce the influence of uncontrolled plant and environmental factors. This proposal constituted the base for several research studies (Ortuño et al. 2010; Ru et al. 2021) and produced interesting water-saving results. They directly reflect imbalances between the dynamic fluxes of transpiration and root water uptake. Their monitoring helps detecting the onset of water deficit several days before observing any visible symptoms (Wheeler et al. 2023; Blaya-Ros et al. 2024) or even before significant changes in predawn stem water potential as reported in young lemon trees by Ortuño et al. (2004). Nevertheless, its implementation has not extended beyond research centers because it involves additional infrastructure and personnel skills; a group of plants of the same type and species need to be established under the same local edapho-climatic conditions and managed under optimum soil water content to produce daily reference values of MDS (Zhao et al. 2024; Fosalau 2025).

The mechanistic models proposed by Molz and Klepper 1972, Steppe et al. (2006, 2008a and 2008b), De Schepper and Steppe (2010) and Mencuccini et al. (2013), provide mathematical equations to explain and estimate water and sugar transports among plant tissues and organs as well as their relation to the reversible shrinking of stems and fruits but none explored their potential application for irrigation scheduling purposes. A careful revision of these models and a solid field experience on the use of LVDT sensors for TDVs monitoring and interpretation for decision-support purposes, drove the authors of this study to explore new water stress indicators with minimum physiological and operational limitations. Thus, they hypothesized that the relative response of stem diameter shrinkage to accumulated reference evapotranspiration between sunrise and midday reflects the progressive depletion of internal stem water storage and therefore integrates the effects of hydraulic conductance, capacitance, and stomatal regulation into a single measurable variable. Consequently, the coefficients of a third-degree polynomial relating accumulated ETo to stem diameter variation represent successive hydraulic response regimes and can be used to derive a robust decision-support indicator of plant water status. An ideal water stress indicator should be physiologically integrated with the whole plant, responds rapidly to changes in the soil–plant–atmosphere water balance, is simple to detect and record, and operates on a standard scale that is easy to read, interpret, and integrate into automated irrigation systems.

To test this research hypothesis, continuous time series of trunk diameter measurements and climatic variables (temperature, relative humidity, solar radiation, wind speed) were carefully supervised and recorded along with periodic collection of midday stem water potential on fig trees exposed to different water-deficit periods and intensities during the 2024 growth seasons.

Material and methods

Location

The present study was developed at the department of Biosciences and Agrotechnology of the Research Center for Applied Chemistry (CIQA_SECIHTI: Centro de Investigación en Química Aplicada), located in Saltillo_Coahuila, Mexico (GPS: 25° 27' 38.458" N; 101° 58' 08.00" W, at 1500 m.a.s.l). Saltillo has a semi-arid climate with annual averages of 28°C, 60%, 1500 mm and 200 mm for temperature, relative humidity, reference evapotranspiration and precipitations respectively.

Experimental plot and agronomic design

An experimental plot of 450 m² under a white shade-net cover (10-20% shading) hosted 56 fig trees (*Ficus Carica* cv. Black Mission) arranged in 4 lines of 14 trees each, considering a distance of 2.0 m between trees and 3.6 m between rows. The trees were 5 year-olds and had, since their transplanting in May 2020, the root system separated in two compartment of 80 liters each, filled with a mix substrate (20% zeolite, 20% perlite and 60% peat-moss) compacted to a bulk density of 1.4 g/cm³. The substrate water holding capacities were 0.38 cm³ cm⁻³ and 0.18 cm³ cm⁻³ for field capacity and permanent wilting point respectively.

Every year, in February/March, each tree was severely pruned, conserving one central vertical stem that is cut at a height of 2m and four pairs of alternate horizontal branches (each of 30 to 40 cm in length), separated vertically by 30 to 40 cm and oriented in the direction of the tree rows. Three galvanized wires (3 mm diameter) were horizontally installed (starting at 1 m height from the soil surface and separated by 0.5 m between each other) to help support the trees in place. The trees rest on raised soil beds with tapered sides to facilitate drainage toward water conveyance canals.

The irrigation system consisted of a single lateral drip line per tree row, providing one pressure-compensating emitter of 4 L/h for each root compartment (2 emitters per tree). The irrigation doses and frequency were adjusted frequently after the soil water mass balance was monitored in three reference trees, each equipped with four rain gauges; one under each emitter registering water input and one below each root compartment recording water output by drainage. The fertilizers were applied through the irrigation system by considering the chemical equilibrium reported by Melgarejo et al., 2007 and using an automatic fertigation system to control the application doses and frequency and to adjust the pH and EC values at average values of 6.0 and 3.0 dS/m respectively.

The meteorological variables were monitored by two automatic weather stations (Campbell Scientific Ltd, Shepshed, UK); one located in open field at 500 m away from the experimental plot and the second installed between the trees under the shade-net.

Irrigation treatments and measured variables

To collect a wide range of stem water potential (-0.5 to -2.5 MPa) and trunk diameter shrinkage values (100 to 900 µm), the irrigation schedules were managed such to fully cover the plant water requirements during May, July and September, and to develop one or more progressive water deficit periods by differentiating four irrigation treatments (Ctrl: No water deficit, WD1: Mild water deficit, WD2: moderate water deficit and WD4: sever water deficit) in June, August and October using the following equation:

$$D_{T(i,n)} = \max(1 - Def_f * (i + n - 2), threshold) * D_{Ctrl} \quad \text{Equation 1}$$

147 Where:

- i : Index of the deficit irrigation treatment series (2, 3 and 4 for WD1, WD2 and WD3 respectively)
- n : is the number of irrigation reduction steps since water deficit initiation.
- $D_{T(i,n)}$: irrigation dose (mm) applied to deficit irrigate treatment “i” at reduction step n
- D_{Ctrl} : irrigation dose (mm) applied to the control treatment.
- Def_f : fraction of irrigation water reduced for WD1 on the first day of each deficit period.
- $threshold$: user-defined lower-bound for the reduction factor. It is the minimum allowable fraction of the control irrigation dose; below this value, no further reductions are applied.

148 At the start of each water-deficit period, the Def_f and $threshold$ fractions were set to 0.1 and 0.5 respectively
 149 except in October, the $threshold$ was set to 0. The latter action was to extend the deficit period and intensify
 150 its magnitude to further enrich the database with extreme Ψ_{stem} values. This irrigation management proposal
 151 aimed to assess the impact of water deficit on trunk diameter variations during one-month followed by a
 152 recovery month to avoid potential harsh impact on plant growth and development.

153

154 *Experimental design and data processing and analysis*

155 Each treatment consisted of 12 trees distributed in a complete randomized block design. Three blocks were laid
 156 out perpendicular to the tree rows (North-South direction) to reduce the confounding effect of radiation
 157 heterogeneity across the plot during the year (morning vs. afternoon sunlight, shading patterns, and seasonal
 158 sun angles).

159 During the morning period from sunrise to solar noon, cumulative Reference evapotranspiration (ET_o) was
 160 calculated daily by integrating time-resolved FAO56_ ET_o values from sunrise onward (Equation 2). Trunk
 161 diameter shrinkage was expressed relative to the trunk diameter measured at sunrise (Equation 3).

162

$$t \in [t_{sr}, t_{sn}]$$

$$ET_{o_t} = \int_{t_{sr}}^t ET_o(\tau) d\tau \quad \text{Equation 2}$$

163

$$DS_{(t)} = D_{(t)} - D_{sunrise} \quad \text{Equation 3}$$

164

165

166

Where:

- t_{sr} : Sunrise time estimated using the National Oceanic and Atmospheric Administration (NOAA) solar position algorithm.
- t_{sn} : Solar noon time estimated using the NOAA solar position algorithm.
- ET_{o_t} : Cumulative morning evapotranspiration demand
- $DS_{(t)}$: Diameter shrinkage at time t
- $D_{(t)}$: Diameter at time t
- $D_{sunrise}$: Diameter at sunrise

For each day, the relationship between DS and cumulative ETo was described using a third-degree polynomial function (Equation 4):

$$DS_t = aET_o^3_t + aET_o^2_t + cET_o_t + d \quad \text{Equation 4}$$

Where coefficients a, b, c and d are estimated by least-squares regression using all observations between sunrise and time t. At each time step, the contribution of each monomial term (aET_o^3 , bET_o^2 , cET_o , and d) was evaluated separately using cumulative ETo as input. The individual monomial contributions were then partitioned according to their sign. Negative contributions ($DS_i(t) < 0$) were interpreted as demand-driven contraction associated with increasing atmospheric evaporative demand (Equation 5), whereas positive contributions ($DS_i(t) > 0$) were interpreted as buffering-driven resistance associated with the release of internal stem water storage and hydraulic regulation processes (Equation 6). The ratio between the cumulative buffering-driven resistance and the cumulative demand-driven contraction was defined as the Diameter Relative Resistance to Shrinking (DRS), which represents the relative resistance of trunk tissues to shrinkage during the morning period (Equation 7).

Demand-driven contraction:

$$DS^-(t) = \sum DS_i(t) \quad \text{for } DS_i(t) < 0 \quad \text{Equation 5}$$

Buffering-driven resistance:

$$DS^+(t) = \sum DS_i(t) \quad \text{for } DS_i(t) > 0 \quad \text{Equation 6}$$

Diameter relative resistance to shrinking

$$DRS_t = \frac{\sum_{t_{sr}}^t DS^+(t)}{|\sum_{t_{sr}}^t DS^-(t)|} \quad \text{Equation 7}$$

MDS and DRS were first correlated with the midday stem water potential. Then, the model performance was evaluated using 5-fold cross-validation. The dataset was partitioned into five equally sized folds; in each iteration, four folds were used for training and one for testing. This process was repeated until each fold had served as the test set once. Model accuracy was quantified using the root mean square error (RMSE) and the normalized RMSE (NRMSE), where NRMSE was computed by dividing RMSE by the global mean of observed values. The mean, standard deviation, and 95% confidence interval of NRMSE across folds were calculated

Results

Soil water mass balance

The climatic variables and all the terms of the soil water mass balance were recorded frequently (every 5 min) in order to calculate the reference daily evapotranspiration “ET_o”, the actual crop evapotranspiration and their respective crop coefficient. As can be inferred from Figure 1, the integrated ET_o and ET_c, as well as the applied irrigation depths totaled up to 860, 684 and 604 mm respectively while a dynamic crop coefficient was recorded (0.4 in May to a maximum of 0.73 early September). The average daily drain output was between 15 and 20% of the applied water. The total irrigation depth applied for the deficit treatments was 581, 518 and 508 mm/year for WD1, WD2 and WD3 respectively.

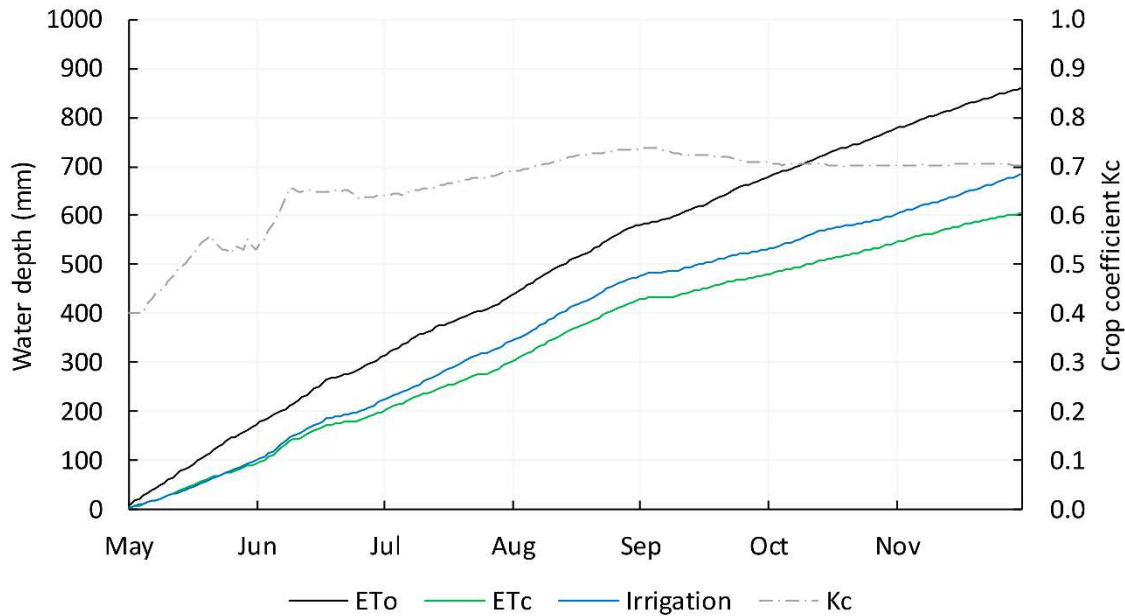


Fig. 1 Evolution of accumulated ET_o, ET_c, applied irrigation water and crop coefficient of fig trees under shading-net between May and November 2024.

Seasonal trunk diameter variations

The time-based development of trunk diameter variation (TDV) followed a sigmoid pattern comprising three growth stages (Figure 2). Stage I was a brief period of slow growth in early May, followed by Stage II, which featured rapid growth from mid-May to mid-September with a consistent weekly average increase (WAI) exceeding 0.5%. Stage III began in mid-September, during which the trunk diameter of control (Ctrl) trees remained nearly constant. In deficit treatments, Stage II exhibited significant sensitivity to water deficit levels, as indicated by a reduction in WAI immediately after the initial deficit period began in June for WD2 and WD3, and in early July for WD1. Additionally, the duration of Stage II was reduced by approximately 10 days in WD1 and by more than 30 days in WD2 and WD3.

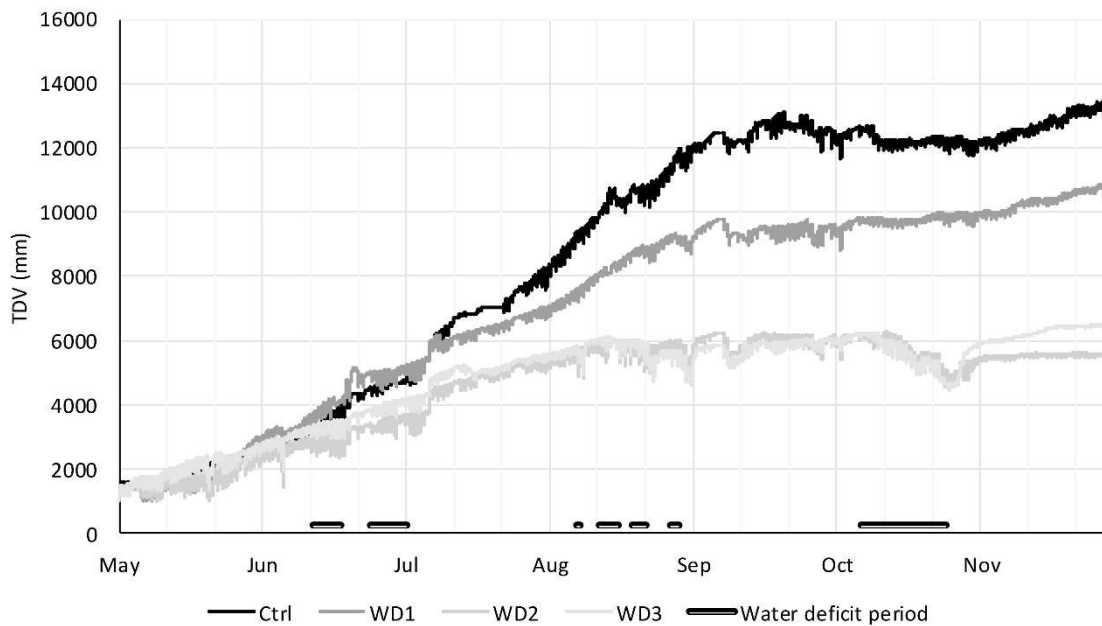


Fig. 2 Evolution of trunk diameter variations of fig trees exposed to intermittent periods (horizontal black lines) of gradual (between treatments: Ctrl, WD1, WD2 and WD3) and progressive water deficit during the months of Jun, Aug and Oct 2024.

Trunk-diameter relative resistance to shrinking

Figure 3A illustrates the shrinkage of the trunk-diameter “DS”, while Figure 3B presents its relative resistance to shrinking “DRS” and figure 3C and 3D show the corresponding signal intensity in the morning for two contrasting irrigation deficits treatments (Ctrl and WD3), on two separate days characterized by significant evapotranspiration and soil-water imbalances. On the 5th of October, the natural conditions presented a reduced evapotranspiration rate of 2 mm per day combined with a 20 mm precipitation event, ensuring that all the trees maintained optimum water conditions. In contrast, during the subsequent period until the 20th of October, the trees of the Ctrl treatment received daily irrigation equivalent to 100% of the water lost by ET_c, whereas trees in the WD3 treatment experienced a progressive watering deficit ranging from 30% on October 5 up to 100% of the ET_c on October 20. The evolution of both indicators and their signals intensity manifested the presence

of statistically significant differences between treatments starting around 10 AM. At noon, the maximum values of DS (MDS), DRS (MDRS), SI_MDS and SI_MDRS were 160 μm , 0.76, 0.76, 1.07 and, 480 μm , 0.42, 2.96, 0.56 for the well-watered (Ctrl_06Oct, Ctrl_20Oct and WD3_06Oct) and deficit plants (WD3_20Oct) respectively. On October 20, the SI_MDS of WD3 reached 3 folds that of the Ctrl whereas, the SI_MDRS barely reached 2 folds.

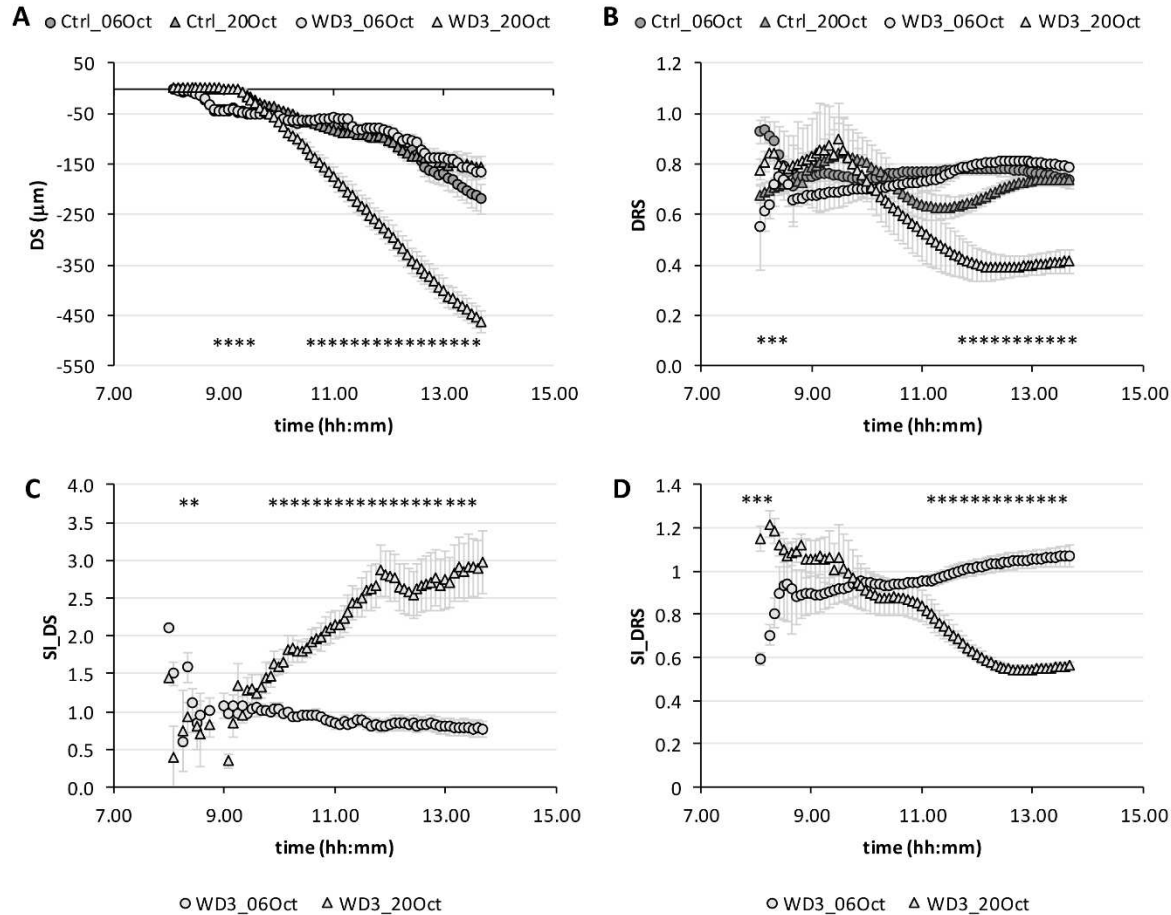


Fig. 3 Trunk-diameter shrinkage “DS” (A) and diameter relative resistance to shrinking “DRS” (B) and their corresponding signal intensities “SI” (C and D) for two contrasting irrigation deficits (Ctrl and WD3) on two separate days (06 and 20 October) characterized by significant evapotranspiration and soil-water imbalances. Each point is the average of three readings. The asterisks highlight the presence of a statistically significant difference ($p < 0.05$).

Plant's water stress indicators

Discontinuous periods of gradual (between treatments) and in time progressive water deficit were implemented during June, August and October 2024 to generate and collect continuous recording of trunk diameter variations alongside periodically distinct data series of variable stem water potential. For the sake of clarity, the following figures depict the data collected in October for being the longest and most intensive period of water deficit with

the clearest differences between treatments. The whole set of data recorded all over the experimental period was used for correlation purposes between Ψ_{stem} as the independent variable and MDS and MDRS as the dependent variables.

During the last water deficit period imposed in October, the Ctrl treatment exhibited an average Ψ_{stem} value of -0.92 ± 0.06 MPa, while the water deficit treatments (WD1, WD2 and WD3) demonstrated gradual and statistically significant differences compared to the Ctrl and among each other (Figure 4). These differences were particularly pronounced on the 21st of October after 3 days of complete cessation of watering in WD3. This extreme deficit pulled the Ψ_{stem} down to -2.6 MPa and induced a full defoliation of the trees.

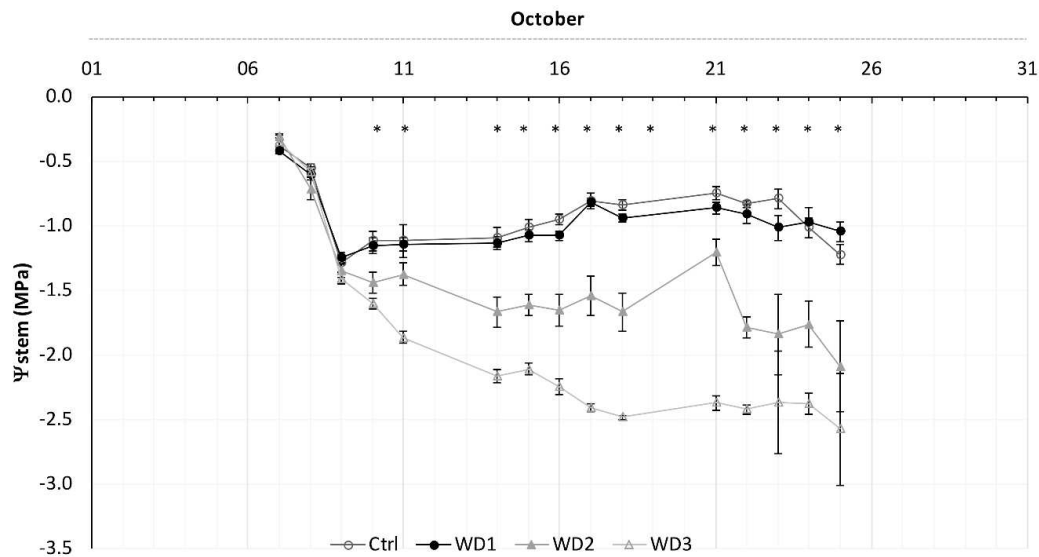


Fig. 4 Evolution of midday stem water potential in fig trees exposed to a gradual (between treatments: Ctrl, WD1, WD2 and WD3) and progressive water deficit during Oct 2024. Each value is the average of 6 readings and the asterisks indicate the presence of statistically significant difference between treatments ($p < 0.05$).

The SI_MDS for WD3 and WD4 increased significantly, reaching three to four times the levels recorded in the Ctrl and WD1 from October 10th onward, before decreasing to 1 on October 25th (Figure 5). Despite the ongoing progressive water deficit, mild weather conditions occurred between October 16th and 21st, followed by severe defoliation in the stressed trees. The DRS values for the Ctrl and WD1 treatments ranged from 0.6 to 0.8, whereas those for WD3 and WD4 decreased to 0.46 and 0.35, respectively (Figure 6). The overall pattern of DRS variations closely resembled that of Yx, with significant differences observed from October 12th for WD4 and from October 17th for WD3, indicating sensitivity to the applied water stress levels.

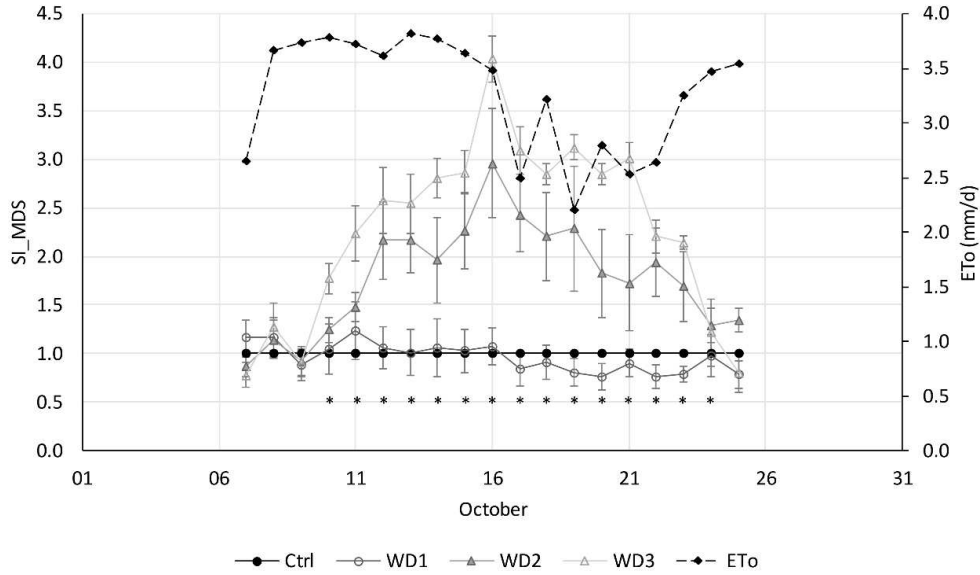


Fig. 5 Evolution of reference evapotranspiration (ETo) and signal intensity of the maximum diameter shrinkage (SI_MDS) in fig trees exposed to a gradual (between treatments: Ctrl, WD1, WD2 and WD3) and progressive water deficit during Oct 2024. Each value is the average of 3 readings and the asterisks indicate the presence of statistically significant difference between treatments ($p < 0.05$).

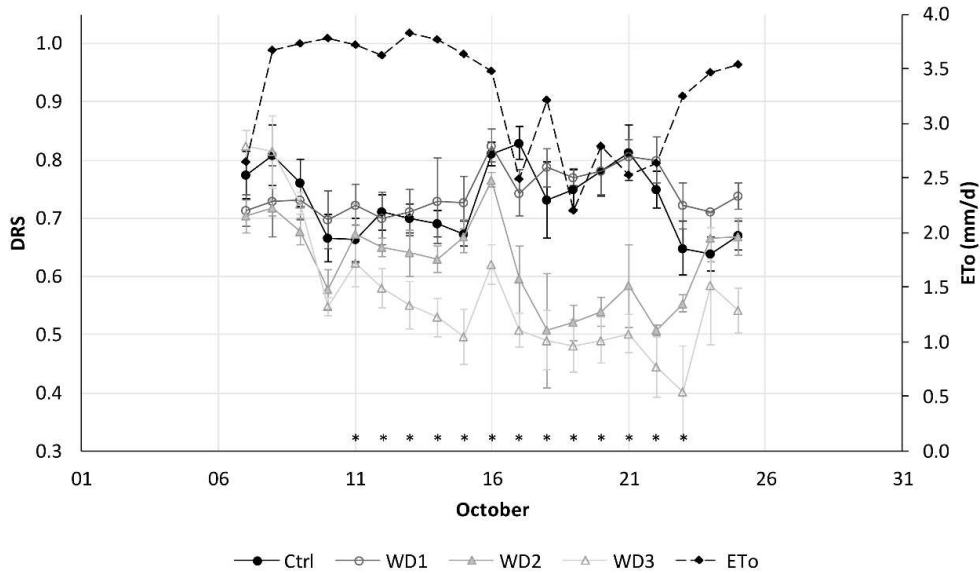


Fig. 6 Evolution of ETo and diameter relative resistance to shrinking at solar noon ($DRS_{t_{sn}}$) in fig trees exposed to a gradual (between treatments: Ctrl, WD1, WD2 and WD3) and progressive water deficit during Oct 2024. Each value is the average of 3 readings and the asterisks indicate the presence of statistically significant difference between treatments ($p < 0.05$).

Statistical performance of Correlation of the trunk-diameter relative resistance to the stem

The linearly fitted regression of MDS and DRS against the midday Ψ_{stem} produced a determination coefficient of 0.5993 and 0.2772 respectively. Whereas, the 5-fold cross validation of the previously determined linear

models returned a significantly higher NRMSE for MDS (0.328 ± 0.051 , 95%CI: 0.063) than DRS (0.197 ± 0.015 , 95%CI: 0.019).

The MDS exhibited a stronger linear relationship ($R^2 = 0.5993$), indicating a better ability to capture variability in midday Ψ_{stem} . However, its higher NRMSE (0.328 ± 0.051) suggests limited predictive accuracy. In contrast the DRS showed lower explanatory power ($R^2 = 0.2772$) but significantly improved predictive accuracy (NRMSE = 0.197 ± 0.015), indicating more reliable estimates despite weaker correlation. These results reveal a trade-off between trend representation and prediction accuracy.

Although the MDS explains a larger proportion of variance in midday Ψ_{stem} , its higher prediction error limits its practical applicability. Conversely, the DRS, despite its lower explanatory power, demonstrates superior performance and robustness, making it more suitable for estimation purposes.

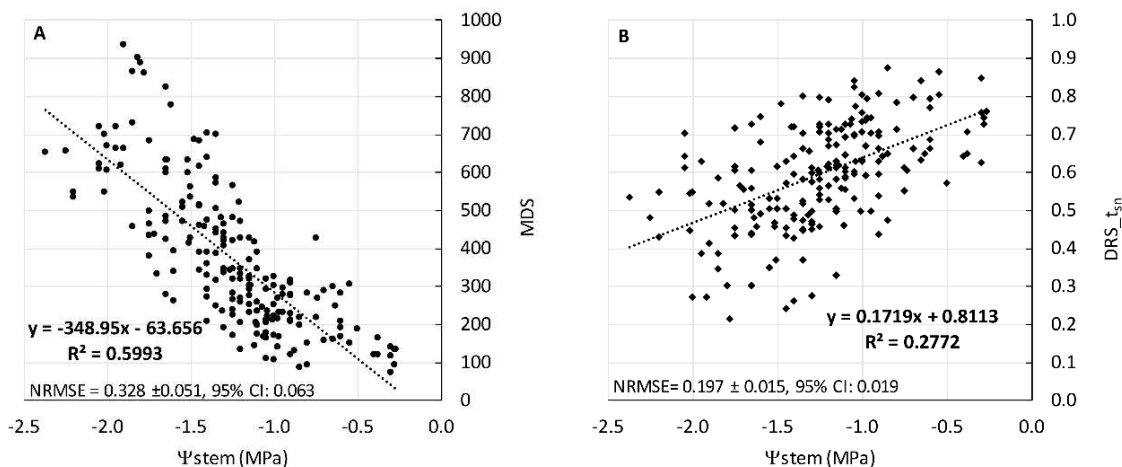


Fig. 7 Relationship between midday stem water potential “ Ψ_{stem} ” and water stress indicators derived from trunk diameter variations ((A) MDS: Maximum diameter shrinkage and (B) $DRS_{t_{sn}}$: diameter relative resistance to shrinking at solar noon) of fig trees. The performance of the linear fitted regression was evaluated using randomized 5-fold cross validation with a 95% confident interval.

Discussion

The newly derived water stress indicator called DRS is self-informant with no need for comparison with well-watered plants and easy to interpret in the range from 0 to 1 for decision-support purposes. It responded to the applied level of water deficit, enabled detecting significant differences between treatments and fairly correlated with the stem water potential and outperformed MDS, exhibiting a lower prediction error (NRMSE 0.197 ± 0.015).

On daily basis, from sunrise to solar noon, the characterization of the relationship between accumulated ETo and trunk DS by a third degree polynomial tendency ($DS = aETo^3 + bETo^2 + cETo + d$) confirmed the presence of untapped eco-physiological information and led to proposing the DRS as an intrinsic and independent biological indicator that precisely detect the onset of plant water stress with a high potential for use in precise automatic irrigation scheduling. Each monomial of this third-degree polynomial could have a physiological interpretation. The constant term “d” refers to the diameter shrinkage right at sunrise when ETo is still very close to zero. It reflects how well the plant recovered overnight. The linear term “cETo” captures the early-morning response when the sun is still low in the horizon, the illuminated area of the plant canopy is in progress and the transpiration flux is gradually developing with minimum internal resistance from the soil to the leaves; the stem shrinkage is almost proportional to ETo accumulation. The quadratic term “bETo²” captures the curvature of the relationship reflecting the transition from elastic (linear) to inelastic (nonlinear) behavior. As ETo increases toward mid-morning, the transpiration flux increases faster than water can be replaced by the intake water flux from the root zone and thus, the trunk tissues begin releasing stored water from deeper layers. The cubic term “aETo³” captures the highest order nonlinearities and reflects late-morning hydraulic stress, near solar noon. The plant approaches its hydraulic limits; the stomatal regulation become a heavy-duty, the trunk water reservoirs approach depletion and the xylem tension reaches maximum level.

In mathematical terms, the cubic polynomial approaches a reduced-form solution of part of the Steppe et al. (2006) tree water flow model describing the transient imbalance between transpiration demand and root water uptake buffered by internal stem capacitance. Within this framework, the progressive transition from the linear to the quadratic and cubic components of the relationship suggests that trunk diameter shrinkage integrates successive hydraulic response regimes occurring during the morning depletion phase of internal water storage. Such a sequence is consistent with the conceptual description proposed by Molz and Klepper (1972), in which radial stem variation results from diffusion-type propagation of water potential gradients across adjacent tissues. In the present study, however, the segregation of the positive and negative contribution to shrinkage allowed these internal hydraulic adjustments to be expressed relative to each other, thereby reducing the confounding influence of day-to-day meteorological variability and emphasizing the intrinsic biological response of the plant. Under favorable watering conditions, characterized by adequate soil water availability and non-stressing atmospheric demand, plant hydraulic regulation efficiently preserves stem internal capacitance and limits the amplitude of trunk shrinkage, resulting in DRS values approaching unity. In contrast, under unfavorable watering conditions, the capacity of the plant to buffer increasing transpiration demand progressively weakens

as internal water reserves become depleted and stomatal regulation intensifies. As a consequence, the resistance of stem tissues to further contraction declines and DRS values progressively decrease toward zero, reflecting the transition from a capacitance-buffered hydraulic regime to a demand-dominated shrinkage response. These results support the interpretation of DRS as an integrative indicator of the efficiency with which internal stem water storage contributes to maintaining plant water balance during the morning period of increasing atmospheric evaporative demand.

From a hydraulic perspective, DRS can be interpreted as a proxy of the efficiency with which internal stem capacitance contributes to buffering increasing atmospheric evaporative demand during the morning period. Because the sunrise-to-solar-noon interval corresponds to the phase in which transpiration progressively exceeds root water uptake and stored stem water temporarily compensates this imbalance, the relative resistance to trunk shrinkage integrates the dynamic interaction between transpiration demand, radial water redistribution, and stem elastic properties. Consequently, DRS represents an indirect but physiologically meaningful descriptor of the capacity of the plant hydraulic system to maintain internal water balance before the onset of midday stomatal regulation.

Although Maximum Daily Shrinkage (MDS) and Early Daily Shrinkage (EDS), as well as their corresponding signal intensities, are strongly related to stem water potential (Ψ_{stem}) and have proven effective for water stress detection in fruit trees (Galindo et al. 2013; De la Rosa et al. 2016), the DRS showed improved predictive performance (lower NRMSE). On the one hand, DRS is normalized with respect to the accumulated maximum expected atmospheric water demand of the day, expressed through cumulative Reference evapotranspiration (ET_o), and on the other hand, it quantifies the internal hydraulic adjustment relative to the shrinkage response of the same plant. As a consequence, DRS behaves as a self-informative indicator that can be interpreted directly without the need for reference plants or the computation of signal intensity ratios. This property suggests that DRS may be less sensitive to structural differences among plants, including trunk diameter, plant age, and stage-specific developmental behavior. Nevertheless, further studies are required to confirm this potential independence and to evaluate the extent to which DRS depends on species and varietal hydraulic traits. A key advantage of the proposed indicator lies in the normalization of trunk diameter shrinkage with respect to accumulated atmospheric evaporative demand during the same period. By expressing shrinkage relative to cumulative Reference evapotranspiration rather than absolute diameter variation alone, DRS reduces the influence of day-to-day meteorological variability and isolates the intrinsic hydraulic response of the plant. This normalization allows comparisons across days with contrasting climatic conditions and improves the interpretability of dendrometric signals for irrigation decision-support purposes.

From an operational perspective, the computation of DRS requires only continuous trunk diameter measurements and time-resolved estimates of atmospheric evaporative demand, both of which are increasingly available in commercial orchard monitoring systems. Because the indicator does not require reference plants and can be calculated automatically during the morning period, it is particularly suitable for integration into real-time irrigation scheduling algorithms aimed at optimizing water use efficiency under variable climatic

conditions. Although the present results demonstrate the robustness of DRS under the experimental conditions evaluated, the hydraulic interpretation of the polynomial coefficients suggests that species-specific differences in stem capacitance, xylem vulnerability, and stomatal regulation strategies may influence the magnitude and temporal evolution of the indicator. Future studies should therefore evaluate the performance of DRS across contrasting hydraulic functional types, including isohydric and anisohydric species, in order to determine its general applicability in different cropping systems.

It is worth noting that trunk diameter-based indicators generally exhibit relatively high variability; however, part of this variability is likely associated with the quality of the dendrometric measurements themselves rather than with physiological noise alone. The acquisition of high-quality continuous time series of trunk diameter variation remains technically challenging due to the micrometric resolution required by the sensors, the mechanical stability and geometry of sensor holders, the need to accurately align the sensing core with irregular trunk circumferences, and the risk of external disturbances caused by insects, animals, human intervention, falling leaves, or intense rainfall events. Therefore, continued scientific and technological efforts toward improving sensor robustness and installation reliability are essential for enhancing the operational applicability of dendrometer-based indicators such as DRS in precision irrigation scheduling systems.

Overall, the proposed DRS indicator provides a novel framework for interpreting trunk diameter variation by separating demand-driven contraction from buffering-driven resistance during the morning depletion phase of internal stem water storage. This approach extends the physiological interpretation of dendrometer signals beyond traditional amplitude-based metrics and highlights the potential of combining high-resolution trunk diameter measurements with cumulative atmospheric evaporative demand to derive mechanistically meaningful indicators of plant water status. As such, DRS represents a promising tool for improving the reliability of dendrometer-based irrigation scheduling strategies under field conditions.

The proposed DRS indicator provides a novel framework for interpreting trunk diameter shrinkage by quantifying the balance between demand-driven contraction and buffering-driven hydraulic resistance during the morning period of increasing evaporative demand. The indicator responded consistently to irrigation treatments, showed a strong relationship with stem water potential, and improved prediction accuracy compared with traditional dendrometric indices such as MDS. Because DRS is normalized to cumulative atmospheric demand and does not require reference plants, it represents a promising tool for automated irrigation scheduling under field conditions. Future work should evaluate its robustness across species, canopy architectures, and contrasting hydraulic regulation strategies.

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406 **Declarations**

407 The authors used AI-assisted language tools to improve clarity of expression. The scientific content and
408 interpretations remain the responsibility of the authors.

409 **Competing Interests**

410 The authors declare no competing interests.

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