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Automated irrigation of apple trees based on dendrometer sensors

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ABSTRACT

This study evaluates the efficiency of an automated irrigation system using dendrometer sensors in apple orchards and compares it to a standard grower commercial irrigation approach based on soil moisture sensors. An algorithm was developed to balance daily stem shrinkage (water loss) and expansion (water uptake), aiming for a stable dendrometer signal. The dendrometer-based irrigation system (DENDRO) significantly reduced water use—by 38 % in 2022 and more than 45 % in 2023—while maintaining yields similar to those of the soil moisture-based system (SOIL). The DENDRO responded quite well to plant water stress, as indicated by stem water potential (WP). Although the tested algorithm proved to be efficient, the results also indicated the potential for optimization. One example is shortening the averaging period used to calculate stem recovery (R_{Δ}). The SOIL method was effective in fruit production but proved to be less efficient in reflecting water needs. Alternative approaches, including FAO-based irrigation (FAO) and a linear regression model combining dendrometer parameters and climatic data (MODEL), were also assessed. The FAO method tended to overestimate water requirements, while the MODEL method showed promise for dynamic irrigation adjustment based on climatic conditions and dendrometer values. Overall, the findings highlight the advantage of integrating plant-based sensors, such as dendrometers, for more precise irrigation management in orchard systems, leading to more sustainable water use without compromising crop yield.

1. Introduction

Growing global awareness of water scarcity has accelerated the development of advanced precision irrigation systems. These systems improve irrigation efficiency through a data-driven approach (Visconti et al., 2020). They allow real-time decision-making by continuously monitoring, analyzing, and using data to manage crops more effectively, thereby improving productivity and minimizing water and energy consumption (Benzaouia et al., 2023; Ouafiq et al., 2021). Irrigation systems can be operated either fully automatically or by involving human input. Automated systems are based mainly on two approaches: closed-loop (feedback) and open-loop (non-feedback) control systems (Buchleiter, 2007; Venkatapur and Nikitha, 2017). The primary difference between these systems lies in their operation: closed-loop systems rely on feedback to adjust irrigation based on pre-set conditions, whereas open-loop systems operate based on empirical decisions made by the operator without real-time adjustments (Abioye et al., 2020).

Commercial irrigation, also known as grower irrigation, is a method of irrigating crops in which the soil moisture level is maintained close to field capacity throughout the growing season (Wan Zaliha and Singh, 2009). This can be accomplished by both closed-loop (feedback) and open-loop (no feedback) control systems. Open-loop systems are still widely used by farmers, where decisions on the volume of water to be irrigated are typically based on crop knowledge and traditional reference methods, such as those provided by the FAO (Allen and Pereira, 2009). Using this method, the total amount of water used through plant transpiration and soil surface evaporation is estimated by crop evapotranspiration, which is calculated by multiplying the crop coefficient (Kc) and ET_0 ($ETc = Kc \times ET_0$). ET_0 is a reference evapotranspiration rate obtained through weather parameters, while Kc is obtained normally by calibration for each crop (Allen and Pereira, 2009; Hafian et al., 2023). With this, the required volume of water (ETc) can be calculated, which is typically managed using irrigation timers or controllers that activate one or more valves at a specified time of day (Abioye et al.,

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2020).

Feedback control systems for irrigation typically rely on soil moisture sensors or plant-based sensors to determine irrigation needs (Venkatapur and Nikitha, 2017). Soil moisture sensor systems are widely used across various crops due to their ability to reduce water wastage and their economic feasibility for farmers (Asharaf et al., 2012; Gagandeep et al., 2017; Muangprathub et al., 2019; van Mourik et al., 2021; Venkatapur and Nikitha, 2017). Soil moisture sensors measure soil water content through reflectometry, capacitance, or other sensing mechanisms, providing real-time data on soil moisture levels (Kuncham and Rao, 2014; Shock and Wang, 2011). These sensors are valuable tools for optimizing irrigation practices, and each method has its own set of advantages and limitations. Thompson et al. (2006), demonstrated the efficiency of Watermark sensors (Irrometer Co., Riverside, CA, USA), which use a granular matrix to measure soil matric potential through electrical resistance. They further emphasized the potential of these sensors for irrigation scheduling on commercial farms and in research applications, noting their attractiveness due to their low cost, simple installation, straightforward setup, and minimal maintenance requirements. For a more comprehensive analysis of soil humidity sensors, including their strengths and drawbacks in both research settings and vegetable production, a detailed report is presented by Bwambale et al. (2022).

The effective use of soil moisture sensors for irrigation requires an understanding of the soil's water retention capacity, where it is also important to consider factors such as root water absorption variability, surface evaporation, and partial soil moistening prior to sensor installation (Shock and Wang, 2011). Soil moisture sensors provide an indirect measure of a plant's water status. Thus, their effectiveness can be questioned because plants' access to water may well exceed the sensor's range, or sensors could be improperly positioned (Bwambale et al., 2022). To enhance the efficiency of soil moisture-based irrigation systems, integrating additional plant-based sensors and climatic parameters can be advantageous (Adeyemi et al., 2017). For instance, Venkatapur and Nikitha (2017) demonstrated the use of thermographic cameras to capture infrared images of the plant canopy in conjunction with soil moisture sensors, while Al-Ali et al. (2019), combined soil moisture, temperature, and humidity values to control the opening and closing of irrigation valves for more precise irrigation control.

Although commonly not used for automated irrigation, dendrometers are considered promising plant-based sensors for quantifying water requirements (Casadesús et al., 2012; Corell et al., 2014). The daily variations in the stem radius reflect changes in water storage within stem tissues in response to soil water availability and atmospheric conditions, expressed as stem diameter variation (SDV). The 24-hour cycle of stem shrinkage and swelling provides essential variables for monitoring plant water status, such as maximum daily shrinkage (MDS), which provides the difference between the daily maximum and minimum values of stem diameter and daily stem growth (DG), which is calculated by the difference between the maximum stem diameter values of 2 consecutive days. These metrics are critical for understanding a tree's water balance (Corell et al., 2014). MDS is referred to as a parameter related to climatic variations (De la Rosa et al., 2013; Ortuño et al., 2009). DG, on the other hand, is associated more with the level of water stress in the plant (Martín-Palomo et al., 2022). Other parameters derived from the dendrometer sensors were also highly effective in reporting the tree's water status, especially tree water deficit (TWD) (Zweifel et al., 2005), which was shown to be species-independent.

Fernández and Cuevas (2010), reviewed the use of SDV in precise irrigation scheduling, emphasizing its benefits and limitations. They highlighted MDS and DG as the most frequently used parameters derived from dendrometer sensors, underlining their importance in ensuring effective water management in agricultural practices for closed-loop systems. Meanwhile, other authors have identified the use of SDV as a limited tool for automating irrigation (Fernández and Cuevas, 2010; Lin et al., 2016). Still, Fereres and Goldhamer (2003), demonstrated the effectiveness of MDS parameters for automated irrigation based on predefined thresholds, highlighting that defining appropriate thresholds is complex and cannot be universally applied across all crops or at every phenological stage. The variability in crop types, growth stages, and environmental conditions necessitates careful calibration of these thresholds to ensure optimal irrigation scheduling. Casadesús et al. (2012) presented an automated irrigation system in which the crop coefficient (Kc) was adjusted in response to MDS values. Waldburger et al. (2025) proposed a model in which SDV, in combination with vapor pressure deficit (VPD), was used to replicate stem WP, suggesting it as a potential method for enhancing automated irrigation systems. This model seeks to integrate plant physiological responses with environmental factors, providing a more comprehensive approach to irrigation management through the simulation of WP values. In addition to agronomic considerations for determining daily water volume, scheduling must also account for the farm's hydraulic system to ensure irrigation is performed at the right time and in the correct amount (Casadesús et al., 2012).

The aim of this work was to evaluate the effectiveness of a new closed-loop control system for dendrometer-based irrigation in comparison to traditional commercial irrigation based on soil moisture levels (SOILs). The study compared an automated closed-loop DENDRO system with a semi-automated open-loop systems - SOIL. The two systems were assessed in a field trial with apple trees through final yield and manual WP measurements. Additionally, the research highlights its advantages and disadvantages, providing a comprehensive analysis of this new irrigation system.

2. Materials and methods

2.1. Site

The experiment was conducted over two growing seasons (2022 and 2023) on an apple farm in the Lake Geneva region of Switzerland (coordinates: N 46.3969, E 6.195993) at an elevation of approximately 400 m above sea level. The region has a temperate oceanic climate, according to the Köppen-Geiger classification (Kottek et al., 2006). It is characterized by an average temperature of 11.2 °C and an average annual rainfall of about 1030 mm. Fig. 1 illustrates the rainfall patterns for 2022 and 2023.

During the 2022 growing season (June 1–September 30), the maximum temperature reached 36.5 °C, with a maximum VPD of 4.8 KPa, and the highest daily rainfall recorded was 31.2 mm. In 2023 (June 1–September 30), the maximum temperature was again around 36.5 °C, with a VPD maximum of 4.4 KPa, and the highest daily rainfall was 55.4 mm.

2.2. Experimental set up

Forty-five Gala variety apple trees (*Malus domestica*) were selected for an ongoing experiment organized into three randomized blocks (A, B, and C), each representing one replicate with two treatments, forming a Latin square design. To investigate the potential of an irrigation system based on dendrometers during the 2 years of research, two irrigation systems were compared:

- SOIL: Semi-automated soil moisture-based irrigation (commercial irrigation).
- DENDRO: Automated dendrometer-based irrigation.

Water was delivered via a drip line with emitters spaced 0.75 m apart with a flow rate 2.3 L/h. The tree density was 2083 trees per hectare, with an individual tree spacing of 1.2 m and row spacing of 4 m. The soil composition in the plots consisted of 48 % silt, 41 % sand, and 11 % clay, with a pH of approximately 7.7 (data from the farm).

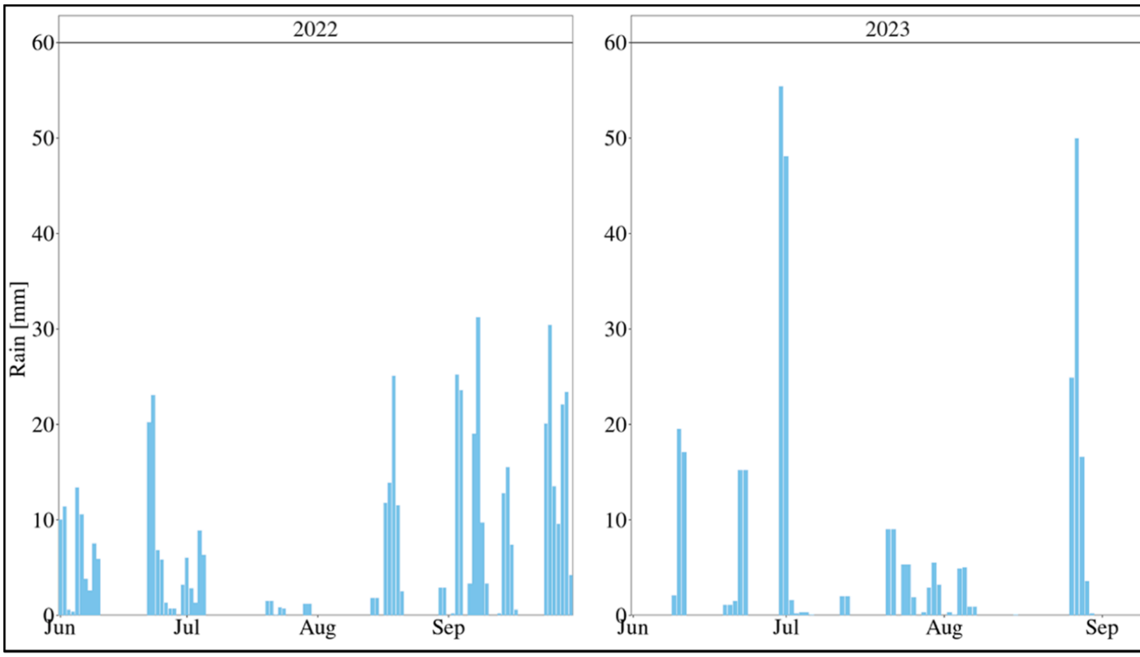

Fig. 1. Precipitation during the years of the experiment (2022 and 2023).

2.3. Irrigation treatments

2.3.1. SOIL: semi-automated soil moisture-based irrigation

A closed-loop soil moisture-based irrigation system was operated using 6 Watermark sensors (Irrometer Co., Riverside, CA, USA), with three placed at a depth of 25 cm and three at a depth of 50 cm in the soil. The values used to determine the irrigation were based on the median data from the 3 × 25-cm and 3 x 50-cm sensors. This configuration of sensors followed the methodology outlined by Waldburger et al. (2019). Data from these sensors were processed through edge computing by the Sensorscope DS3 data logger (Sensorscope, Lausanne, Switzerland). A threshold of −30 to −60 KPa was set based on the median soil moisture value at a depth of 25 cm and −20 to −40 KPa median at a depth of 50 cm (Thompson et al., 2007). However, the farm had the option of setting the thresholds at a more comfortable humidity levels for the plants, ranging from −30 to −20 Kpa. In certain instances, the irrigation schedule was modified on a weekly basis to align with the farmer's needs, thereby transitioning from an automated to a manual irrigation system. The irrigation was activated by opening a solenoid valve. The system was designed for three irrigation pulses per day.

2.3.2. DENDRO: automated dendrometer-based irrigation

A closed-loop irrigation system was developed based on data collected from dendrometer sensors (DENDRO). These sensors were constructed by Agroscope using a linear potentiometer (Model SLPT 25 mm, Opkon, Istanbul, Turkey) mounted on an aluminum frame, as presented in Fig. 2, providing a resolution of ± 6.1 μm. Each plot had four sensors attached to the stems of apple trees, secured with a 2.5 mm rubber band.

The stem radius was measured as a voltage signal and recorded using an Agriscope data logger (Agribase 2.327, Agriscope, Mauguio, France). These data were then transmitted via a 916 MHz middle wave radio frequency to a modem, which was uploaded to an online platform (www.agriscope.fr). On the platform, the data were converted linearly into a numerical scale representing the stem diameter in micrometers (μm). Of the 12 sensors installed on the trees, only 8 were used after data quality analysis. Data analysis was performed in R version 4.1.3/4.4.1 (R Development Core Team 2018) software with assistance from packages designed for dendrometer work, such as the treenetproc package (Knüsel et al., 2021) for parameters such as tree water deficit (TWD) and cumulative growth per year (gro_yr – parameter) dendRoAnalyst (Aryal et al., 2020) for jump removal and daily parameters. The main parameters required for irrigation control are described below:

Fig. 2. Dendrometer constructed by Agroscope on the stem of an apple tree.

- Maximum daily shrinkage (MDS): The difference between the maximum and minimum stem diameter values recorded each day.
- Daily recovery (DR): The difference between the maximum stem diameter of the current day and the minimum of the previous day.
- Recovery Δ (R_Δ): Calculated as the difference between the 7-day average DR and the 7-day average MDS.
- Daily growth (DG): The difference between the maximum stem diameter of the current day and the maximum of the previous day.

The daily backend routine consisted of the following steps: First, the dendrometers' data were fetched every day at 8:00 a.m. Each dendrometer time series underwent automated jump removal. If the data contained jumps over 200 μm, the signal was corrected to the diameter value prior to the jump. Afterward, a summary of all the parameters required to determine the irrigation quantity was determined based on the corrected signals.

Commands to open and close the irrigation valve were transmitted using a LoRa antenna. In the field, a solenoid valve (STREGA Smart-Valve, Ohain, Belgium) was integrated into the farm's irrigation system. The irrigation schedule was set between 5:00 p.m. and 11:54 p.m. to minimize water loss from soil surface evaporation. In accordance with the farm irrigation, the effective irrigation periods lasted from June 26 to August 22 in 2022 and from June 1 to August 30 in 2023. The signal distribution from the plant sensors (dendrometers) to the valve opening is illustrated in Fig. 3.

2.4. Algorithm concept

The automated irrigation system, based on dendrometer sensors, calculated the amount of water to be applied using the algorithm conceived in this study. The algorithm aimed to maintain a balance between daily stem shrinkage (water loss) and stem expansion (water uptake) (Fig. 4A). The relationship of water balance over 24-h was previously analyzed by Conejero et al. (2007) (daily sap flow) and Zweifel et al. (2016) (zero growth concept). This balance indicates that the tree's water status is stable, preventing both water stress and over-irrigation. In detail, recovery (R_Δ) was calculated as the difference between the 7-day averages of DR and maximum daily shrinkage (MDS) to distinguish between these two stages. A positive R_Δ indicated that the tree successfully replenished its water loss from daily evapotranspiration, whereas a negative R_Δ suggested a water deficit, implying that the tree had not absorbed enough water. Negative R_Δ indicated shrinking of the tree and water stress. This highlighted the tree's inability to uptake sufficient water during the night, thus requiring increased irrigation the following day.

In the first stage, under stress conditions, a quantile regression was applied between the reduction in the daily growth size (DG) and crop evapotranspiration (E_{crop}) from a dataset obtained from the same plot in 2020 (unpublished data) (Fig. 4B). The stress conditions were based on the filter of data with high values of environmental parameters (ET_0, Temperature and VPD). E_{crop} was calculated as previously mentioned, using a Kc of 0.85, based on the guidelines provided by the FAO (Allen and Pereira, 2009). The use of quantile regression allowed for the removal of the effects of non-limiting condition, as proposed by Jarvis (1976). In this specific case, the impact of soil water availability on daily shrinkage was mitigated, which could diminish the effect of E_{crop}. Subsequently, the aforementioned relationship facilitated the acquisition of the thresholds necessary for the implementation of the irrigation process, given that the DG is mirrored by the R_Δ. This approach ensured that the water requirements were always met. In the second stage, under non-stress conditions, a linear regression was established between MDS and E_{crop} on the same dataset from 2020 as shown in Fig. 4C. The equation derived from the relationship was incorporated into the irrigation algorithm named E_{crop_irr} (Equation 1). This regression ensured that the water consumption from the previous day was adequately compensated for by irrigation. This relationship was crucial for fine-tuning the algorithm, enabling more accurate predictions of the tree's water needs based on environmental conditions and stem growth patterns.

Based on this approach, a feedback mechanism for estimating water requirements was established (Fig. 5).

Equation 1:

$$Ecrop\_irr = 1.51 + 0.004 * MDS_{(avg.\quad 7days)}$$

where MDS indicates the maximum daily shrinkage on average during 7 days.

2.5. Algorithm evaluation

To evaluate the performance of the DENDRO algorithm, the obtained field data input and outputs of the 2 years were compared with two other theoretical approaches: the classical FAO algorithm for calculating E_{crop} and a published algorithm using dendrometer measurements (Waldburger et al., 2025). The first method followed the traditional FAO approach, which is based on crop evapotranspiration (ETc), in which effective irrigation should match the amount of water evaporated (FAO irrigation).

The second method used the regression model proposed in our previous work Waldburger et al. (2025), which calculates WP using stem daily variation and average daily VPD, as shown in Equation 2. Based on the derived WP values, irrigation amounts were simulated according to specific thresholds: WP < -1.7 MPa resulted in 3 mm of irrigation; WP between -1.7 and -1.5 MPa resulted in 2 mm; WP between -1.5 and -1.3 MPa resulted in 1 mm; and WP ≥ -1.3 MPa resulted in no irrigation (MODEL irrigation).

Equation 2:

$$WP = (11.34 \quad - 0.02 * d\_day + \quad 0.04 * \min\_twd + \quad 1.93 * avg\_VPD)$$

Where the WP values are the stem WP values predicted, d_day refers to the difference between the regression reference (first week experimental data: dataset from the regression between stem diameter and VPD) and

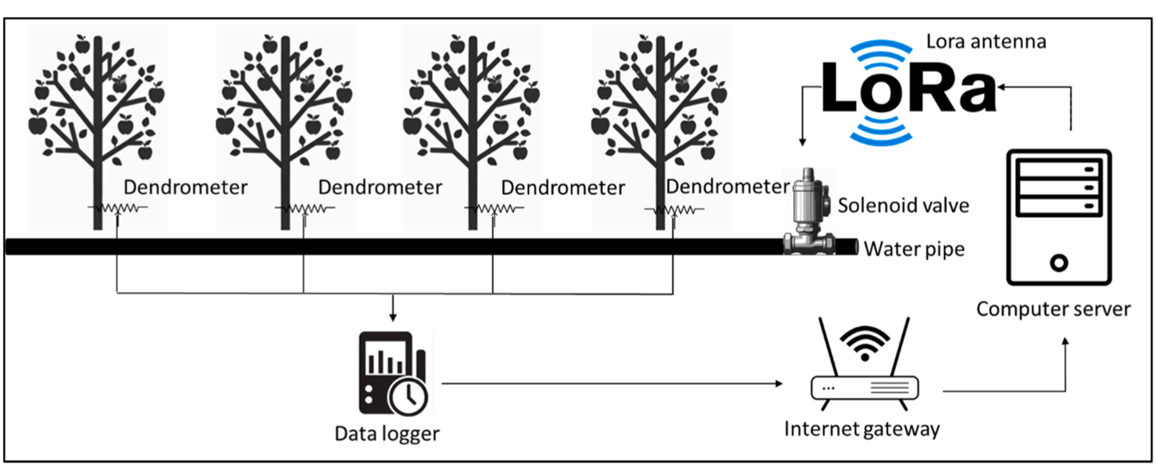

Fig. 3. Irrigation system scheme installed on the farm. Dendrometer sensors were connected to a data logger, which sent the data to a cloud where the parameters were computed, and which later transmitted the sign through a Lora antenna to give the irrigation command to a solenoid valve.

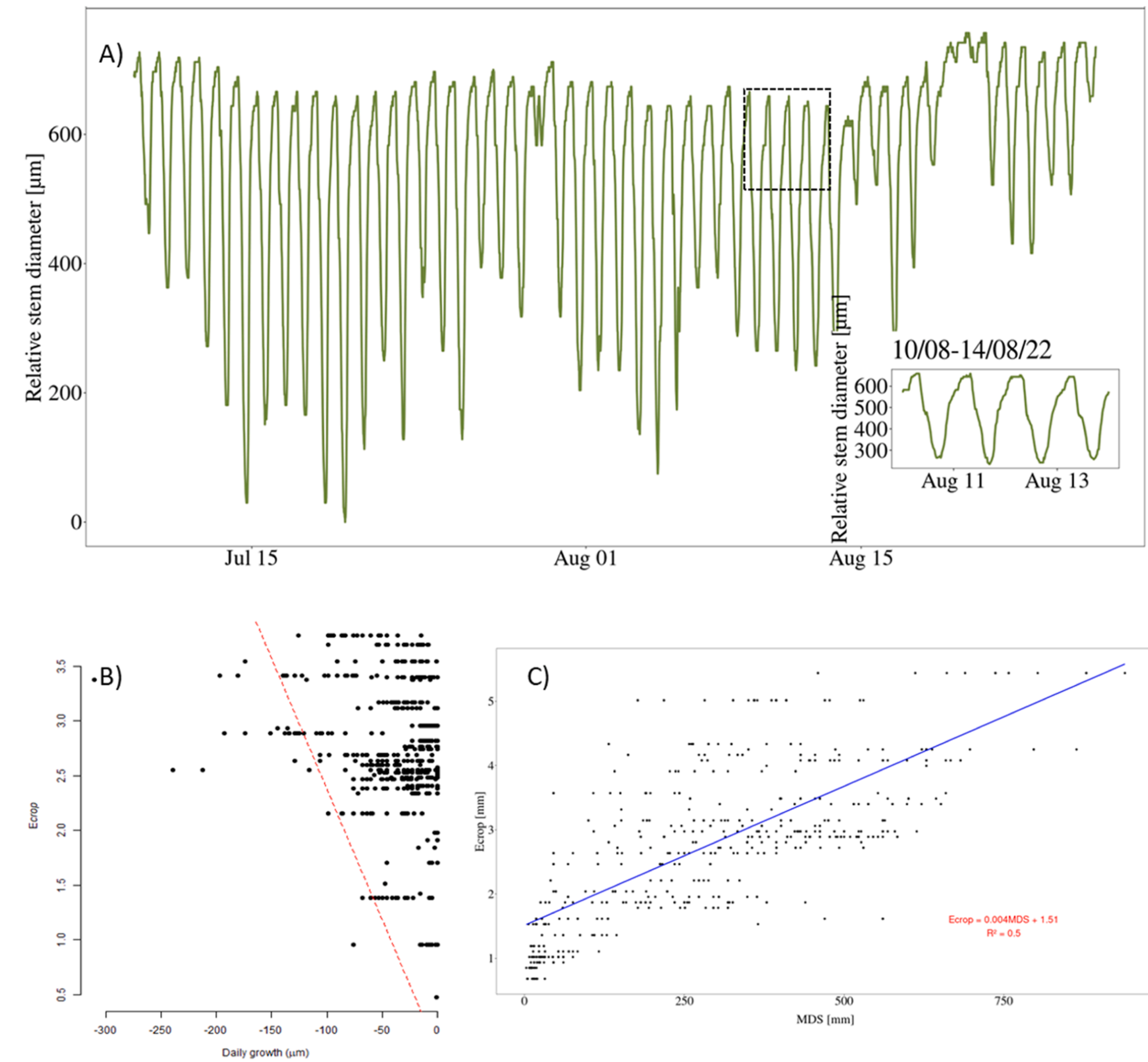

Fig. 4. Graph (A) displays the curve obtained from the dendrometer sensor, with a focus on the period from August 10 to August 14, 2022, during which the daily growth patterns were balanced. (B) illustrates the relationship between crop evapotranspiration (E_{crop}) and daily growth (DG) both for 2022, highlighting the thresholds established. (C) shows the linear regression between E_{crop} and maximum daily shrinkage (MDS), which produced the equation used in the irrigation algorithm.

regression per day (consecutive days of the experimental data: dataset from the regression between stem diameter and VPD per day), and min_twd is the minimum daily value obtained from the tree water deficit (TWD) (Knüsel et al., 2021) in addition to the daily average of VPD (avg_VPD).

These simulations were conducted without considering the effect of daily irrigation on future irrigation values. Instead, they relied solely on the interaction of the parameters already collected during the experiment for the DENDRO treatment. The DENDRO model provides values as reported by the model itself.

2.6. Stem water potential and yield

2.6.1. Stem water potential

The level of water stress in the trees was assessed using stem WP values obtained from the Scholander chamber (model M-600, 1725, PMS Instrument Company, Albany, USA). Measurements were taken weekly around noon (12:00–14:00 p.m.) during the season, following the methodology described by (Moriana et al., 2012). Data were not collected in weeks with heavy rainfall or precipitation, mainly in 2023.

2.6.2. Production

Harvest took place at the end of August 2022 and the first week of September 2023. On the same day, harvest of the 24 selected apple trees were weighed and the fruit was counted and recorded separately for each tree. This process was carried out during the farm's annual harvest.

2.7. Statistical analysis

A one-way ANOVA was performed with yield and stem WP as the

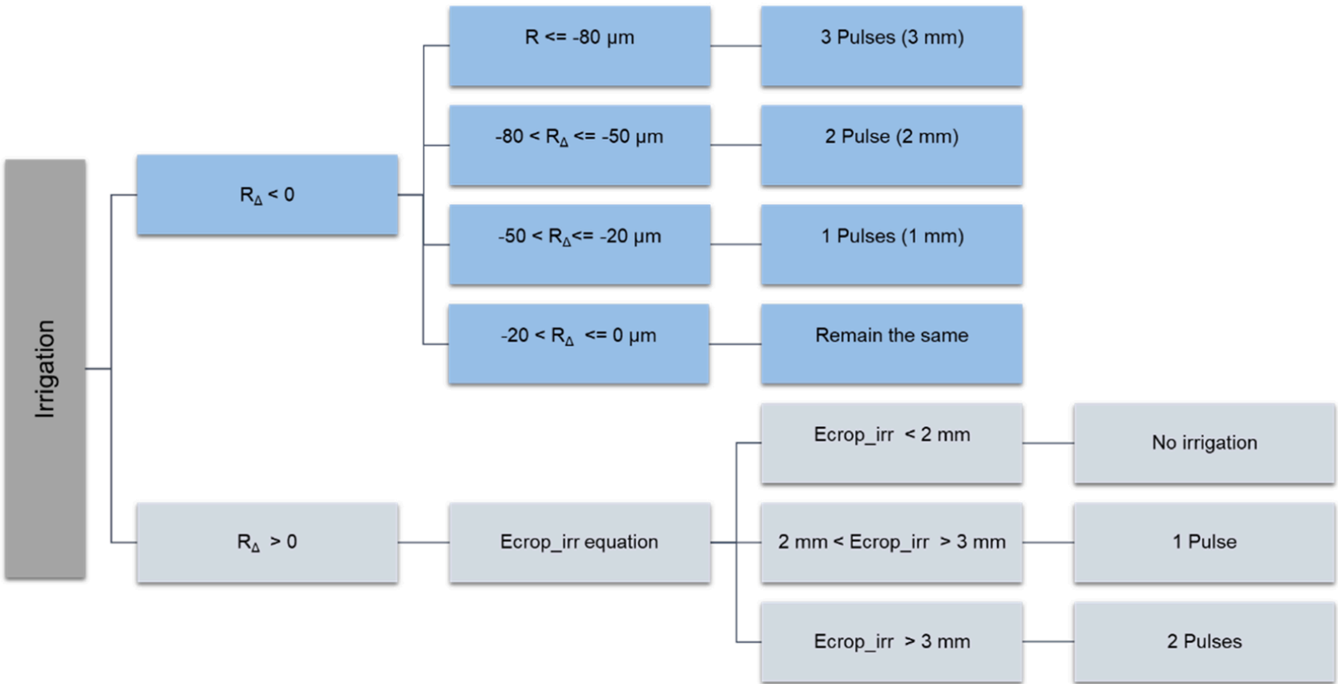

Fig. 5. Proposed protocol based on R_Δ (calculated as the difference between the 7-day average DR and the 7-day average MDS). On the top are the procedures when R_Δ was negative, and on the bottom when R_Δ was positive. The colors (blue and grey) indicate the irrigation schedule applied.

outcome variables. Treatment was considered a fixed effect, while year or block was considered a random effect. A Turkey test for pairwise comparison followed, considering each treatment-year combination as a different level of a same factor. The irrigation algorithms were compared based on their mean irrigation values and the associated standard deviation (SD) over the observed period. This approach provided insights into the average amount of water applied by each irrigation method as well as the variability in water application across different days.

3. Results

3.1. Irrigation performance by treatment

Water savings in the DENDRO treatment were statically higher than in the SOIL treatment over each year of the study ($p_{value} < 0.05$). Moreover, the level of water stress experienced by the plants in the DENDRO treatment was not significant.

3.1.1. Irrigation by DENDRO

The DENDRO irrigation was based on the R_Δ values presented in Fig. 6, which were used to calculate the amount of water that should be

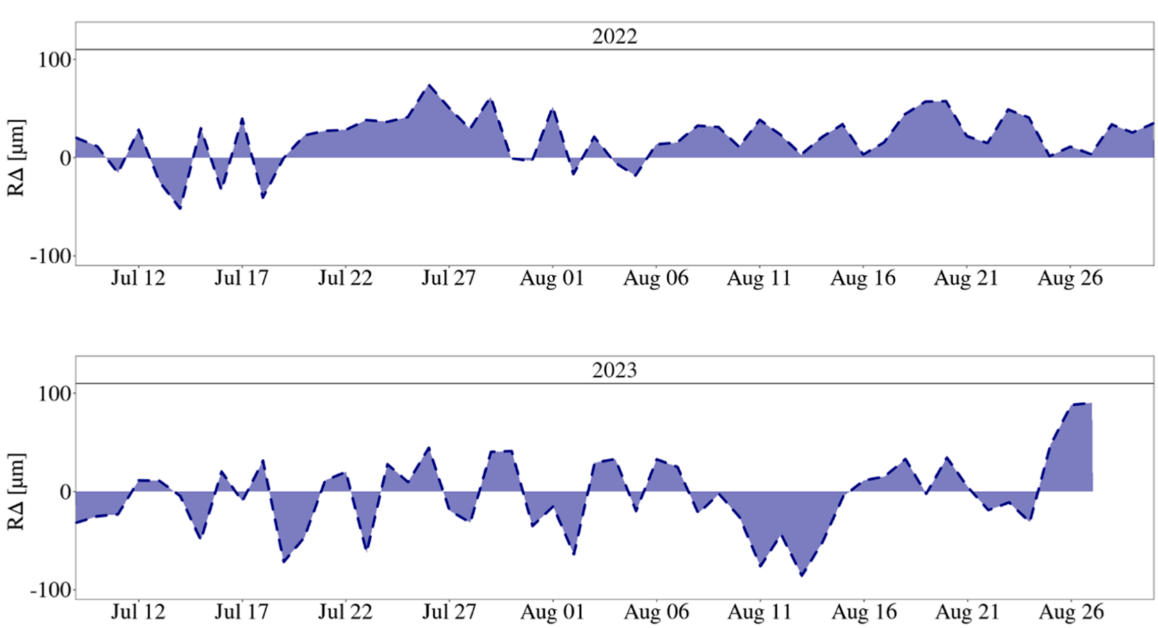

Fig. 6. R_Δ values obtained during the two-year period of the experiment.

irrigated per day. If the R_{Δ} was positive, irrigation schedules were based on MDS. In 2022, the R_{Δ} was positive in 74.2 % of the time, which resulted in an irrigation protocol strongly based on the MDS values per day. In 2023, however, the irrigation was less dependent on MDS as only 57.3 % of the R_{Δ} values were positive.

The median values of the soil moisture sensors installed in the DENDRO treatment (Fig. 7) demonstrated that the soil was predominantly dry on most days, falling outside the established comfort zone proposed by the SOIL treatment irrigation (yellow stripe), particularly in 2022. In 2022, the values at the deeper level exceeded the sensors' measurement limits, while in 2023, both depths exhibited dry conditions, though not as extreme.

3.1.2. Irrigation by SOIL

The SOIL treatment was determined by the soil moisture sensors, as illustrated in Fig. 8. The soil in the experimental plots exhibited a heterogeneous compacted structure, with some plots demonstrating greater compaction than others. In both years, the deeper layer (50 cm) indicated very wet soil, whereas the top layer (25 cm) exhibited some very dry periods but mostly remained within a comfortable level (ranging from −30 to −20 Kpa). Over-irrigation was observed in the months of August for both years, due to manual irrigation carried out by the farm.

3.2. Comparison of the performance of irrigation systems

3.2.1. Crop yield

Both treatments achieved similar yields in both years, with no significant differences between the yields of the SOIL and DENDRO treatments (Fig. 9) within each year. The SOIL treatment produced 43.4 tons/ha in 2022 and 50.5 tons/ha in 2023, while the DENDRO treatment yielded 42.8 tons/ha in 2022 and 48.7 tons/ha in 2023. Although there were differences in production parameters (fruit diameter, number of fruits, and fruit weight) among the treatments, these differences were not statistically significant (Fig. 9).

3.2.2. Stem diameter variation and water potential values in response to water irrigation

The amount of water irrigated during the 2-year experiment influenced both the daily stem diameter variation and the WP values of the trees. Fig. 10 presents the average daily irrigation amount of water irrigated per treatment for both years, based on weekly averages from 2022 and 2023, along with the corresponding weekly average stem WP values. The maximum daily shrinkage (MDS) for both treatments is displayed alongside the evapotranspiration rate (ET_o) during the two-year period of the experiment (Fig. 11). Fig. 12 reports the cumulative growth during the experiment per treatment per year.

In 2022, the experiment lasted approximately 57 days (June 26–August 22). During this period, the DENDRO treatment received a total of 80 mm of water—38 % less than the SOIL treatment, which received 130 mm. The average per week was 1.3 mm in the DENDRO plots and 2.4 mm in the SOIL plots (Fig. 10). This difference in irrigation did not significantly affect the average potential stem water values between the treatments. Trees under the DENDRO treatment had an average stem WP of −1.2 MPa, with a minimum value of −1.5 MPa, while trees in the SOIL treatment showed an average value of −1.0 MPa and a minimum value of −1.4 MPa. The influence of irrigation was more pronounced in the daily stem diameter variation between the treatments, but the average difference across treatments was not always significant. In the DENDRO treatment, the average MDS across all trees was about 320.9 µm, with a maximum MDS of 605 µm. In comparison, the SOIL treatment had an average MDS of approximately 246.27 µm and a maximum MDS of 525.6 µm (Fig. 11). The cumulative growth differed significantly between the two treatments (Fig. 12), with DENDRO reaching the highest value in 2022. That year, the stem diameter showed a positive increase. DENDRO treatment had an average daily growth of 2.7 µm, while the SOIL treatment had an average of approximately 1.2 µm per day (data not shown). In the DENDRO and SOIL treatments, 60 %–62 % of the DG values were positive. During the 2022 period, the average ET_o was approximately 4.1 mm/day, with a maximum of 9.1 mm/day (Fig. 11).

In 2023, the experiment spanned 90 days (June 1–August 30). Rainfall was more intense this year, with amounts exceeding 50 mm in a single week, resulting in no irrigation during that period (10/07–17/07). Additionally, a valve malfunction left the trees in the DENDRO treatment without irrigation for over 10 days. Consequently, the DENDRO treatment received a total of 90 mm of irrigation, which was more than 45 % less than the SOIL treatment, which received 205 mm. The average per week was 0.7 mm in the DENDRO plots and 2 mm in the SOIL (Fig. 10). Despite these conditions, the average stem WP values did not differ significantly between the two treatments. The DENDRO treatment trees had an average WP of −1.2 MPa (min. −1.7 MPa), while the SOIL treatment trees averaged slightly higher at −1.0 MPa (min.

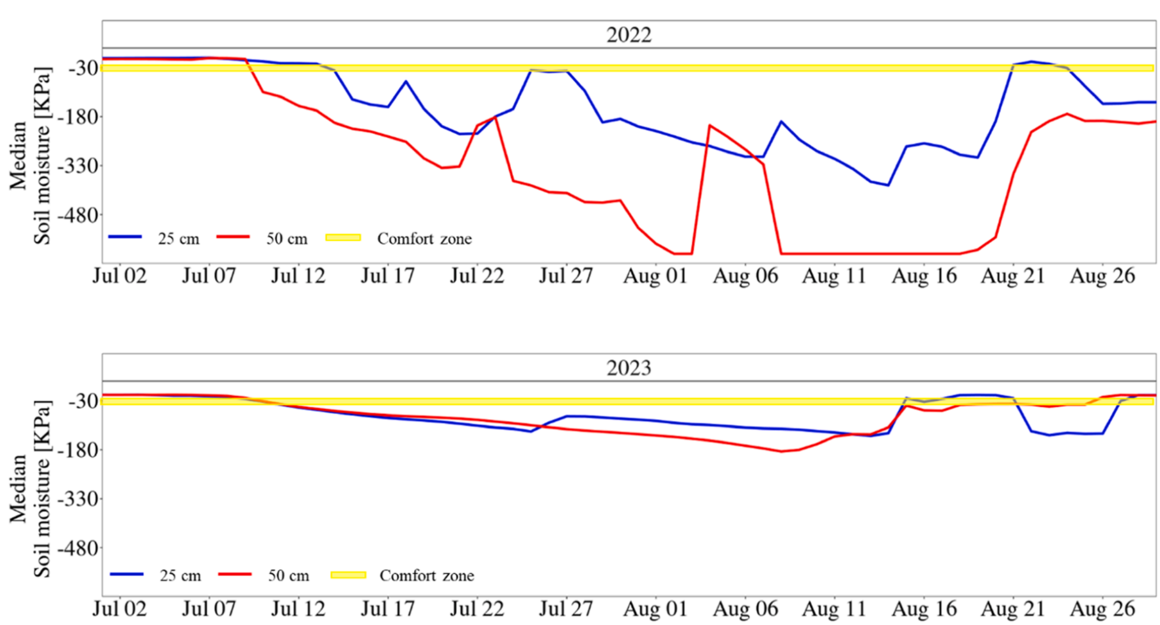

Fig. 7. The median values from the soil moisture sensors installed in the DENDRO treatment to observe the effect of the amount of irrigated water on the soil.

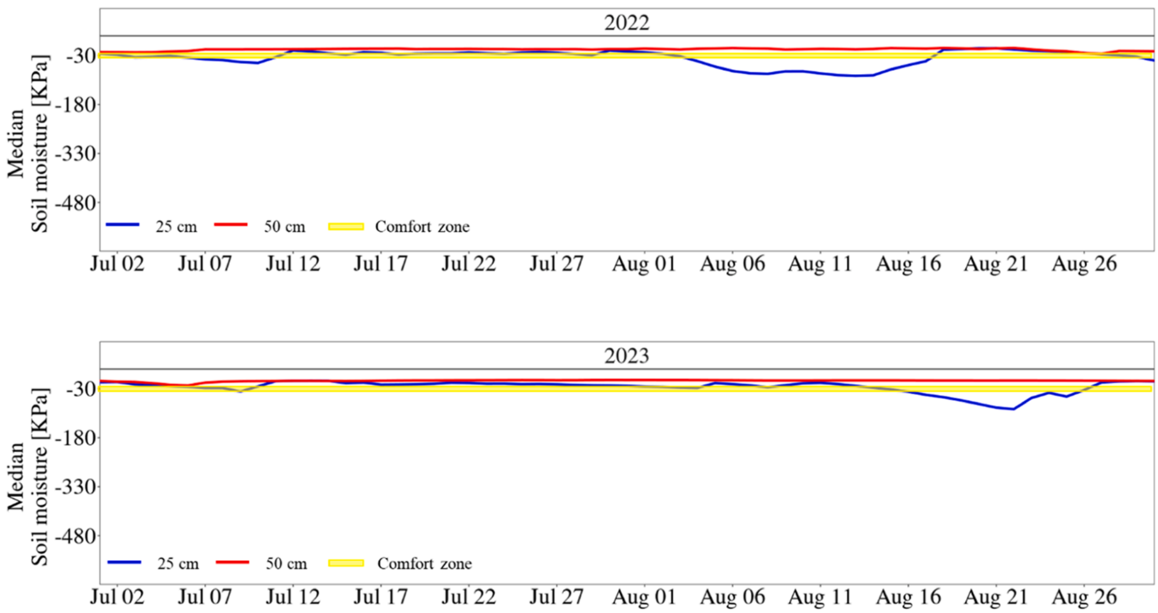

Fig. 8. The median values from the soil moisture sensors installed by the farm serve as a reference point for the daily irrigation amounts during the years 2022 and 2023 from SOIL treatment.

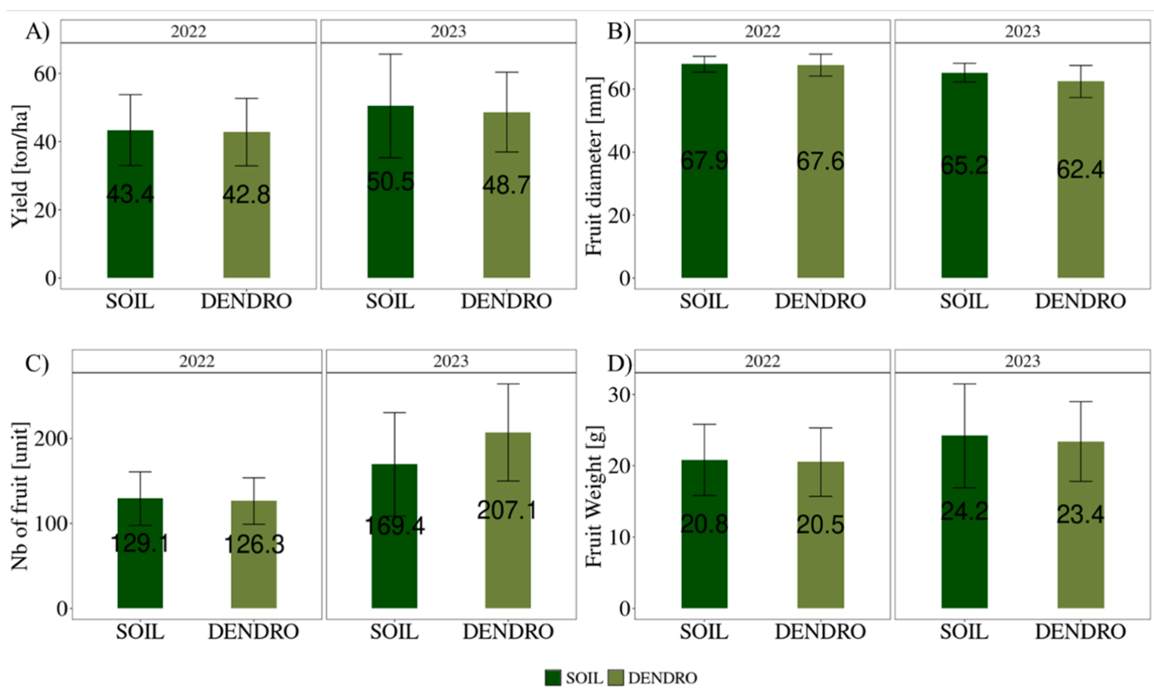

Fig. 9. The production parameters per treatments - SOIL (dark green) and DENDRO (olive green) for 2022 and 2023. A) The yield per treatment, B) The average fruit diameter in the end of the experiment. C) Number of fruit and D) the average weight per treatment.

−1.2 MPa). Similar to the first year, the MDS values showed only slight differences between treatments. The maximum MDS was 715 µm for the DENDRO trees and nearly 640 µm for the SOIL trees. The average MDS was also similar for both treatments, with the DENDRO treatment at 358.7 µm and the SOIL treatment at 272.5 µm (Fig. 11).

By 2023, significant differences in cumulative growth were also observed (Fig. 12). However, the stem exhibited negative development that year, leading to periods of no growth. The average DG for the DENDRO trees was 4.1 µm, with a maximum growth of 105 µm, while for the SOIL treatment, the average was −1.3 µm, with a maximum of 102.6 µm (data not shown). During this year, the DENRO treatment DG values were 64 % positive against 53 % of the SOIL treatment, and the average ET_o was 3.9 mm/day and the maximum value was 8.4 mm/day (Fig. 11).

3.3. Comparison of different irrigation algorithms models

To compare the two field tested irrigation models SOIL and DENDRO we virtually applied the two models FAO and MODEL on the daily data, being aware that this is not an independent test, but to see the reaction of the different algorithms.

Among the tested algorithms (DENDRO, SOIL, FAO, and MODEL),

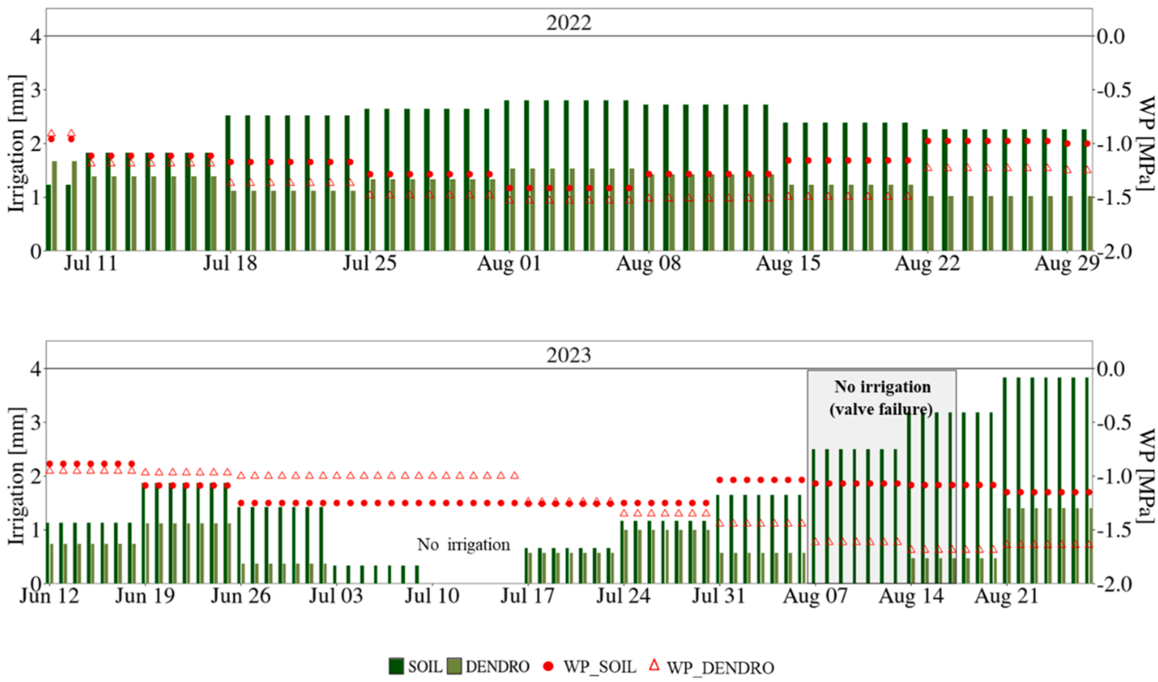

Fig. 10. Daily average amount of irrigated water (mm) of each of the two treatments, SOIL and DENDRO, for the years 2022 and 2023. The average stem WP values of the trees are shown for both treatments (red circle = SOIL and red triangle= DENDRO). The total irrigated water for the DENDRO treatment was 80 mm in 2022 and 90 mm in 2023, while for the SOIL treatment, it was 130 mm in 2022 and 205 mm in 2023.

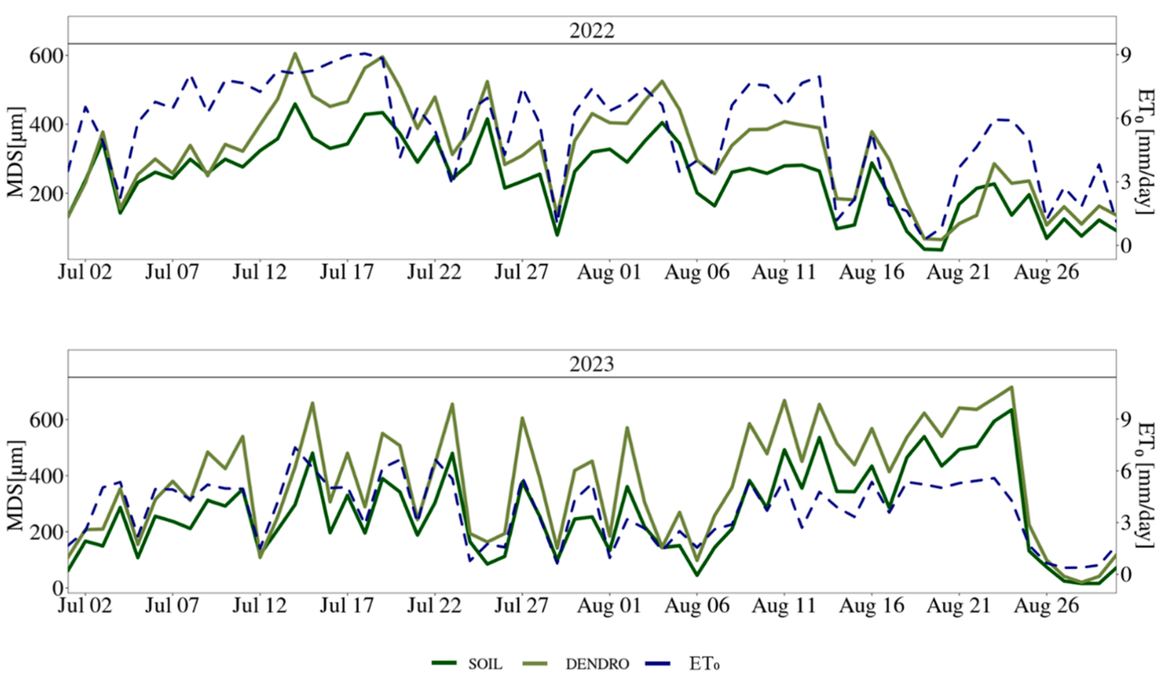

Fig. 11. Average maximum daily shrinkage of all trees in the SOIL experiment (dark green bars, n = 8) and the DENDRO treatment (olive green bars, n = 8). The evapotranspiration rate (ET_0) is represented by a dashed dark blue line for both years, alongside each treatment.

the FAO method consistently applied the highest amount of irrigation per day in both years, with a maximum of 6.7 mm in 2022 and 5.6 mm in 2023 (Fig. 13). Of the remaining models, based on the average daily irrigation in 2022, the SOIL applied the most water per day, reaching a maximum of 2.8 mm. This was followed by the MODEL model, with a maximum of 2.1 mm per day, and the DENDRO model, with a maximum of 1.4 mm. In 2023, the MODEL exhibited a consistent irrigation rate, with a maximum of 3 mm per day. This was followed by the DENDRO model, which reached a maximum irrigation rate of 3 mm per day, and the SOIL model, which increased to a maximum irrigation rate of 3.8 mm per day.

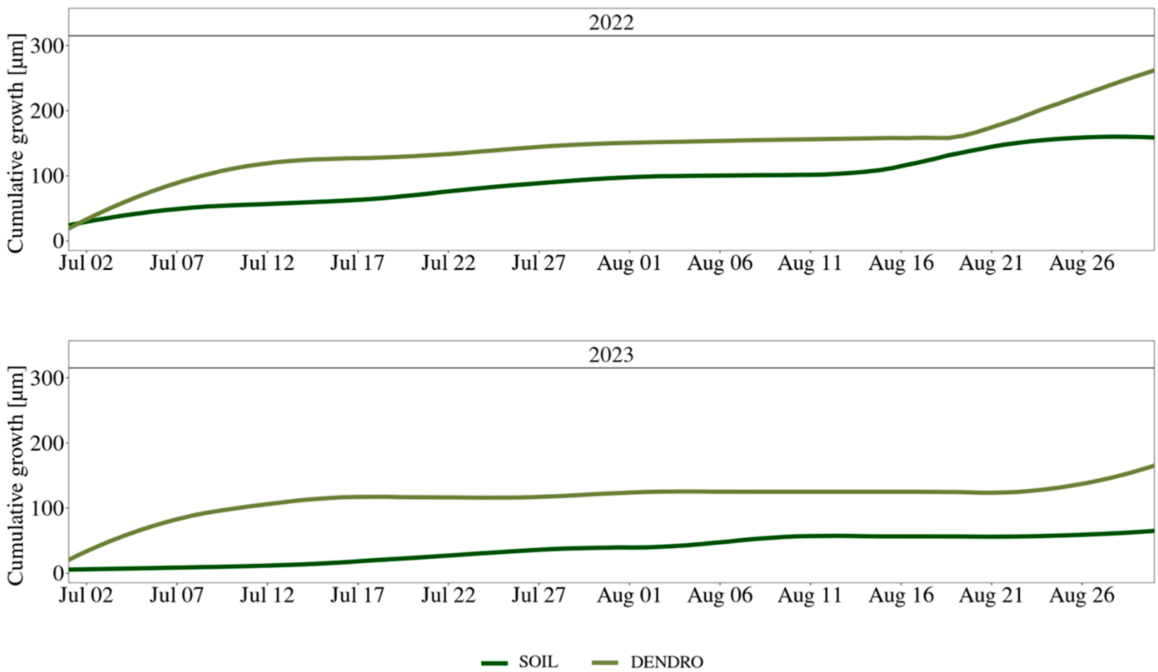

Fig. 12. The cumulative average growth (lines) is shown per treatment (SOIL = dark green, DENDRO = dark olive) for both years of the experiment.

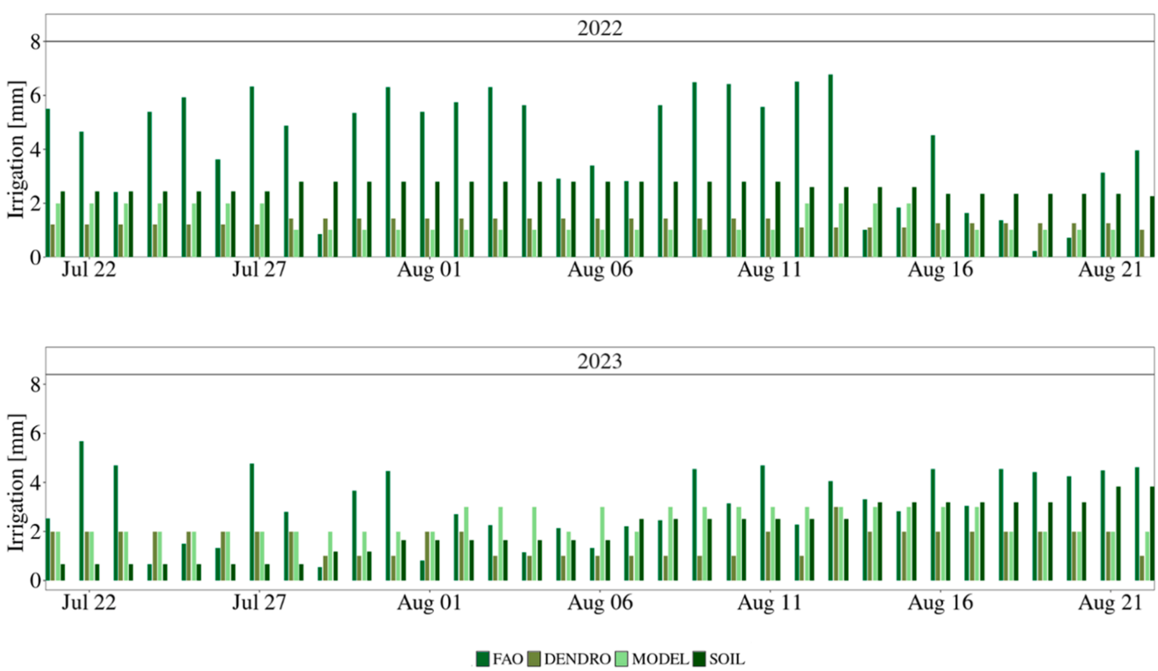

Fig. 13. Comparison of four irrigation methods: FAO-based irrigation (FAO: green bar, SD = 1.5), dendrometer-based irrigation (DENDRO: dark olive , SD = 0.5), regression model-based irrigation (MODEL: light green, SD = 0.6), and soil moisture sensor-based irrigation (SOIL: dark green bar, SD = 1.0).

4. Discussion

4.1. Performance of field-tested models SOIL and DENDRO

The results of the automated dendrometer-based irrigation demonstrated that, compared to moisture-driven soil irrigation, substantial improvements in irrigation efficiency can be achieved without any significant loss in yield (Fig. 9). A comparison of production parameters (fruit diameter, number of fruits, fruit weight) between the two years showed no significant differences. In both years and across all treatments, the harvested yield consistently exceeded the annual average for the Gala variety (*Malus domestica*) in Switzerland, which is around 31.6 ton/ha [*Malus domestica*] (Obstverband et al., 2023).

The similarity in yield between the treatments can be explained by the absence of significant differences in the stem WP values measured throughout the experiment. Both treatments successfully maintained the trees within a non-stressful range, with average WP values varying from −1.0 to −1.2 MPa. In 2022, the lowest WP values, reaching −1.5 MPa, were recorded during Week 31, similar to those observed in the SOIL treatment. This stress developed gradually as a result of several consecutive days, with evapotranspiration (ET_o) levels exceeding 5 mm/day. In 2023, a water valve failure led to elevated stem WP ranging from −1.6 to −1.68 MPa over a 3-week period in the DENDRO treatment. This resulted in a 0.4 MPa difference between the maximum WP values of the DENDRO and SOIL treatments, causing misalignment in peak WP values.

Despite this prolonged period of elevated stress, the overall yield was not significantly impacted; however, it likely contributed to a reduction in the final fruit size. Naor et al. (2008), emphasized that maintaining stem WP above −1.5 MPa is crucial for preserving commercial apple crop yields, with fruit diameter exceeding 70 mm. Likewise, Espinoza-Meza et al. (2023) have recommended maintaining WP values above −1.5 MPa to ensure both crop quality and yield. However, the data suggested that maintaining the crop at a moderate stress level, with WP values between −1.5 and −1.6 MPa, was not a problem.

The DENDRO model was based on the 7-day average of MDS; reducing the averaging period could enhance the model's sensitivity to daily fluctuations in stem WP. This would allow for more precise adjustments, ensuring that optimal stress levels are maintained. Current data observations suggest that using 7-day averages for parameters such as DR and MDS makes the system less responsive to rapid changes in climate and soil moisture, indicating that this averaging period may be too long for optimal irrigation management. Bonany et al. (2000) tested potted apple trees and observed that stress symptoms typically manifested within 3–4 days. Although this setting differs from the water stress conditions in the field, their findings suggest that using a 4-day average for MDS, rather than the 7-day average currently employed, could provide a more responsive and timely adjustment to irrigation needs but further investigation would be required as when using dendrometers direct accumulative stress output from the trees is possible, what remove the necessity of using averages which compensate for previous errors.

Among the two evaluated irrigation systems, DENDRO demonstrated higher efficiency in water conservation (Fig. 10) compared to SOIL. The analysis of soil moisture data (Fig. 7) revealed that despite dry soil surrounding the sensors, the trees showed no signs of water deficit (Fig. 9). This observation remained consistent in 2023, even when a valve malfunction caused several days without irrigation. Notably, the farm maintained optimal soil moisture levels to support fruit development and achieve the desired final diameter, as evidenced also by the WP values for this treatment. However, this approach resulted in over-irrigation without necessarily improving the final production. At the onset of the 2022 growing season the DENDRO treatment applied more irrigation water than the SOIL treatment (Fig. 10). This was likely due to early-season stem shrinkage, during which trees displayed WP values above −1.0 MPa and exhibited negative R_Δ values (Fig. 6). Once moderate stress of a WP of −1.2 MPa was reached, the amount of irrigation applied decreased. These findings suggest that slight stem shrinkage early in the season could be tolerated up to a level of mild water stress without negative impacts on yield. However, this approach would benefit from additional calibration using a Scholander pressure chamber at the beginning of the season to fine-tune stress levels. Overall, the DENDRO method, which bases irrigation decisions on stem shrinkage, proved highly efficient. This finding aligns with the results reported by Casadesús et al. (2012), who observed a 47 % reduction in water usage for peach trees irrigated based on dendrometer parameters (MDS). The enhanced performance of DENDRO can be attributed to its ability to more accurately assess plant responses to water availability.

It is assumed that, in this experiment, the trees' root systems extended into deeper subsoil layers beyond the reach of the soil moisture sensors placed at a depth of 50 cm. This hypothesis is supported by the soil moisture data from the DENDRO treatment in both years (Fig. 7). Further evidence comes from the trees' WP values, which remained above −1.4 MPa (data not shown) in early August, despite the soil moisture sensor at 50 cm recording −100 kPa. This shows that plant-based sensors, such as dendrometers, can provide a more direct measure of tree water status (Doltra et al., 2007; Jones, 2004; Ortuño et al., 2010), leading to more precise irrigation scheduling. This limitation could be addressed by using additional sensors to provide a more comprehensive picture of soil moisture distribution. However, even with extra sensors, it is very difficult to adequately express the characteristics of the soil-root system, as this is complex and heterogeneous. In addition, such an approach would lead to increased costs.

Weather conditions were also taken into account in the DENDRO treatment. During Week 28 (July 11 to July 17, 2022), which recorded the highest ET_o values (mean = 8.1 mm), the average irrigation was slightly higher in the DENDRO treatment compared to the SOIL treatment, with 1.4 mm and 1.1 mm irrigation, respectively. This was achieved due to positive R_Δ values (29 μm), indicating stem recovery, even under such high ET_o values. This suggests that despite the intense heat, the plants were able to access sufficient water from the soil, effectively mitigating the effects of climatic stress.

On average, the stem variations of the trees in the two treatments displayed comparable responses. Across the entire experiment, both MDS and DG values remained relatively similar between the treatments. These comparable values in MDS can likely be attributed to the similar mean evapotranspiration rates (ET_o) recorded in both years—4 mm/day in 2022 and 3.9 mm/day in 2023 (Fig. 11). This is because MDS is known to be influenced by climatic variations (De la Rosa et al., 2013; Ortuño et al., 2009).

In 2022, stem diameter values were more consistent across treatments, with DENDRO showing the highest cumulative growth (Fig. 12). In 2023, cumulative growth remained low and comparable between treatments. However, stem development was negative that year, with a decline in stem diameter, particularly in July, for both treatments. Despite these variations, the treatments' effect on cumulative growth did not differ significantly across years. Rainfall played a crucial role, as substantial growth in 2022 following intense rainfall in late August, as well as in August 2023, suggests that the distribution of rainy days influenced cumulative growth.

This parallel performance among the treatments reflects the efficiency of the DENDRO treatment in providing irrigation. Even with a reduced water supply, the DENDRO treatment achieved nearly the same output as the SOIL treatment, demonstrating that plant-based systems are more suitable for steering irrigation systems.

4.2. Calculated characteristics of FAO and MODEL algorithms

4.2.1. FAO irrigation

Of the algorithms analyzed, the FAO-based irrigation method (FAO) applied the most water in both years (Fig. 13). The FAO method effectively tracks the reference evapotranspiration (ET_o) trend, including its peaks, which results in higher daily water requirements. The FAO method is driven by Kc, which is difficult to estimate and depends on leaf area, crop variety, and other parameters (Mobe et al., 2020).

Some corrections and updates have been published regarding Kc calculations, but significant inaccuracies remain (Pereira et al., 2021). Moreover, these corrections were not incorporated into this research due to the requirement for additional variables. Recent studies have shown improved accuracy in estimating Kc values by incorporating data from thermal cameras or satellite images to obtain vegetation indices, such as the Normalized Difference Vegetation Index (NDVI) (Parmar et al., 2023).

Casadesús et al. (2012) introduced the FAO model as a foundational approach, recommending its use as an initial step to establish the upper and lower bounds for irrigation. Although this method has not been extensively validated for production outcomes, our measurements suggest that it serves as a valuable basic framework. For example, the FAO-CROPWAT 8.0 model has been utilized to estimate reference evapotranspiration and net irrigation water requirements (Gabr, 2022).

4.2.2. MODEL irrigation

The MODEL approach also proved to be a viable option for automating irrigation management (Fig. 13). In 2022, this method ranked as the second lowest in terms of daily water irrigation. However, in 2023, it moved to the third position. This output is considered acceptable since it was based on a single simulation. In addition, the correlation between actual stem WP values and those predicted by the model has fluctuated over the years. This inconsistency suggests that, while the model shows promise, its accuracy in predicting real-time water stress varies depending on external factors, such as environmental conditions or the physiological state of the trees. Additionally, the trees used for the simulation were at a disadvantage due to technical issues, which likely impacted the results.

Despite these challenges, the MODEL approach effectively captured WP fluctuations, making it more responsive than other methods in the study. In early 2022, it reduced irrigation levels even as WP increased, as WP values remained below the stress threshold and vapor pressure deficit (VPD) was low, preventing excessive irrigation. The method dynamically adjusted irrigation rates in response to WP fluctuations, demonstrating its ability to simulate and react to changing plant water status.

The inclusion of VPD in the regression model significantly influenced irrigation decisions. In 2023, persistently high VPD values led to sustained high irrigation levels. Even when VPD declined in early August, irrigation did not decrease proportionately due to elevated dendrometer parameter (d_day) values, suggesting that stem diameter variations also played a key role in irrigation adjustments. Using VPD instead of ET_0 may be an advantage. The VPD directly reflects the atmospheric demand for water on the plant by measuring how much the atmosphere "pulls" water from the leaves. Additionally, VPD influences the plant's vascular tissue, including xylem, which is the primary channel for water transport (Hacke et al., 2017; Song et al., 2021). This can impact the plant's overall water status and stress response more directly than ET_0. However, studies have indicated that these parameters can be linearly related (Massmann et al., 2019).

Further field studies are necessary to better evaluate this algorithm, as its evaluation was based on data collected from trees irrigated by different algorithms. Nonetheless, when considering the plant's water status as a key factor for ensuring optimal production, the MODEL method proved suitable for maintaining stem WP values below stress levels that could adversely affect production.

4.3. Comparison of different irrigation algorithms

At the conclusion of the experiment, four different approaches for automatically steering the irrigation of an apple orchard were compared, with the properties summarized in Table 1. It is important to note that only the soil moisture-based method provided actual field values for both 2022 and 2023. In 2023, although data were collected using the dendrometer method, water was not applied for nearly 2 weeks. For the FAO and MODEL treatments, water application was simulated for both years, influencing the overall comparison and the conclusions drawn from the results. Despite this, an assessment of the models' performance can still be observed.

By comparing the four different approaches for steering of irrigation systems, it becomes clear that the FAO method (FAO) was not optimal for exploiting stored soil water. Particularly in deep soils, this limitation is a significant disadvantage. Soil moisture sensors (SOIL) mark an important improvement, proving to be efficient and reliable, although they fail to account for plant-available water in deeper subsoil layers. Despite this limitation, farms in Switzerland and other countries have already successfully adopted this irrigation model. However, as observed in the study, some farmers tend to irrigate more than the system's sensors recommend.

The dendrometer-steered irrigation system performed exceptionally well, particularly with the simple DENDRO algorithm based on stem shrinkage. Although it slightly overestimated water needs early in the season, it effectively maintained stem diameter and optimized irrigation once moderate water stress was reached. A more complex algorithm (MODEL), which incorporated VPD and tree water deficit, did not outperform DENDRO. However, since MODEL was applied retrospectively, its full potential may not have been captured, as irrigation on one day can influence tree performance the next. Additionally, the correlation between the algorithm's output and actual WP values varied significantly between years.

Despite this variability, integrating climatic factors (e.g., VPD) with tree-specific parameters like water deficit and stem shrinkage (d_day) could enhance irrigation accuracy beyond dendrometer-based methods alone. Further trials are needed to evaluate this hypothesis and refine the MODEL algorithm for improved reliability.

5. Conclusions

The DENDRO method proved to be a more water-efficient alternative to the SOIL method without compromising apple yield. This efficiency was achieved by effectively responding to fluctuations in stem WP, demonstrating the advantages of plant-based sensors for precision irrigation. However, the use of 7-day averages in the DENDRO algorithm caused delays in adjusting irrigation to rapid WP changes. Future improvements should explore shorter averaging periods (e.g., 4 days or less) and adjustments to algorithm thresholds to assess their impact on tree growth dynamics.

In contrast, the SOIL method, though effective for maintaining production, applied more water than DENDRO. This over-irrigation resulted from farm irrigation practices aimed at maintaining comfortable soil moisture levels. Additionally, soil moisture measurements did not always reflect water availability in deeper layers, exposing a limitation of this approach. Combining soil moisture sensors with plant-based measurements could enhance irrigation precision.

Alternative methods, such as FAO, provided useful insights but were insufficient as standalone irrigation strategies. The MODEL method, integrating dendrometer and climatic data, showed promise for

Table 1
Summary of the methodology and the performance of the analyzed algorithms and water applied.

Algorithm	Basis of method	Advantage	Disadvantage	Average mm/ day (2 years)
DENDRO	Shrinking stem diameter: Increase irrigation Expanding stem diameter: Reduce irrigation during high climatic stress	Reports the plant's water stress to recover the development of the stem	Delayed response to fluctuations in WP values	1.4
FAO	Crop evapotranspiration $ETc = Kc*ET0$	Provides the amount lost by the crop evapotranspiration	Does not account the water available in the soil	3.6
MODEL	Predicted WP values $WP = (11.34 - 0.02 *d\_day + 0.04 *min\_twd + 1.93 *avg\_VPD$	Shows the plant's water stress taking into account weather constraints	Variations due to environmental conditions or tree physiology	1.8
SOIL	Moisture content > -30 KPa (25 cm)	Displays the water availability around the sensors	Does not display the whole soil water availability	2.2

automating irrigation by capturing WP fluctuations more effectively. However, occasional discrepancies in WP predictions suggest that variability in model parameters affects reliability. Fine-tuning these parameters could improve accuracy. While further field testing is required, MODEL presents a strong framework for developing responsive, automated irrigation systems.

Overall, this study highlights the benefits of integrating plant-based sensors to optimize water use in orchard systems, promoting more sustainable irrigation practices. Advancing precision irrigation technologies will improve water-use efficiency and support long-term agricultural sustainability.

CRediT authorship contribution statement

Chiang Camilo: Writing – review & editing, Data curation. **Hatt Matthias:** Validation, Conceptualization. **Nasser Hassan Roland:** Writing – review & editing, Validation, Software, Methodology, Formal analysis, Conceptualization. **Anken Thomas:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Waldburger Thainna:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Data curation, Conceptualization. **Walter Achim:** Writing – review & editing, Supervision. **Cockburn Marianne:** Writing – review & editing, Writing – original draft, Validation, Supervision, Investigation, Conceptualization.

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.

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Data availability

Data will be made available on request.

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