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Research Paper

Impact of altitude and irrigation on sweet cherry tree water status and fruit production in the mountain agroecosystem of the Jerte valley

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ABSTRACT

High environmental variability within a valley challenges fruit production in mountain systems and requires site-specific irrigation management. This study evaluates the effects of altitude (480 m vs. 1030 m a.s.l.) and irrigation strategies (regulated deficit irrigation, RDI, vs. conventional farmer-managed irrigation, FRM) on sweet cherry trees (Prunus avium L.) in the Jerte Valley, Spain, focusing on tree water status, vegetative growth, and fruit quality. Results showed that altitude significantly impacted meteorological variables, tree water needs and water status, phenology, and fruit growth. Trees at 1030 m, under cooler, more humid conditions, exhibited a longer fruit development and less negative values of stem and trunk water potential (>-1.3 MPa), resulting in larger fruit (50% of the cherries were larger than 28 mm) compared to those at 480 m (hotter and drier environment), where fruit grew faster and high evaporative demand led to water stress (water potential below -2.0 MPa) and smaller fruit (50% of the cherries had diameters between 24 and 26 mm). RDI maintained better tree water status and enhanced fruit size, particularly at lower altitudes. Soil water content and stomatal conductance varied by altitude and irrigation treatment, with RDI helping to mitigate water deficit stress in both situations. This research highlights the importance of altitude and irrigation strategy in determining the sustainability and resilience of sweet cherry orchards under climate change. Precision irrigation, particularly RDI, offers a viable strategy to optimize water use while improving harvest value in mountain fruit systems.

1. Introduction

Climate change poses a major challenge to horticultural production systems. Rising temperatures, altered precipitation patterns, and increased frequency of extreme weather events are expected to affect crop development, yield stability, and fruit quality (IPCC, 2021; Farah et al., 2025). Mountain agriculture is especially vulnerable to climate change due to its unique soil and climate conditions, limited water availability, and structural constraints that hinder the implementation of adaptive technologies. Fruit tree cultivation in mountainous areas faces increased risks under climate stress, threatening both the economic viability of farms and the sustainability of traditional agricultural systems. In mountainous regions like the Jerte Valley (Extremadura, Spain), characterized by pronounced altitudinal gradients, sweet cherry (*Prunus avium* L.) is a widely cultivated fruit, grown at elevations ranging from 450 to over 1.000 m above sea level (m.a.s.l.). However, little is known about how changes in altitude affect the physiological traits that determine the commercial value of cherries. Altitude-induced temperature gradients directly impact evapotranspiration rates in trees, influencing water demand (Yang et al., 2019). Higher altitudes generally experience lower temperatures, reducing evapotranspiration, while lower altitudes face higher temperatures, increasing water demand. Precipitation patterns often vary with altitude, with high-altitude areas receiving more rainfall or snowfall than low-altitude areas, directly affecting soil moisture availability. Solar radiation intensity and wind speed tend to increase with altitude, potentially leading to higher rates of photosynthesis but also greater evaporative demand, particularly on exposed slopes (Navarro-Serrano et al., 2020). The combined effect of these factors determines the overall water needs and stress experienced by trees at different altitudes within a valley (Naryal et al., 2020),

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Consequently, when water policies are designed and water volumes are allocated, variations in water needs resulting from elevation changes must be taken into consideration to ensure effective and equitable distribution. Thus, in the case of the Jerte Valley, it is expected that the different environmental conditions associated with the altitude might differentially influence sweet cherry trees' phenology and physiology, thereby amplifying variability in yield and cherry quality and forcing growers to carry out differential water management strategies (Rodrigo, 2000; Ramos, 2025).

Sweet cherry is a high-value crop widely cultivated in temperate and Mediterranean climates, including mountain regions. Its sensitivity to environmental stressors—such as heat stress, water scarcity, and excessive rainfall during ripening—makes it particularly susceptible to physiological imbalances, fruit cracking, and reduced market quality (Predieri et al., 2003; Ayala et al., 2026). Moreover, sweet cherry is especially sensitive to water availability during key phenological stages such as flowering, fruit cell division, and floral bud differentiation—critical phases that determine both the current season's yield and the potential productivity of the following year (Marsal et al., 2010; Naor, 2006). To mitigate these effects, precision irrigation strategies such as the regulated deficit irrigation (RDI) have gained importance in cherry orchards. RDI is an irrigation technique that applies controlled water deficits during specific phenological stages, aiming to enhance water use efficiency without compromising fruit quality (Mitchel et al., 1984; Fereres and Soriano, 2007; Intrigliolo and Castel, 2010). For cherries, RDI with a controlled water deficit during postharvest has been shown to be effective in optimizing water use and maintaining productivity and fruit quality (Nieto et al., 2017; Blanco et al., 2019; Küçükyumuk, 2024). In this sense, to successfully apply RDI and avoid any drawback caused by uncontrolled severe water deficit, it is necessary to assess tree water status by plant indicators to quantify the water deficit (Naor, 2000).

Midday stem water potential (Ψ_{stem}) has been accepted worldwide as the most reliable plant water status indicator (Moriana et al., 2012). Blanco et al. (2018) proposed the Ψ_{stem} as a reference indicator of the discontinuous plant water status for drip-irrigation cherry trees. Recent advances in sensor technology have enabled more precise and continuous monitoring of plant water status, offering significant advantages over traditional intermittent, destructive measurements of Ψ_{stem} using a pressure chamber. One emerging tool is the trunk-embedded microtensiometer, which allows in situ, real-time recording of trunk water potential (Ψ_{trunk}) at high temporal resolution (Blanco and Kalcsits, 2021). These devices have shown strong correlation with pressure chamber measurements in species such as nectarine (Conesa et al., 2023), apple (Gonalez Nieto et al., 2023; Girona et al., 2025), pear (Blanco and Kalcsits, 2023), grapevine (Lakso et al., 2022; Pagay, 2022), olive (Villalobos et al., 2025), and kiwifruit (Di Biase et al., 2025) and have demonstrated high sensitivity for early detection of water stress. However, there is still a notable lack of information on the reliability of microtensiometers in many fruit crops, such as sweet cherry, and how they interact with different environments, such as those from the mountain agriculture at different altitudes.

The hypothesis of this work is that providing the same amount of water to orchards located at different altitudes leads to significant differences in tree water status, so applying tailored water irrigation strategies that avoid severe water deficit and consider the soil-plant-atmosphere continuum is essential. This study evaluates the interactional effects of climate-related factors— temperature, humidity, and water deficit—on the agronomical and physiological responses of sweet cherry trees. Specifically, it examines the combined influence of two key variables: altitude (480 vs. 1030 m a.s.l.) and irrigation strategy (regulated deficit irrigation vs. conventional farmer-managed irrigation) on sweet cherry cv. 'Lapins' during the 2023 and 2024 growing seasons in the Jerte Valley (Extremadura, Spain). By integrating plant-based physiological monitoring tools such as microtensiometers, the study aims to assess the effectiveness of precision irrigation strategies under contrasting environmental conditions on the agronomical and physiological responses of sweet cherry trees. The findings are intended to provide a scientific foundation for site-specific irrigation management adapted to water-limited conditions and altitudinal heterogeneity in mountain fruit production systems, contributing to the sustainability and resilience of sweet cherry cultivation under increasing climatic uncertainty.

2. Materials and methods

2.1. Experimental sites

The study was conducted during the growing seasons 2023 (preharvest and postharvest), 2024 (preharvest and postharvest) and 2025 (preharvest), in two commercial sweet cherry orchards of the combination 'Lapins'/*P. avium* (one at low altitude and other at high altitude), both located in El Torno, Jerte Valley, Extremadura, Spain. The low-altitude orchard (480 m a.s.l.; 40° 7′ 10.48′' N, 5° 57′ 4.68′' W) covers 0.54 ha, of 9-year-old trees spaced at 5 m terraces slopes (15%–35%) and trained to low-vase system. At the beginning of the experiment, the mean trunk cross-sectional area (TCSA) was 192.3 ± 14.3 cm^2. The soil was sandy loam (69.5% sand, 20.5% silt, 10.0% clay), moderately acidic (pH 5.8), with low organic matter (1.02%) and total N (0.25%) in the surface layer (0–30 cm depth), and an electrical conductivity (EC) of 71.8 μS/cm. Available phosphorus was 27.22 ppm, while exchangeable potassium, calcium, magnesium, and sodium concentrations were 320.6, 165.4, 79.6, and 42.0 mg/kg, respectively. The irrigation water exhibited a pH ranging between 6.9 and 7.0, with an EC of 116.7 μS/cm. Nitrate (NO_3^-) concentration was 2.00 mg/L (0.452 mg N—NO_3^-/L), and ammonium (NH_4^+) levels were low, (0.114 mg/L;0.088 mg N—NH_4^+/L).

The high-altitude orchard (1030 m a.s.l.; 40° 9′ 9.27′' N, 5° 56′ 4.67′' W) covered 0.49 ha of 4-year-old trees spaced at 6 m on terraces and trained to low-vase system on slopes of 17–25%. Mean TCSA at the beginning of the experiment was 119.7 ± 22.5 cm^2. The soil was sandy loam (77.2% sand, 18.8% silt, 4.0% clay), acidic (pH 5.0), with higher organic matter (3,81%) and total N (0.42%) and an EC of 25.2 μS/cm. Available phosphorus was 23.35 ppm, while potassium, calcium, magnesium, and sodium levels were 208.8, 140.0, 44.4, and 31.2 mg/kg, respectively. The irrigation water had a pH of 7.2 and an EC of 20.3 μS/cm. Nitrate was not detected, while ammonium was present at a concentration of 0.102 mg/L (0.080 mg N—NH_4^+/L).

Horticultural practices (fertilization, pruning, weed control) followed similar commercial practices in both orchards.

2.2. Irrigation treatments

During the 2023, 2024, and 2025 growing seasons, two irrigation strategies were compared: (i) Regulated Deficit Irrigation (RDI), and (ii) Farmer's Irrigation Management (FRM). (i) The RDI treatment supplied 100% of crop evapotranspiration (ET_c) during the preharvest period and the first 20 days following harvest (flower bud induction and early differentiation), and 25% of ET_c thereafter, considered a non-critical period. Crop water requirements under drip irrigation were estimated as: $ET_c = ET_o \times K_c \times K_r$, where reference evapotranspiration (ET_o) was calculated from meteorological data recorded at each site using the FAO-56 Penman–Monteith method (Allen et al., 1998); the crop coefficient (K_c) for sweet cherry varied between 0.30 and 0.80 depending on phenological stage (Marsal et al., 2012); and the ground cover coefficient (K_r) was determined from canopy shadow and drone-based coverage (Fereres et al., 1982). Water was applied daily (April-October) via one irrigation line with four emitters per tree, with an emitter discharge volume of 4 L h^{-1}, spaced 50 cm apart. (ii) The FRM treatment followed local practice, with irrigation applied daily from May to October for a fixed duration of 1 h (19:00–20:00), using two 4 L h^{-1} emitters per tree, delivering a fixed total volume of 8 L $tree^{-1}$ day^{-1}.

The experiment was conducted over three consecutive growing seasons (2023–2025), during which the same irrigation treatments were applied to the same trees. The experimental design included two fixed factors: (i) altitude (480 vs. 1030 m), and (ii) irrigation regime (RDI vs. FRM). At each site, treatments were arranged in a randomized complete block design with five trees per treatment. Thus, a total of 10 experimental trees were monitored per site (2 irrigation regimes × 5 trees × 2 altitudes), resulting in 20 trees in the two experimental orchards. Measurements were taken on all experimental trees, which remained the same throughout the entire duration of the experiment.

2.3. Meteorological and soil monitoring

Hourly meteorological data were recorded by telematic automatic weather stations (iMETOS 3.3, Pessl Instruments, Weiz, Austria) located on each plot. The variables measured included air temperature, relative humidity, wind speed, precipitation, and solar radiation. Daily ET_o and air vapor pressure deficit (VPD) were calculated from the meteorological data according to Allen et al. (1998). Volumetric soil water content (VWC) was continuously monitored at four depths (10, 20, 30, and 40 cm) with one soil moisture probe per irrigation treatment (EP100GL-04 Series, EnviroPro, Precision Soil Probes) installed under the canopy projection and placed 0.25 cm from the drip emitter.

2.4. Phenology and fruit growth

Phenological development was monitored weekly using the BBCH scale (Fadón et al., 2015), from bud swelling (stage 53) to harvest (stage 89). Observations were made on three representative trees for each irrigation treatment and altitude, and phenological stages were documented photographically. Fruit growth dynamics were assessed weekly by recording the fruit equatorial diameter of 10 fruits per tree (three trees per treatment) using a digital caliper (precision ±0.02 mm).

2.5. Stem and trunk water potential

Midday stem water potential (Ψ_{stem}) was measured using a Scholander pressure chamber (Model 3000, Soil Moisture Equipment, Santa Barbara, CA, USA) at solar noon every 15 days on two mature, healthy, and shaded leaves per tree, located near the trunk, five trees per treatment throughout both growing seasons, 2023 and 2024. Before measurement, leaves were enclosed in aluminum foil for at least two hours, following the protocol described by McCutchan and Shackel (1992). Trunk water potential (Ψ_{trunk}) was continuously monitored at 15-minute intervals on three trees per treatment in each plot using microtensiometers connected to a solar-powered data logger (FloraPulse, Davis, CA, USA). Sensors were embedded on the north-facing side of the trunk to avoid direct sunlight, and measurements were conducted during the 2024 season. To validate the reliability of trunk water potential as a plant water status indicator, midday stem water potential was measured weekly in June, July, and August 2024 on three leaves per tree for the trees with microtensiometers installed, allowing for comparison between the two indicators.

Moreover, to assess the daily evolution of the trunk and stem water potential under high evaporative demand conditions, periodic measurements were done from predawn to dusk on four representative hot and sunny days: August 7th and September 10th 2024, in the 480 m plot, and August 8th and September 9th 2024, in the 1030 m plot. On these dates, Ψ_{stem} was measured eight times (06:00, 08:00, 10:00, 12:00, 14:00, 16:00, 18:00, and 20:00 h) in those trees with the microtensiometers.

2.6. Gas exchange

Stomatal conductance (gs) was assessed monthly with a leaf porometer (SC-1, Decagon Devices, USA) under ambient conditions at noon on two sun-exposed leaves per tree (five trees per treatment) at the same time the Ψ_{stem} was measured. Measurements of stomatal conductance were conducted on representative sunny days (Photosynthetic Photon Flux Densit > 1000 μmol·m^{-2}·s^{-1}).

2.7. Vegetative growth

Vegetative growth was measured as pruning wood, cumulative shoot growth, and trunk cross-sectional area (TCSA). Pruning wood was quantified as the fresh mass (kg tree^{-1}) of pruned material per tree, weighed individually in the field each year, five trees per treatment. A subsample of the fresh pruned wood from each tree was dried in a ventilated oven to a constant dry weight to estimate the total pruning wood per tree as dry weight (kg tree^{-1}). Cumulative shoot growth was measured after harvest on 10 shoots per tree in 5 trees per treatment in 2023 and 3 trees per treatment in 2024. TCSA was calculated as the area of a circle based on the trunk perimeter, which was measured in the cultivar using a flexible tape at 20 cm above the ground in five trees per treatment.

2.8. Yield and fruit quality

At harvest (May 23rd and July 4th, 2023; June 3rd and June 28th, 2024; and June 18th and July 9th, 2025; for plots at 480 and 1030 m a.s.l., respectively), cherries from the five selected trees in each treatment were harvested and weighed individually. Yield per tree (kg tree^{-1}), number of fruits per tree, fruit efficiency (number of fruits per cm^2 of TCSA), mean fruit mass, and equatorial fruit diameter were determined. Fruit yield and quality were also measured in 2025 to assess the impact of the irrigation regime imposed in the previous postharvest (2024) on the next year's fruit quality.

2.9. Statistical analysis

All physiological and agronomic variables were analyzed using a factorial design with two fixed factors**:** altitude (480 vs. 1030 m a.s.l.) and irrigation treatment (RDI vs. FRM). Prior to statistical analysis, assumptions of normality and homogeneity of variances were evaluated. Normality of residuals was tested using the Shapiro–Wilk test and inspection of Q–Q plots, and homoscedasticity was assessed using Levene's test. When the assumptions for parametric ANOVA were satisfied, a factorial analysis of variance (ANOVA) was performed to evaluate the main effects and their interaction. When significant differences were detected ($p < 0.05$), means were separated using Tukey's Honestly Significant Difference (HSD) test. When normality and/or homogeneity assumptions were not met, even after data transformation, the non-parametric Kruskal–Wallis test was used to assess treatment effects.

All statistical analyses were performed using IBM SPSS Statistics software (version 22). Relationship between Ψ_{stem}, gs and Ψ_{trunk} were evaluated using linear regression analysis performed in Microsoft Excel. Residuals were examined to verify linearity, normal distribution, and homoscedasticity before interpreting model parameters.

3. Results

3.1. Meteorological variables and irrigation water applied

Air temperature clearly reflected the altitudinal gradient (Fig. 1, see supplementary Table S1). At 480 m, mean annual temperatures were 17.6 (2023) and 17.1 °C (2024), compared to 13.8 and 13.5 °C at 1030 m. The difference between sites ranged between 3 and 5 °C for mean maximum and minimum values. Absolute extremes emphasized this contrast, with maximum temperatures higher than 41 °C in summer at 480 m vs. lower than 36.4 °C at 1030 m; while minimum temperature in winter reached –2.0 and 0.2 °C at 480 m, and –5.0 and –2.0 °C at 1030 m, in 2023 and 2024, respectively. Relative humidity was consistently higher at 1030 m (59–67%) than at 480 m (55–61%), resulting in lower

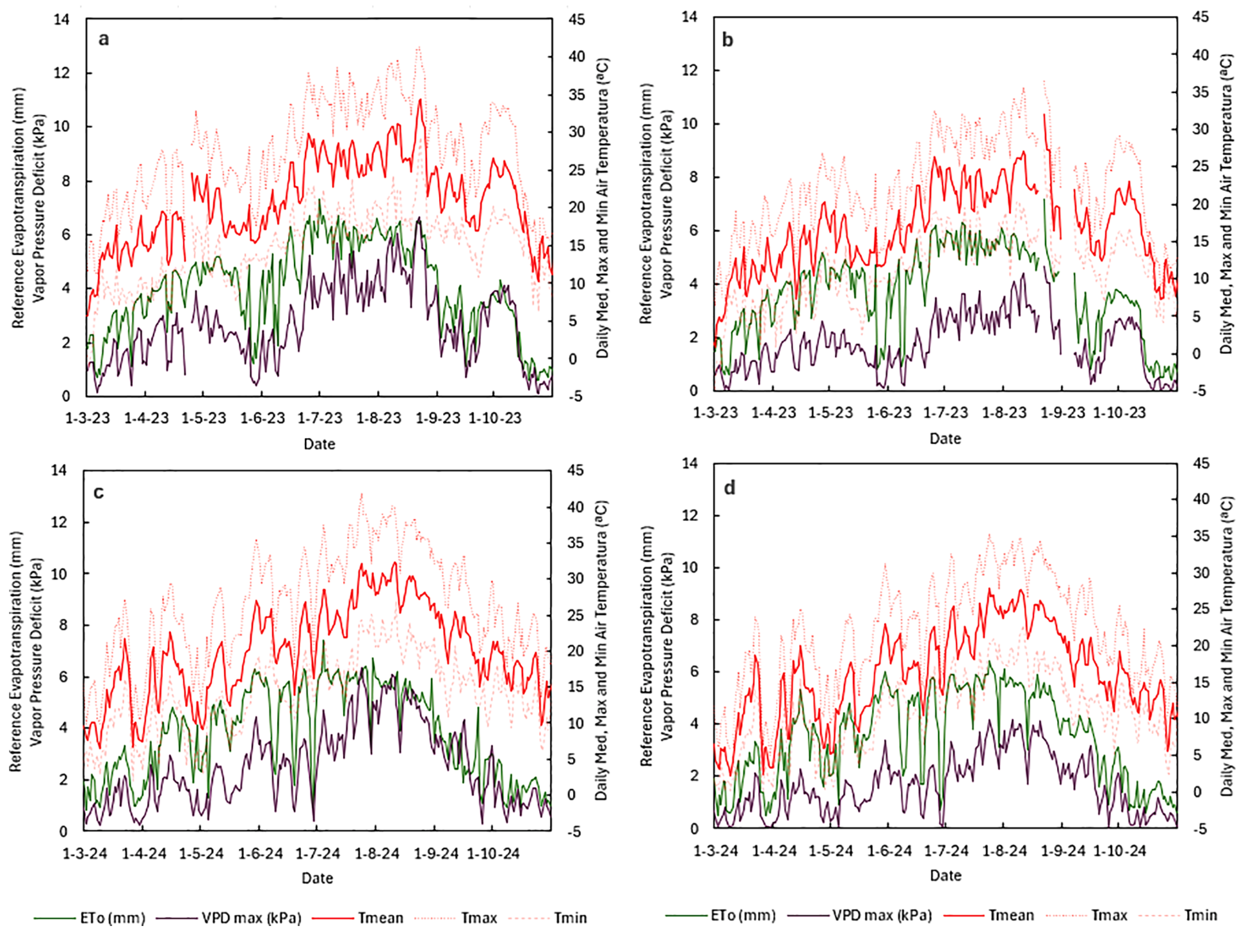

Fig. 1. Daily evolution of mean (Tmean), maximum (Tmax), and minimum (Tmin) air temperature (°C), reference evapotranspiration (ETo, mm d^{-1}), and Vapor Presure Deficit (VPD, kPa) at two commercial sweet cherry orchards located at 480 m (a, c) and 1030 m (b, d) in the Jerte Valley (Spain) during the 2023 (a, b) and 2024 (c, d) growing seasons.

mean values of VPD. Maximum daily VPD reached 6.3–6.6 kPa at 480 m and 4.2–4.7 kPa at 1030 m.

Reference evapotranspiration (ET_o) averaged 3.16–2.86 mm d^{-1} at 480 m and 2.89–2.65 mm d^{-1} at 1030 m, with maxima of 7.3–7.4 mm d^{-1} and 6.4–7.2 mm d^{-1}, respectively. Rainfall was greater and more irregular at high altitude, ranging from 1619 to 2229 mm at 1030 m, compared to 1238–1352 mm at 480 m. Precipitation at 1030 m was concentrated in autumn storms, while rainfall at 480 m was lower and more evenly distributed throughout the year (Fig. 2).

Seasonal crop evapotranpiration (ET_c) was higher at 480 m (609 and 574 mm) than at 1030 m (288 and 352 mm), with more than 65% of demand concentrated in the postharvest period. Rainfall totals varied strongly between years and sites, from 768 to 439 mm at 480 m and > 950 mm at 1030 mm (Fig. 2, see supplementary Table S2).

Irrigation strategies differed markedly. Regulated deficit irrigation (RDI) applied 176–221 mm at 480 m and 126–131 mm at 1030 m, mostly concentrated during preharvest and floral bud differentiation. In contrast, farmer-managed irrigation (FRM) applied only 41–53 mm at 480 m and 54–79 mm at 1030 m, distributed uniformly across the season regardless of ETc or rainfall. Fig. 2 shows the differential distribution of the water for each treatment, highlighting the adaptive nature of RDI compared to the fixed, non-responsive pattern of FRM.

3.2. *Soil water content*

Seasonal dynamics of volumetric soil water content (VWC) showed clear differences between sites, treatments, and years (Fig. 3). At 480 m, VWC ranged from 20 to 40%. In 2023 (Fig. 3-A), FRM plots exhibited frequent declines in VWC, particularly at 20 cm depth, with values dropping below 25% before harvest (May 23rd, 2023), reflecting limited irrigation volumes (53 mm for the season) and high evaporative demand. In contrast, RDI plots maintained slightly higher VWC due to the greater water application during preharvest phase (37 mm, an increase of 70% over the water applied for the same period in the FRM treatment). In 2024 (Fig. 3-C), soil moisture at 480 m again declined sharply during the preharvest period, coinciding with the delay on the irrigation start (May 17th, 2024) and the increments in the atmospheric water demand. FRM plots consistently showed lower VWC than RDI, and postharvest recovery was only evident under RDI.

At 1030 m, VWC remained consistently higher (40–65%) both years (Fig. 3-B, D). In 2023, heavy rainfalls during spring maintained VWC above 55% early in the season, with moderate declines before harvest for both treatments. On the other hand, in 2024, FRM plots showed sharper preharvest declines of VWC, while RDI had values similar to 50% even after harvest.

Across both years and sites, RDI consistently maintained higher VWC than FRM, with the largest treatment differences observed at 480 m in 2024.

3.3. *Phenology and fruit growth*

Phenological development followed the BBCH scale and was different at each altitude (Figs. 4, 5). From full bloom to harvest, all stages occurred earlier at 480 m than at 1030 m, and with small interannual variation, 3–5 days in advance in 2024 compared to 2023. At 480 m, full bloom occurred on day of year (DOY) 89 in 2023 and DOY 86 in

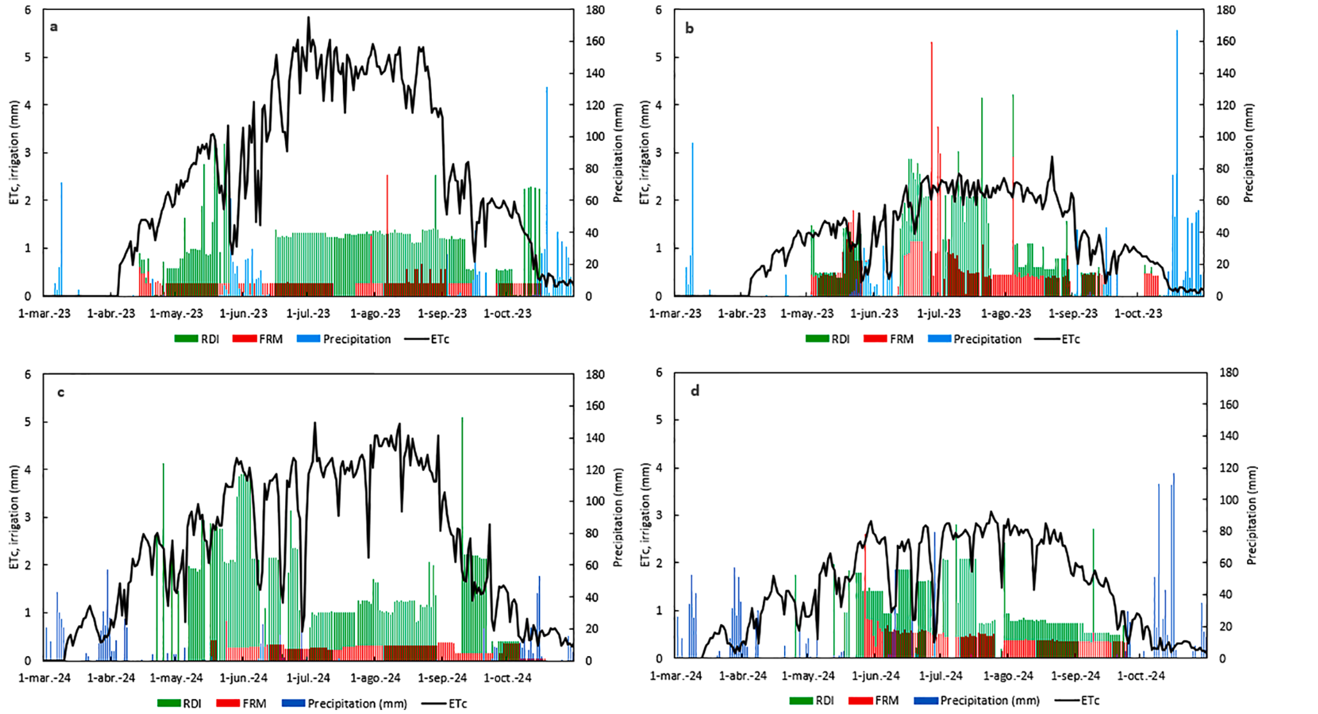

Fig. 2. Daily Irrigation water applied under Farmer's irrigation management (FRM) and Regulated Deficit Irrigation (RDI), reference crop evapotranspiration (ET_c), and precipitation at 480 m (a, c and 1030 m (b, d) altitude orchards during the 2023 (a, b) and 2024 (c, d) irrigation seasons.

2024; seven to ten days earlier than at 1030 m, where it was on DOY 96 both years. Similarly, harvest dates were on DOY 143 and 155 at 480 m, while at 1030 they were 42 and 25 days later for 2023 and 2024, respectively (DOY 185 and 180).

Fruit growth followed a typical double-sigmoid pattern (Fig. 6). Development began earlier at 480 m, but final fruit size was larger at 1030 m. Altitude significantly affected fruit diameter throughout the season ($p < 0.001$). Likewise, irrigation treatments also influenced fruit growth. Thus, for RDI trees, fruit equatorial diameter reached values similar to 27–28 mm (at 480 m) and 29–30 mm (at 1030 m), while for FRM trees, cherry diameters were 25–26 mm (at 480) and 28–29 mm (at 1030). The positive effect of RDI on fruit size was the most pronounced at low altitude (480 m), as confirmed by the significant interaction between altitude and irrigation ($p < 0.001$).

3.4. Trunk and stem water potential. microtensiometers and pressure chamber

Seasonal patterns of stem water potential (Ψ_{stem}) confirmed the combined effects of altitude and irrigation regime (Fig. 7). At 480 m, trees under FRM frequently dropped below –2.0 MPa, while those under RDI maintained values between −1.2 and −1.6 MPa. At 1030 m, Ψ_{stem} values for both treatments were in a similar range and significantly less negative than those measured at lower altitudes (–0.7 to –1.2 MPa). Our results highlight that altitude, on its own and in combination with the irrigation treatment, had a significant effect on the tree water status according to ANOVA.

In 2023 (Fig. 7A), significant differences were observed between irrigation treatments during the period with the highest evaporative demand, from July to September. Trees under FRM at 480 m reached minimum Ψ_{stem} values close to –2.5 MPa, while RDI trees at the same altitude maintained Ψ_{stem} values above –1.8 MPa. At 1030 m, differences between FRM and RDI were mainly observed in midsummer, although Ψ_{stem} values remained above –1.0 MPa. In 2024 (Fig. 7B), the Ψ_{stem} of FRM trees at 480 m sharply declined during preharvest and early postharvest periods, reaching values near –2.2 MPa in August, while RDI trees maintained less negative Ψ_{stem}. At 1030 m, significant differences between treatments were also observed in July and August.

Continuous measurements of trunk water potential (Ψ_{trunk}, Figs. 8 and 9) matched those results provided by Ψ_{stem}, pointing out altitude as the dominant factor. At 480 m, predawn Ψ_{trunk} declined to –0.6 to –1.1 MPa in midsummer, with anomalies during irrigation failures (early September 2024). At 1030 m, values remained less negative (–0.2 to –0.5 MPa). The impact of the irrigation treatments assayed on the Ψ_{trunk} was lower than that caused by the altitude; however, FRM trees showed consistently lower values of Ψ_{trunk} than those trees from RDI at both altitudes (Fig. 9). At 480 m, RDI trees had similar, or slightly less negative, minimum daily values of Ψ_{trunk} than FRM trees but significantly less negative predawn (maximum) values (Fig. 9A). On the other hand, at 1030 m, RDI and FRM trees had similar values of Ψ_{trunk} at predawn, while FRM trees had significantly more negative values at midday (Fig. 9B) and during the afternoon (daily minimum, (Fig. 9C). In general, differences between FRM and RDI trees in Ψ_{trunk} were more pronounced at 1030 m than at 480 m, with more negative values for FRM trees; however, it was also noticed at 480 m, that during the peak evaporative demand period in midsummer, RDI trees maintained slightly less negative values of Ψ_{trunk} than FRM trees.

Diurnal patterns (Fig. 10) showed predawn recovery (–0.3 to –0.5 MPa) followed by midday minima between –2.0 and –2.5 MPa at 480 m, and –1.5 to –1.8 MPa at 1030 m. Ψ_{stem} was consistently more negative than Ψ_{trunk} at midday. A linear relationship between Ψ_{trunk} (microtensiometers) and Ψ_{stem} (pressure chamber) was observed (Fig. 10C). Under RDI, correlation was strong ($R^2 = 0.72$), while under FRM it was weaker ($R^2 = 0.54$). When grouped by altitude, regression slopes were similar (~0.54), but correlations were stronger at 1030 m ($R^2 = 0.82$) than at 480 m ($R^2 = 0.59$).

3.5. Gas exchange Stomatal conductance

Stomatal conductance (gs) showed marked seasonal and interannual variation, strongly influenced by altitude and irrigation strategy (Fig. 11A–B). In 2023 (Fig. 11A), gs values were initially high in June,

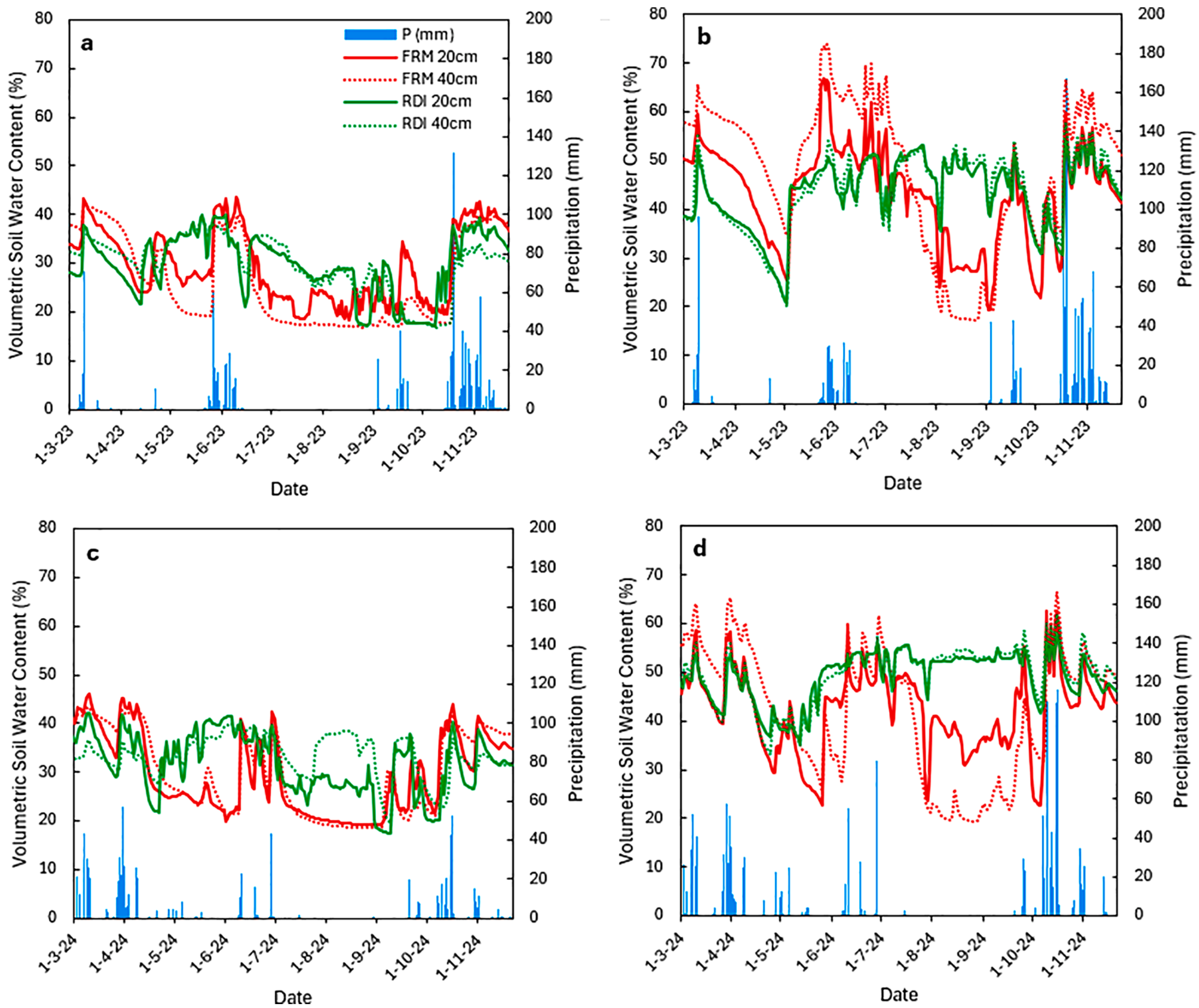

Fig. 3. Seasonal dynamics of volumetric soil water content (VSWC, %) at 20 and 40 cm depth under Farmer's irrigation management (FRM) and Regulated Deficit Irrigation (RDI) in two sweet cherry orchards located at 480 m (a, c) and 1030 m (b, d) a.s.l. in the Jerte Valley (Spain) during the 2023 (a, b) and 2024 (c, c) irrigation seasons. Blue bars represent daily rainfall. Vertical variation reflects differences between preharvest and postharvest phases, with harvest occurring on 23 May 2023 and 3 June 2024 at 480 m, and on 4 July 2023 and 28 June 2024 at 1030 m. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

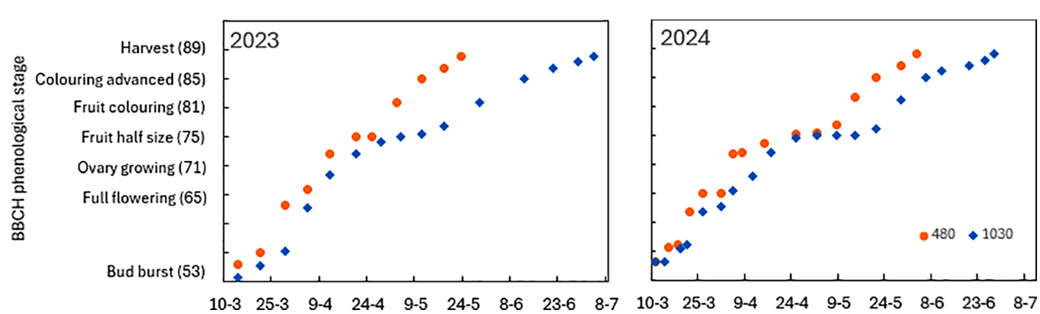

Fig. 4. Phenological development of sweet cherry (*Prunus avium* L., cv. 'Lapins') in two commercial orchards located at 480 m and 1030 m.a.s.l. in the Jerte Valley (Spain) during the 2023 and 2024 growing seasons. Phenological stages were recorded using the extended BBCH scale. Dates represent the calendar day corresponding to the observed phenological stage: Bud burst (Stage 53), full flowering (Stage 65), Ovary growing (Stage 71) Fruit about half final size (Stage 75), Beginning of fruit coloring (Stage 81), Coloring advanced (Stage 85), and fruit ripe for harvesting (Stage 89). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

exceeding 600 mmol m^{-2} s^{-1} at 480 m and approaching 1000 mmol m^{-2} s^{-1} at 1030 m, indicating a favorable water status. From July onwards, gs drop at both sites, particularly at 480 m, where FRM trees reached minimum values below 100 mmol m^{-2} s^{-1} in late August. In contrast, trees at 1030 m maintained significantly higher gs (>300 mmol m^{-2} s^{-1}), reflecting the mitigating effect of altitude on water stress. ANOVA confirmed significant altitude effects from July to September ($p < 0.05$). Differences between irrigation treatments were also evident at both altitudes. RDI trees consistently exhibited higher gs than FRM, with significant differences on several dates ($p < 0.05$), especially during August

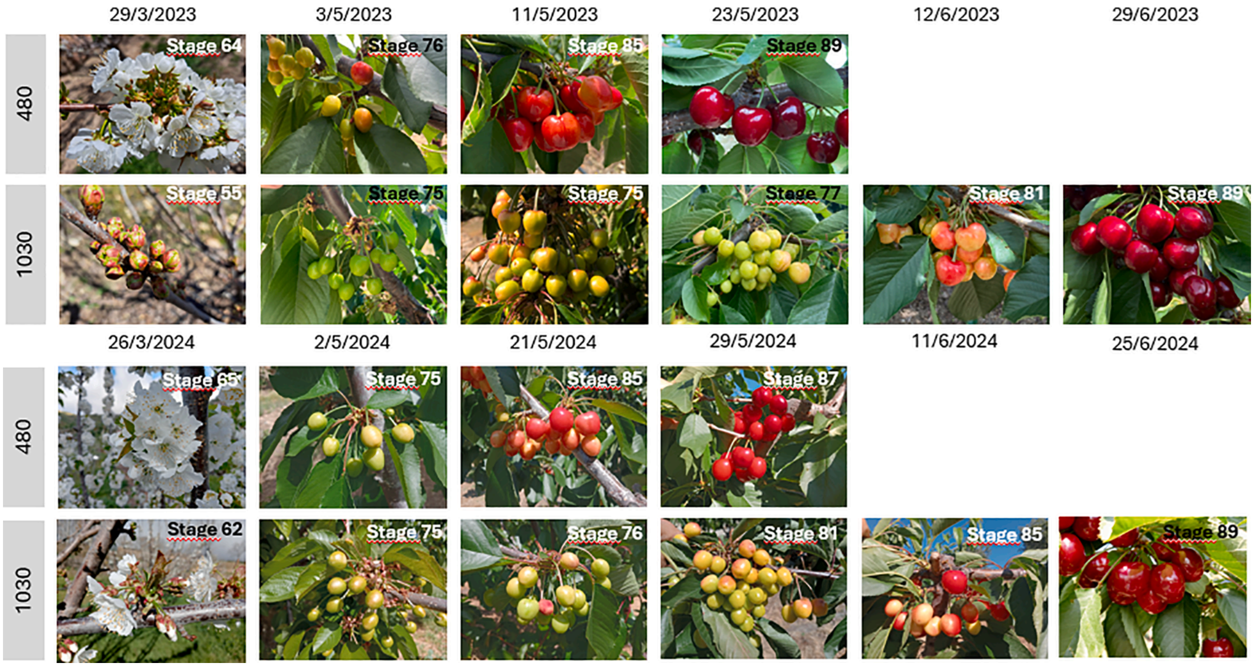

Fig. 5. BBCH stages observed from flowering to maduration in 2023 and 2024 in both plots (480 and 1030 m a.s.l.). Photographic sequence of BBCH phenological stages (62–89) of sweet cherry (Prunus avium L. cv. 'Lapins') recorded during the 2023–2024 growing season at two altitudes (480 and 1030 m a.s.l.) in the Jerte Valley, Spain. Dates indicate the day of year corresponding to each observed stage.

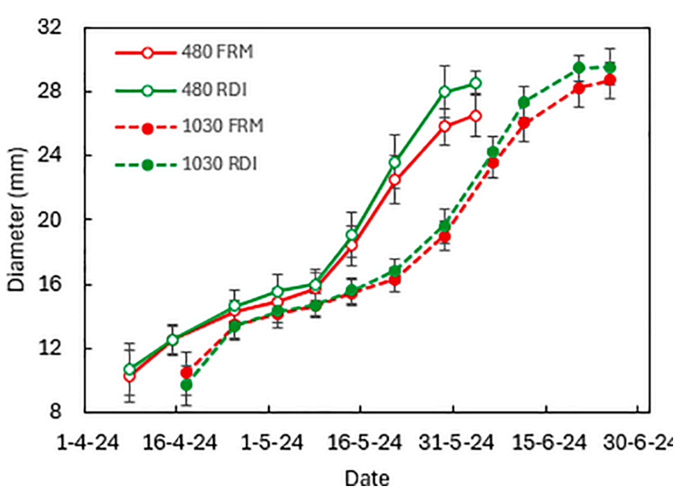

Fig. 6. Fruit growth dynamics (equatorial diameter) of sweet cherry (*Prunus avium* L. cv. 'Lapins') under Regulated Deficit Irrigation (RDI) and Farmer's irrigation management (FRM) at two altitudes (480 and 1030 m a.s.l.) in the Jerte Valley during the 2024 growing season. Values are means ± standard deviation (n = 30 fruits per treatment).

and September.

In 2024 (Fig. 11B), gs values were generally lower than in the previous year, with maximums around 600–650 mmol m^{-2} s^{-1} in July at both altitudes. Significant differences between altitudes were detected in late summer (August–September), with trees at 1030 m maintaining higher gs than those at 480 m ($p < 0.05$). Irrigation strategy continued to play a role, with RDI trees showing significantly higher gs than FRM in August ($p < 0.05$), particularly at 480 m.

Overall, the results demonstrate that altitude exerted a strong influence on stomatal regulation, with higher gs maintained at 1030 m throughout the season. Irrigation strategy modulated the intensity of water stress within each site.

A significant relationship was observed between stem water potential (Ψ_{stem}) and stomatal conductance (gs) (Fig. 12). A linear model ($\Psi_{stem} = 0.0017 \cdot gs - 1.968$) explained 63% of the variability ($R^2 = 0.63$, RMSE = 0.25, $p < 0.001$). However, the logarithmic model ($\Psi_{stem} = 0.602 \cdot \ln(gs) - 4.776$ provided a better fit, accounting for 73% of the variability ($R^2 = 0.73$, RMSE = 0.24, $p < 0.001$).

3.6. Vegetative growth

Pruning dry weight showed high variability among individual trees, ranging from 2.05 to 4.09 kg $tree^{-1}$ across years, altitudes, and irrigation treatments. Although some trees at 480 m (both FRM and RDI in 2023) and at 1030 m (in 2024) exhibited relatively higher values, no consistent patterns were observed (Table 1). Two-way ANOVA revealed no significant effects of irrigation regime, altitude, or their interaction ($p > 0.05$), as confirmed by Tukey's HSD test. These results suggest that pruning biomass was not exclusively influenced by water management or site altitude, and that the variability was primarily attributable to tree-to-tree differences rather than experimental factors.

Accumulated shoot growth differed significantly between altitudes in both years, with trees at 1030 m consistently showing greater elongation than those at 480 m (Table 1). In 2023, irrigation treatment had no significant effect on shoot growth, neither at 480 m nor at 1030 m. However, in 2024, at 480 m, trees under RDI had longer shoots than those from FRM. On the other hand, at 1030 m, no differences were observed among treatments. ANOVA confirmed altitude as the main source of variation ($p < 0.001$) for shoot growth, followed by the irrigation strategy ($p < 0.05$).

Annual trunk cross-sectional area (TCSA) growth showed high variability and no significant main effects of altitude, while the effect of irrigation treatment was marginal ($p \approx 0.08$). The Altitude × Irrigation interaction approached significance ($p \approx 0.09$), suggesting that trunk growth response to irrigation varied across sites (altitudes) (Table 1). Similar to the values reported for the dry mass of pruning wood, the high variability of the TCSA growth should be interpreted within the framework of the differences among individual plots, with younger trees of smaller trunk cross-sectional area in the higher-altitude orchard compared to the lower-altitude orchard. Estimated marginal means

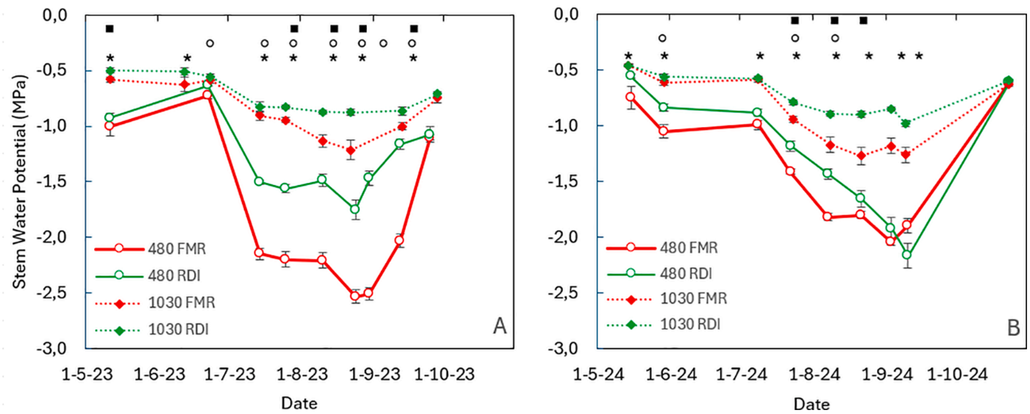

Fig. 7. Seasonal dynamics of stem water potential (Ψ_{stem}, MPa) in sweet cherry trees at two altitudes (480 and 1030 m a.s.l.) under two irrigation strategies: Farmer's irrigation management (FRM) and regulated deficit irrigation (RDI) during 2023 (A) and 2024 (B). Values are means ± standard error ($n = 10$). Symbols above the curves indicate significant effects detected by ANOVA at each sampling date: ° and ■ indicate significant differences between 480 FRM vs. 480 RDI and 1030 FRM vs. 1030 RDI, respectively ($p < 0.05$); * indicates a significant altitude effect ($p < 0.05$).

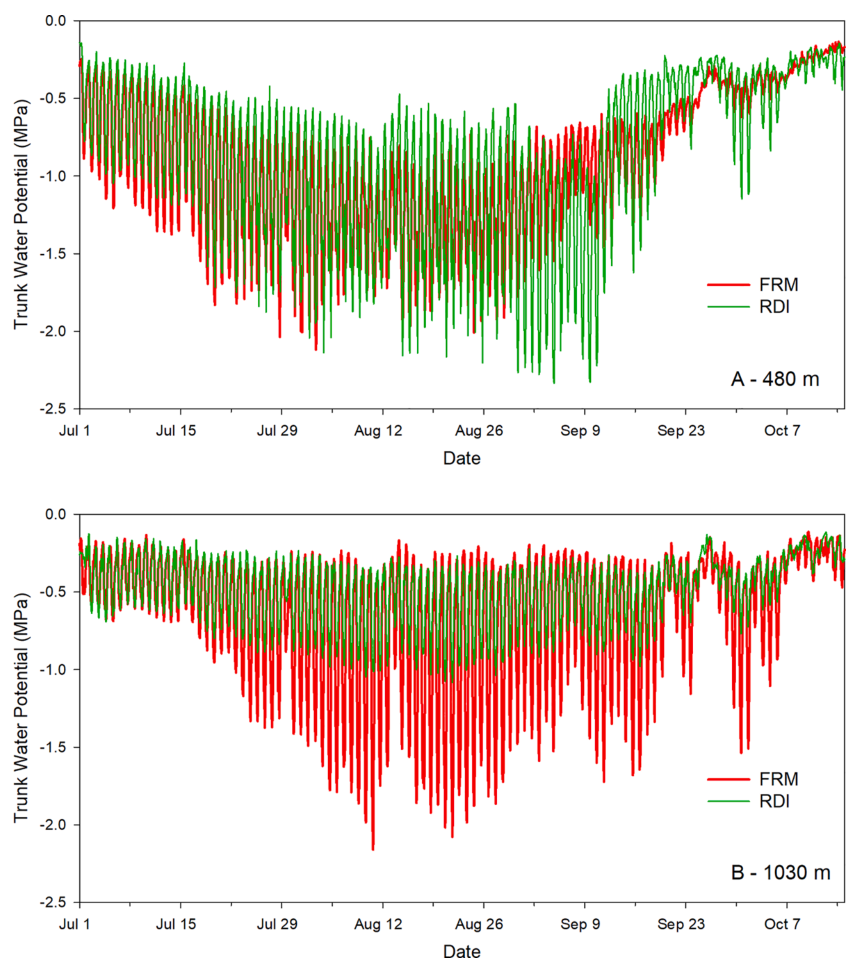

Fig. 8. Hourly trunk water potential (Ψ_{trunk}, MPa) continuously monitored with microtensiometers under Farmer's irrigation management (FRM, red) and regulated deficit irrigation (RDI, green) from July 1 to October 30, 2024, in sweet cherry orchards located at low altitude (480 m, A) and high altitude (1030 m, B).(For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

indicated that, in general, trees at 1030 m exhibited greater increases in TCSA than those at 480 m, and that RDI tended to promote greater growth than FRM, although the pattern was not consistent across years. In 2023, RDI trees grew more than FRM trees at both altitudes. However, in 2024, the effect was inconsistent: at 480 m, FRM trees showed slightly higher TCSA increases than RDI trees, while at 1030 m, RDI maintained its advantage. Taken together, these results indicate that TCSA growth is less sensitive to irrigation strategy than shoot elongation but tends to benefit from greater water availability under specific site and seasonal conditions, particularly at high altitude.

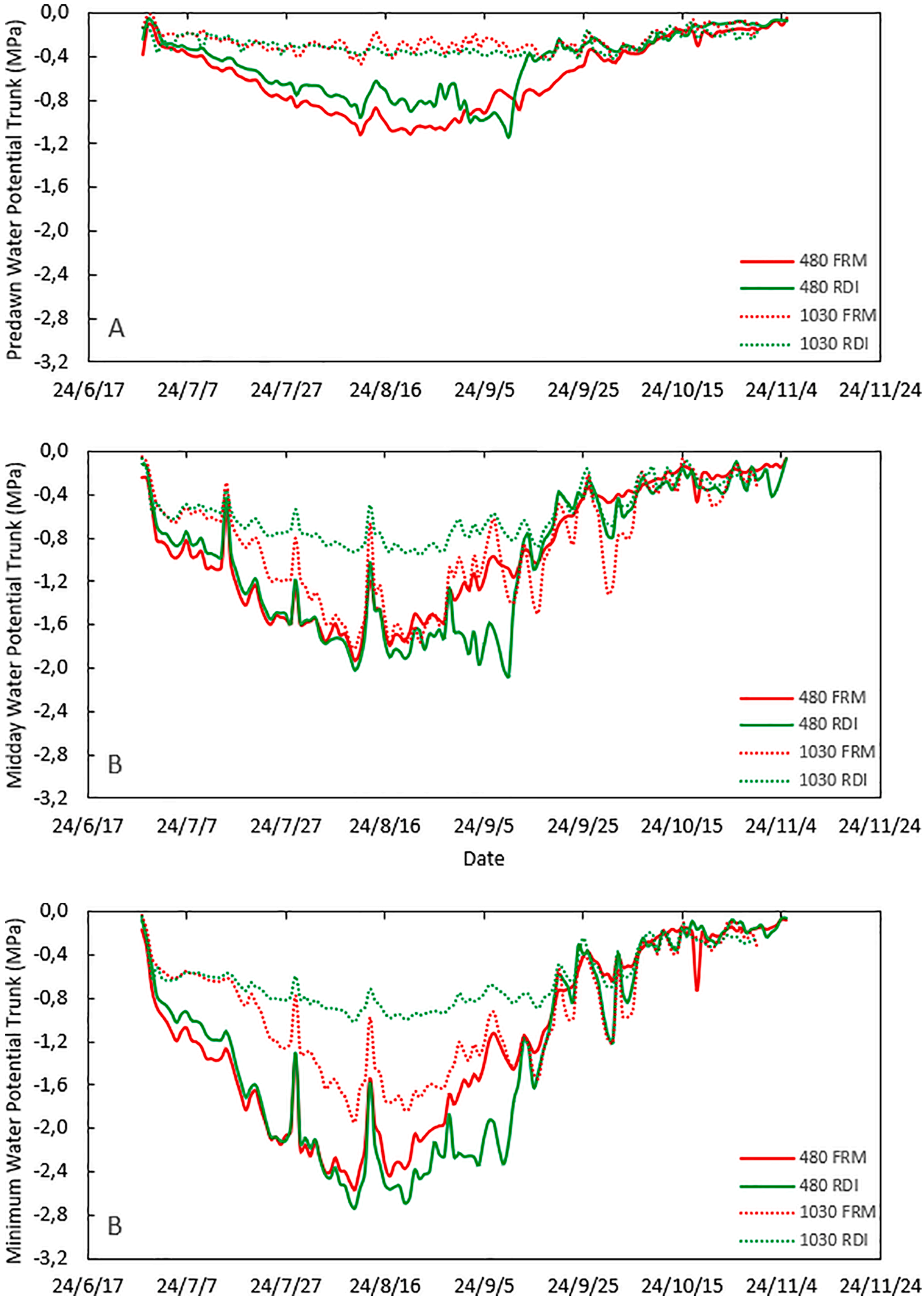

Fig. 9. Seasonal dynamics of trunk water potential under different irrigation treatments. (A) Predawn trunk water potential, (B) midday trunk water potential, and (C) minimum trunk water potential in plants subjected to Farmer's irrigation management (FRM) and regulated deficit irrigation (RDI) in sweet cherry orchards located at low altitude (480 m) and high altitude (1030 m). Represents the daily mean of measurements collected during the 2024 growing season.

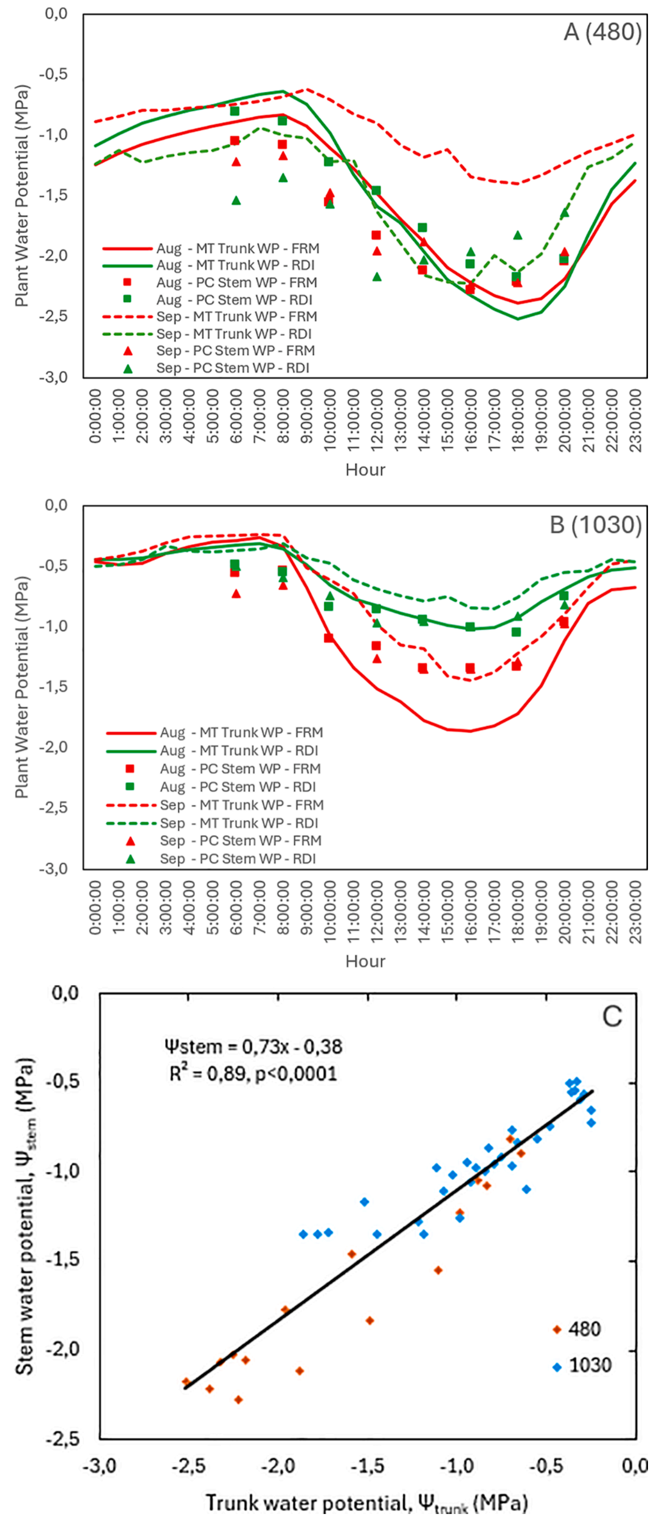

Fig. 10. Diurnal dynamics of trunk water potential (Ψ_{trunk}, MPa) measured with microtensiometers (MT, solid and dashed lines) and stem water potential (Ψ_{stem}, MPa) measured with a pressure chamber (PC, symbols) under two irrigation strategies (FRM: farmer's irrigation management; RDI: regulated deficit irrigation) at low altitude (480 m, B) and high altitude (1030 m, A). Measurements were conducted during two consecutive heat-stress days in August (solid lines, filled squares and circles) and September (dashed lines, open squares and circles) of 2024. C) Relationship between Ψ_{trunk} and Ψ_{stem} during two hot days at different altitudes. Each point represents paired measurements taken at the same time of day.

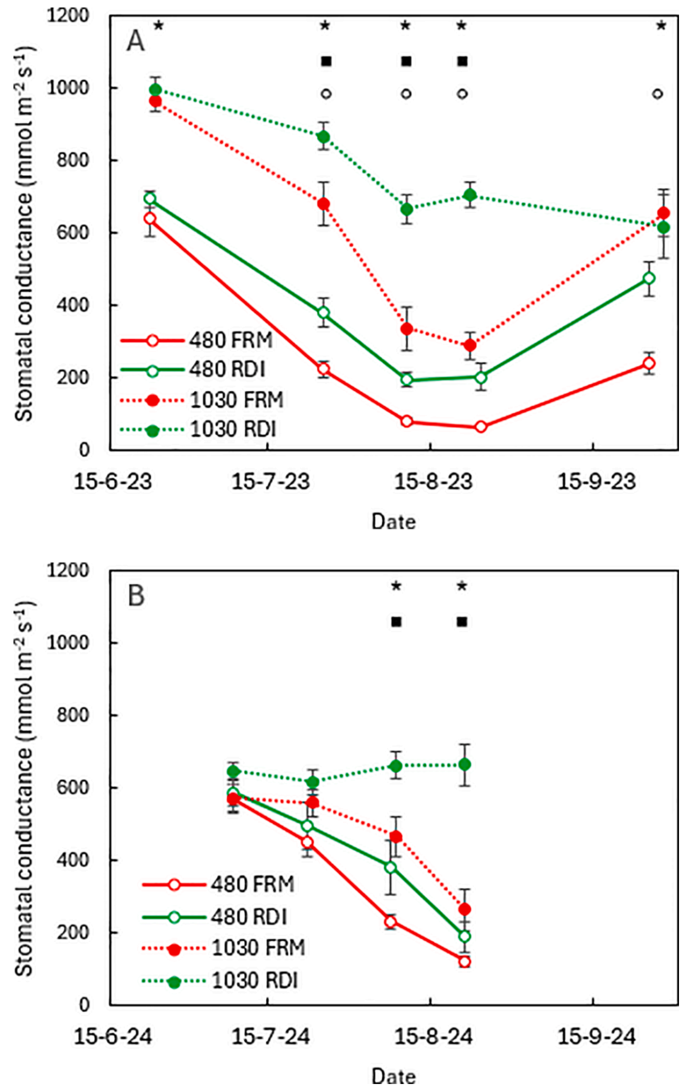

Fig. 11. Seasonal evolution of stomatal conductance (gs, mmol m^{-2} s^{-1}) in sweet cherry trees grown under two irrigation strategies —Farmer's irrigation management (FRM) and regulated deficit irrigation (RDI)— at two altitudes: 480 and 1030 m a.s.l., during the 2023 (A) and 2024 (B) seasons. Values represent means ± error deviation ($n = 10$). Symbols above the curves indicate significant effects detected by ANOVA at each sampling date: ° and ▪ denote significant differences between FRM and RDI at 480 m and 1030 m, respectively ($p < 0.05$); * indicates a significant altitude effect ($p < 0.05$).

3.7. *Yield and fruit quality*

Fruit production per tree showed pronounced variability, both between altitudes and among individual trees within the same irrigation treatments. Despite a consistent altitudinal trend, with trees at 1030 m generally exhibiting higher productivity than those at 480 m, substantial dispersion in yield was observed within each treatment at both sites. Across the two seasons, yield at 1030 m ranged from 15 to 36 kg tree^{-1}, whereas at 480 m it varied between 13 and 32 kg tree^{-1}, reflecting considerable intra-treatment variability. Yield efficiency, expressed as kg of fruit per cm^2 of trunk cross-sectional area (TCSA), was significantly greater at 1030 m (0.26–0.35 kg cm^{-2}) than at 480 m (0.07–0.15 kg cm^{-2}). However, this difference should be interpreted in the context of tree age, as yield efficiency is inherently influenced by tree size. Trees located at the higher altitude (1030 m) were younger and consequently had smaller TCSA, which contributes to higher efficiency values. Therefore, the observed differences in yield efficiency are likely attributable, at least in part, to age-related structural differences rather than

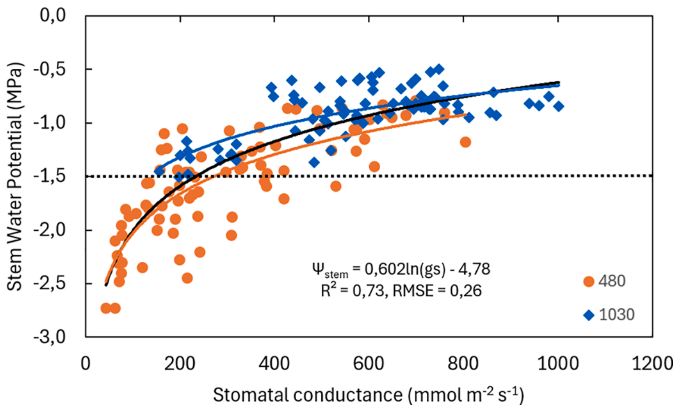

Fig. 12. Relationship between gs Ψ_{stem} considering both irrigation strategies and altitudes. The logarithmic model provided the best fit ($\Psi_{stem} = 0.602 \cdot \ln(gs) - 4.78$), explaining 73% of the variability ($R^2 = 0.73$, RMSE = 0.26, $p < 0.001$). Each point represents the mean of simultaneous measurements of gs and Ψ_{stem}.

exclusively to environmental or treatment effects. In contrast, differences among irrigation strategies were less consistent. No significant differences in yield or yield efficiency were detected among irrigation treatments for RDI and FRM trees (Table 2).

Fruit diameter parameters, including equatorial diameter and fresh weight, were significantly affected by altitude, irrigation regime, and their interaction. Across seasons, fruit diameter averaged 25–27 mm at 480 m and 28–30 mm at 1030 m, while fruit weight ranged from 8 to 10 g at 480 m to 11–14 g at 1030 m. RDI consistently improved both diameter and weight relative to FRM, particularly at 480 m. Thus, in 2024, fruit unitary mass increased from 8.4 g under FRM to 9.8 g under RDI at 480 m, and from 11.4 g (FRM) to 12.6 g (RDI) at 1030 m (see supplementary Table S1)

The distribution of commercial fruit sizes was also strongly influenced by altitude, irrigation strategy, and year. High-altitude plots (1030 m) produced a greater proportion of large-caliber fruits (>30 mm), reaching up to 59.9% in 2023 under RDI. Intermediate sizes (26–28 mm) predominated at 480 m, especially under RDI, with proportions exceeding 59% in 2025. The highest percentage of small fruits (<24 mm) was recorded in 2024 under FRM at 480 m (34.8%), indicating greater sensitivity to water stress under warmer conditions (Fig. 13).

4. Discussion

4.1. Altitude and vulnerability of mountain cherry orchards

The altitudinal gradient between 480 and 1030 m a.s.l. generated distinct microclimates that strongly influenced crop development. At 480 m (low altitude), hot and dry conditions promoted a faster accumulation of growing degree days, which led to a rapid fruit development compared to the site at 1030 m (high altitude), warm and slightly wet, where the phenological stages were always reached later. This pattern is consistent with previous reports in Mediterranean fruit crops, where altitude delays phenological stages and reduces evaporative demand (Usenik and Štampar, 2011; Wenden et al., 2016). Phenological stages were delayed by approximately 7–12 days at bloom and 30–40 days a harvest at the higher site, consistent with temperature-driven responses in *Prunus* spp. (Inouye and Wielgolaski, 2025; Wenden et al., 2016; Blanco et al., 2021).

Overall, altitude buffers atmospheric water demand by lowering temperature and increasing relative humidity, thereby reducing evaporative gradients (Körner, 2007). This microclimatic modulation has direct implications for water requirements; while sweet cherry is a

Table 1

Influence of irrigation treatment on the vegetative growth. Dry weight of pruning wood (kg tree^{-1}), accumulated shoot growth (cm), and annual trunk cross-sectional area (TCSA, cm^2) of sweet cherry trees as affected by altitude (480 and 1030 m), irrigation regime (FRM, RDI), and year (2023–2024). Values are means ± standard error ($n = 5$). Different letters within a column of shoot growth indicate significant differences among Altitude × Irrigation combinations according to Tukey's HSD test ($p < 0.05$).

		Dry weight pruning wood kg tree^{-1}		Accumulated shoot growth (cM)		Trunk Cross Section Area (cm^2)	
		2023	2024	2023	2024	2023	2024
480	FRM	4,09 ± 1,44	2,51 ± 0,81	27,31 ± 2,87b	38,45 ± 3,71b	0,13 ± 0,03	0,11 ± 0,03
	RDI	3,34 ± 2,39	2,05 ± 1,36	27,08 ± 2,87b	49,74 ± 3,71a	0,16 ± 0,03	0,09 ± 0,03
1030	FRM	2,48 ± 1,70	3,49 ± 2,17	53,79 ± 2,87a	46,50 ± 3,77a	0,18 ± 0,03	0,15 ± 0,03
	RDI	2,86 ± 2,03	2,78 ± 1,77	60,15 ± 2,87a	47,70 ± 3,71a	0,20 ± 0,03	0,20 ± 0,03
	Statistical Analysis						
ANOVA	Altitude (A)			n.s.		n.s.	
	Irrigation (I)			n.s.		n.s.	
	A*I			n.s.		n.s.	

Each value in the mean of the replicates. Different letters within a column indicate significant differences among Altitude x Irrigation combinations according to Tukey multiple range test ($P < 0.05$). *, ** and *** indicate significance at $P \leq 0.05$, 0.01 and 0.001, respectively; n.s., not significant.

Table 2

Productive performance of sweet cherry cv. 'Lapins' under two irrigation strategies (farmer-managed irrigation, FRM; regulated deficit irrigation, RDI) and two altitudes (480 and 1030 m a.s.l.) in the Jerte Valley, Spain, during 2023–2025. Values are expressed as mean ± standard deviation (SD) for yield efficiency (kg cm^{-2} TCSA), yield per tree (kg), fruit diameter (mm), and fruit weight (g). Different letters within the same year indicate significant differences among treatment combinations according to Tukey's HSD test ($p < 0.05$).

		Yield per tree (kg)			Yield efficiency (kg cm^{-2})			Equatorial Diameter (mm)			Fruit weight (g)		
		2023	2024	2025	2023	2024	2025	2023	2024	2025	2023	2024	2025
480	FRM	14.4 ± 9.9a	32.0 ± 10.7a	30.4 ± 8.2a	0.08 ± 0.06a	0.15 ± 0.05a	0.10 ± 0.08a	25.9 ± 1.8a	25.2 ± 1.7a	25.6 ± 1.5a	8.8 ± 1.5a	8.4 ± 1.5a	8.7 ± 1.2a
480	RDI	13.0 ± 8.1a	21.3 ± 9.3a	26.3 ± 14.6a	0.07 ± 0.05a	0.10 ± 0.04a	0.11 ± 0.04a	26.4 ± 1.8a	26.8 ± 2.0b	26.2 ± 1.3b	9.2 ± 1.6a	9.8 ± 1.9b	9.7 ± 1.2b
1030	FRM	30.3 ± 14.8b	36.1 ± 19.2b	30.9 ± 21.4b	0.35 ± 0.21b	0.34 ± 0.16b	0.26 ± 0.23b	29.1 ± 1.8b	28.5 ± 1.7c	28.2 ± 1.9c	13.2 ± 1.9b	11.4 ± 1.6c	11.0 ± 1.8c
1030	RDI	22.1 ± 7.9b	17.3 ± 2.4a	14.6 ± 7.0a	0.21 ± 0.13b	0.15 ± 0.12a	0.08 ± 0.02a	30.3 ± 2.0c	29.6 ± 1.6d	29.4 ± 1.3d	13.7 ± 2.0b	12.6 ± 1.7d	12.0 ± 1.3d

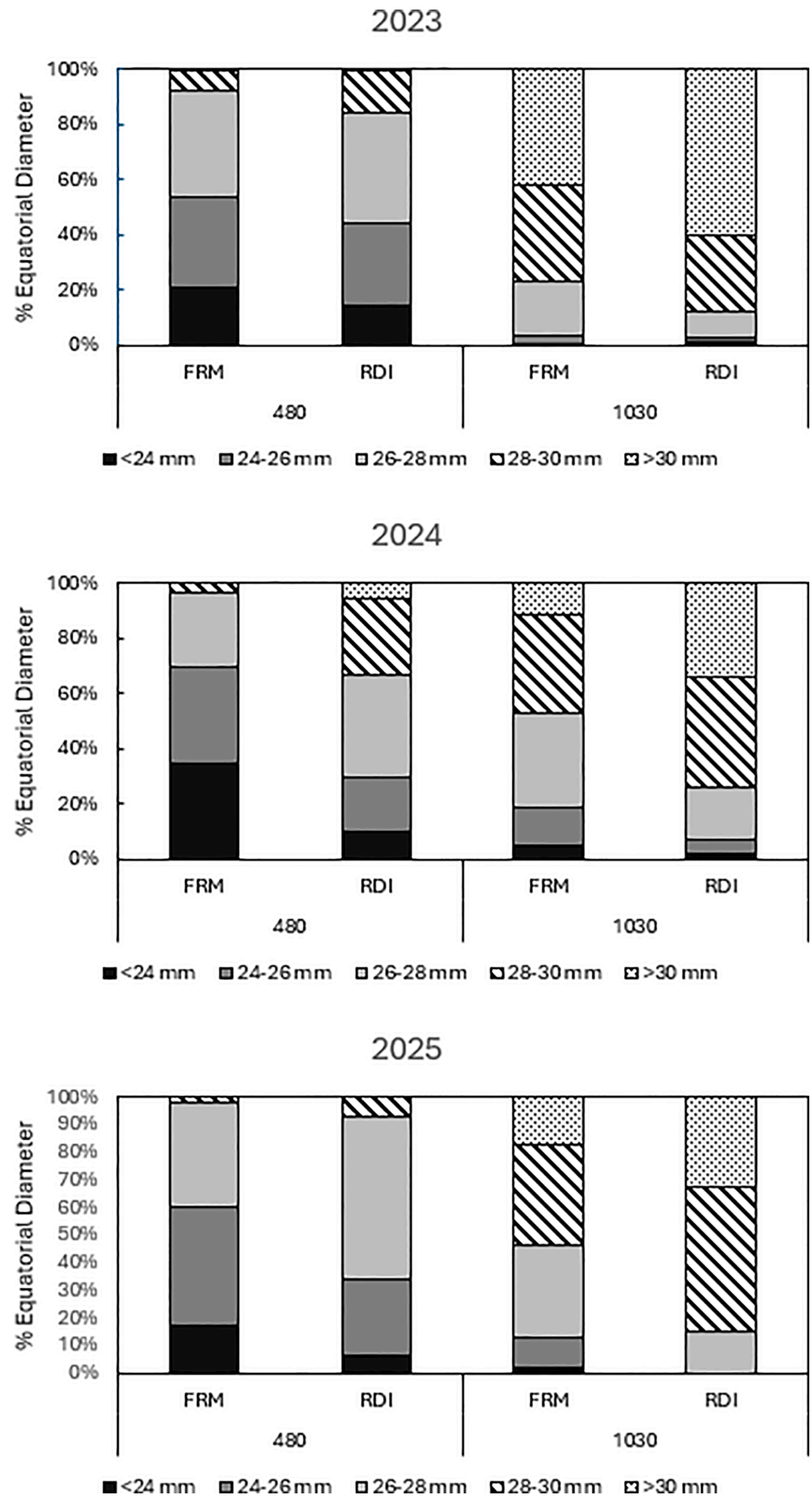

Fig. 13. Fruit size distribution at harvest (2023–2025) of 'Lapins' sweet cherry trees affected by altitude (480 and 1030 m) and irrigation treatment: Farmer's irrigation management (**FRM**) and regulated deficit irrigation (**RDI**). Each distribution is the mean of 25 fruit per tree, and 5 trees per treatment.

high-demand crop (ET_o ~6–7 mm d^{-1}; Blanco et al., 2019), the degree of irrigation dependence and risk of water stress differ substantially between lowland and highland mountain orchards. This effect was evident during the 2024 postharvest for FRM trees, when FRM trees at 480 m were irrigated with similar water volumes than those at 1030 m (30 mm at 480 m a.s.l. and 25 mm at 1030 mm) despite doubling the ETc for the same period (359 and 162 mm of ETc at 480 and 1030 m a.s.l., respectively). Growers' irrigation scheduling in the region follows a similar pattern, independent of altitude; consequently, tree water status is highly dependent on environmental conditions, resulting in a wide range of water deficits that match orchard altitude. The lower the altitude of the plot, the higher the water deficit to which the tree is subjected. These results highlight the susceptibility to water deficit that farmers at low altitudes in the valley are facing and how the volume of water available for irrigation under those conditions is drastically below tree water needs, which negatively impacts tree water status and fruit quality, which in the end, penalizes farmers' revenue. Conditions currently observed at low altitude—reduced vegetative growth, smaller fruit, and more negative water status—may foreshadow future scenarios at higher elevations under climate change. Projections indicate rising temperatures and increased drought intensity in Mediterranean regions (IPCC, 2021), which could compromise the sustainability of mountain cherry systems that depend on irregular water resources. Recent studies predict that suitable cherry-growing areas will progressively shift to higher altitudes (Lv et al., 2025). Thus, while mountain orchards have been considered more resilient, their vulnerability is likely to increase.

The need of water allocation policies from a physical and ecophysiological (considering tree water requirements) point of view, but also social, is important in regions such as the Jerte Valley with smallholder farmers where while the accumulated rainfall in the year exceeds sweet cherry crop evapotranspiration for a season, as it is unevenly distributed, if there is no infrastructure to store that water, water deficit will hinder cherry production in the area under future climate change scenarios. Previous studies on other regions have called attention to the importance of water allocation practices and investing in proper infrastructure to maintain smallholder farmers (Mul et al., 2011). Take as an example the Pajaro Valley in California, which, like the Jerte Valley, is vulnerable to climate change and is already facing water scarcity problems, and is foreseen to reduce its total agricultural land by 15% in the next 25 years if more efficient land- and water-use planning strategies are not adopted (Garza-Diaz et al., 2019).

4.2. Irrigation strategies: regulated deficit irrigation

Regulated deficit irrigation demonstrated greater adaptability to climatic variability than Farmer`s Irrigation Management, with daily irrigation volumes peaking at ~3.38 mm compared to ~0.28 mm in FRM (Fig. 2). These differences in the water applied among treatments maintained higher soil water content (Fig. 3) in the RDI treatment compared to FRM, causing RDI trees to have less negative water potentials during critical phenological stages (Fig. 7). Thus, FRM trees, under the same environmental conditions than RDI trees, failed to adjust to climatic variability, resulting in more frequent water stress episodes and reduced physiological performance. For sweet cherries, deficit irrigation during mid-, late postharvest has been reported as a successful strategy to manage irrigation in scenarios of water scarcity without affecting fruit quality (Marsal et al., 2010; Nieto et al., 2017; Blanco et al., 2019; Houghton et al., 2023). In this sense, all these studies agree on the need to measure tree water status in order to quantify the impact of deficit irrigation on tree water status. A threshold value of midday stem water potential in the range between −1.3 and −1.5 MPa has been proposed as a limit that should not be exceeded to avoid any penalties on next year's tree responses (Marsal et al., 2010; Blanco et al., 2019). In our experiment, the proposed threshold value was not surpassed by any treatment at 1030 m; however, at 480 m, FRM treatment consistently had values of Ψ_{stem} between −1.5 and −2.5 MPa both years of study, while RDI in 2023 had less negative values, above −1.7 MPa, but in 2024, as a result of an irrigation withholding in the RDI treatment, Ψ_{stem} fell below −2.0 MPa in one measurement. Values of Ψ_{stem} similar to −2.5 MPa, as those measured in the FRM trees at 480 m, have been reported for young 'Lapins' sweet cherry trees as a threshold value for severe water deficit that dramatically restricted vegetative growth and promoted leaf defoliation (Blaya-Ros et al., 2021). It was not noted that the RDI strategy significantly impacted tree yield compared to FRM; however, the improvement of the tree water status observed in the trees from the RDI treatment increased fruit size, particularly at 480 m, when the evaporative demand was highest (Fig. 6, 13 and Table 2). Enhancing fruit size might have a positive impact on growers' revenue as cherry diameter is considered a main factor of cherry pricing (Ladner et al., 2008; Jansen et al., 2025).

4.3. Tree water status. water potential and stomatal regulation

Plant water status reflected the impact of the contrasting evaporative demand of the two sites considered and the irrigation strategies assayed. Stem (Ψ_{stem}) and trunk (Ψ_{trunk}) water potentials were consistently more negative at 480 m than at 1030 m (Figs. 7–10), indicating the impact of the altitude (higher VPD (Fig. 1) and greater soil water availability (Fig. 3)) on tree water status, evidencing stronger plant–atmosphere coupling. The rapid decline of Ψ_{stem} and Ψ_{trunk} observed when sweet cherry trees are under soil water restrictions and high atmospheric water demand confirmed the extremely anisohydric character of sweet cherry trees reported by Blaya-Ros et al. (2021). Anisohydric tree species, such as cherry trees, show a low conservative gas exchange and keep their stomata open under high evaporative demand to maximize photosynthesis, which leads to a significant drop of Ψ_{stem} (Blanco-Cipollone et al., 2017).

As observed for Ψ_{stem} and Ψ_{trunk}, the seasonal evolution of gs was affected mainly by altitude, with consistently lower gs values for trees at low altitude (480 m), highly dependent on VPD, compared to those at high altitude (1030 m), but also by the irrigation strategies assayed (Fig. 11). From an ecophysiological perspective, high VPD at low altitude forces early stomatal closure, restricting carbon assimilation and intensifying drought stress. Conversely, lower VPD at high altitude broadens the operational range for stomatal regulation, sustaining photosynthesis and stabilizing water status. These insights underscore the need to incorporate VPD into irrigation scheduling and to define dynamic thresholds for Ψ_{stem} or Ψ_{trunk} that reflect site-specific atmospheric conditions (Fereres and Soriano, 2007; Blanco et al., 2018).

The physiological relationships calculated confirmed the strong relationship between gs and Ψ_{stem} and their differential relationship depending on the altitude (Fig. 12). This indicates that less negative Ψ_{stem} values were consistently associated with higher gs, reflecting the strong coupling between tree water status and stomatal regulation. The superior performance of the logarithmic model suggests a nonlinear physiological response, with saturation at higher gs values (Fig. 12). The observed relationships are consistent with the non-linear stomatal responses reported in vineyards and other fruit trees (Girona et al., 2006; Intrigliolo and Castel, 2010). Under high VPD conditions at low altitude, midday stomatal closure was more pronounced, resulting in reduced g_s and accentuated water deficits. These results are in line with findings in woody perennials exposed to atmospheric stress (Grossiord et al., 2020; López et al., 2021). At 1030 m, for Ψ_{stem} values of −0.8 MPa, gs ranged between 400 and 1000 mmol m^{-2} s^{-1} depending on the VPD. At that altitude, values of Ψ_{stem} below −0.8 MPa were related to a decrease in the gs values, until values close to 200 mmol m^{-2} s^{-1} at −1.5 MPa. At 480 m, the Ψ_{stem} related to the same range of gs values (400–1000 mmol m^{-2} s^{-1}) was −1.2 MPa, and gs slowly decreased from 400 to 200 mmol m^{-2} s^{-1} when Ψ_{stem} fall to −1.5 MPa. From that point on, gs drastically decreased until values close to a total stomata closure when Ψ_{stem} was below −2.5 MPa. These results showed that a unique Ψ_{stem} threshold value might not be suitable for managing irrigation in both sites (low and high altitude), as it would imply a differential physiological response in the trees. Thus, a Ψ_{stem} threshold value between −1.3 and −1.5 MPa, similar to those proposed in previous works for managing postharvest deficit irrigation in sweet cherry trees (Marsal et al., 2010; Nieto et al., 2017; Blanco et al., 2019), would be appropriate as a limit to avoid severely penalizing the physiological response of the trees at low altitudes but too negative for those sweet cherry trees at high altitudes. The differences found in the tree water status of the sweet cherry trees depending on the altitude bring out the high vulnerability of the agricultural systems in mountainous regions such as the Jerte Valley to rises in atmospheric water demand and water scarcity.

4.4. Microtensiometers. continuous monitoring of the trunk water potential

The strong correlation observed between Ψ_{trunk} measured by microtensiometers and Ψ_{stem} determined with a pressure chamber ($R^2 \approx 0.72$; Fig. 10c) confirms the robustness of this technology for real-time assessment of tree water status and irrigation management in sweet cherry. A major strength of microtensiometers lies in their strong relationship with midday stem water potential, which remains the reference indicator for plant water status and irrigation scheduling in fruit trees (McCutchan and Shackel, 1992; Naor, 2000; Blanco et al., 2018). Their capacity to provide continuous, automated measurements enables high temporal resolution monitoring, facilitating the detection of rapid fluctuations in plant water status and improving the precision of regulated deficit irrigation strategies. To our knowledge, this study represents the first demonstration of the suitability of microtensiometers for continuous monitoring of trunk water potential in commercial cherry orchards. These findings are consistent with previous validations in other woody perennial crops, including apple, pear, grapevine, and nectarine (Blanco and Kalcsits, 2021, 2023; Pagay, 2022; Conesa et al., 2023), further supporting their cross-species applicability.

In this regard, microtensiometers showed high reliability under moderate water deficit conditions, such as those imposed by RDI, where plant water status is the primary driver of variability. Under severe atmospheric demand (high VPD) or rapidly changing environmental conditions, reliability can be classified as moderate, as some discrepancies in absolute values may occur. These discrepancies are likely associated with limitations at the sensor–xylem interface, including imperfect hydraulic contact, stem radial growth over time, and wound-induced anatomical or hydraulic changes following installation (Blanco and Kalcsits, 2021; Lakso et al., 2022). Such factors may compromise long-term measurement stability and absolute accuracy. Therefore, periodic validation against pressure chamber measurements (Ψ_{stem}) is necessary, together with recalibration or, when required, sensor reinstallation. These maintenance requirements represent practical constraints that may limit large-scale adoption, even though the technology itself is user-friendly once properly installed and calibrated.

Continuous monitoring of Ψ_{trunk} using microtensiometers provided valuable high-resolution data on diurnal and seasonal water status. Current evidence suggests that derived Ψ_{trunk} metrics—such as the daily maximum (predawn), daily minimum, or diurnal fluctuation ranges—may be especially informative for irrigation scheduling and link well to growth or sap flow responses (Conesa et al., 2023; Blanco and Kalcsits, 2024). According to our results, it would be recommended to use the daily maximum value of Ψ_{trunk} (predawn) as a reference tree water status indicator for trees under severe water deficit in high water-demanding conditions, such as those recorded at 480 m, as a key factor to measure if the tree water status recovers during the night. On the other hand, for a fast detection of slight water deficit, and for those trees located in high-altitude sites, it was better to use the midday or daily minimum Ψ_{trunk}.

4.5. Vegetative growth, yield and fruit quality

Vegetative growth, particularly shoot elongation, was greater at 1030 m than at 480 m, which matches tree water status (Table 1), reflecting how trees at low altitude, under severe water deficit, have lower shoot growth than those trees at a higher altitude with a better water status. Decreases in shoot growth have been reported as a primary and early response to water deficit in plants (Hsiao, 1973; Chaves and Oliveira, 2004). Other vegetative growth parameters, including the annual increments in trunk cross-sectional area (TCSA) and pruning wood production, were less responsive to the experimental factors. Neither altitude nor irrigation treatments had a significant effect on these variables. Although both orchards represent mature, terraced orchard systems and they were considered agronomically comparable and similarly productive, it is important to acknowledge that the trees at 480 m were older, whereas those at 1030 m were younger. This age difference has been taken into account when interpreting vegetative growth responses, particularly those that consider secondary growth, as the tree developmental stage inherently influences structural growth. In addition, a high degree of variability was observed among individual trees within the same treatment, which likely contributed to the absence of statistically significant differences.

Yield efficiency (kg cm^{-2} TCSA) and fruit quality were also impacted by altitude, although, similar to the vegetative growth, high variability was found. Such variability in tree development, fruit production, and quality is common in agricultural systems located in mountainous regions and is explained by the complex interactions of harsh environmental conditions, topography, soil heterogeneity, and differential tree management (Quevedo-Garcia et al., 2024). The consistent advantage in yield efficiency and fruit size at high altitude supports the idea that sensitive stages to water stress, such as fruit expansion phases in preharvest and bud induction and differentiation in postharvest are highly sensitive to high VPD and benefit from optimized water supply (Carella et al., 2023). High-altitude plots (1030 m) consistently produced a greater proportion of large-caliber fruits (>30 mm), while intermediate sizes (26–28 mm) predominated at 480 m (Fig. 13). These outcomes are also coherent with temperature-driven phenology and the lower evaporative demand at high altitude, which extends the effective growth window for cell expansion (Vignati et al., 2022). The effect of irrigation on fruit quality showed a common trend in both altitudes. RDI shifted distributions toward larger classes compared with FRM at both sites, which stressed that RDI strategies can maintain yield while enhancing size and quality (Marsal et al., 2009; Blanco et al., 2019; Martínez-Hernández et al., 2020). The positive impact of RDI was particularly clear at low altitude, where VPD was high, and trees were exposed to severe water deficit. There, the implementation of the RDI strategy partially alleviated plant water stress (Fig. 7). This mitigation in postharvest avoided severe water deficit while bud induction and differentiation took place, and the mitigation during preharvest likely improved cell expansion and maintained greater fruit turgor during critical stages of fruit development, resulting in larger cherries (Blanco et al., 2019b). Notably, for comparable yield levels, fruit from RDI trees were significantly larger than those from FRM trees, which showed the highest percentage of small fruits (< 24 mm), indicating that water availability, rather than crop load, was the primary limiting factor for fruit growth under these conditions. At higher altitudes, where the atmospheric water demand is lower and the sweet cherry trees experienced only mild water deficit, the application of RDI produced a less pronounced response in fruit quality. Under these conditions, water availability was apparently not the main constraint to fruit growth, and fruit size was more strongly determined by crop load. Thus, within the variability of each treatment, trees with lower crop loads produced larger fruits, highlighting the dominant role of source–sink relationships. Both crop load and tree water status have been identified as primary determinants of cherry size (Blanco et al., 2022). These results are agronomically significant, as market value in sweet cherry is highly dependent on fruit size. The ability of RDI to shift size distribution toward larger categories, even under conditions of high evaporative demand, reinforces its value as a quality-centered irrigation strategy.

5. Conclusion

This study demonstrates that altitude (environmental conditions) is a primary driver of tree water status, vegetative growth, yield potential, and fruit quality in mountain sweet cherry orchards, while irrigation strategy modulates these outcomes. The altitudinal gradient between 480 and 1030 m generated distinct microclimatic conditions, with higher evaporative demand and earlier phenology at low altitude, and cooler, more humid conditions favoring delayed development and larger fruit at high altitude.

RDI consistently improved Ψ_{stem}, Ψ_{trunk}, gs, and fruit size compared with FRM, particularly under the high evaporative demand at low altitude. These benefits confirm the suitability of RDI as a climate-smart irrigation strategy that enhances fruit quality while reducing water use; however, in order to get these benefits, it is necessary to consider site-specific thresholds for each phenological stage and plant-based indicators. In this sense, continuous monitoring of Ψ_{trunk} proved effective for high-resolution assessment of tree water status, although long-term calibration and validation remain necessary.

Water deficit conditions observed at lower altitudes may anticipate the challenges that higher-altitude regions will face under future climate change scenarios. In this context, the adoption of efficient irrigation strategies and adaptive management practices emerges as a critical requirement to safeguard profitability, fruit quality, and long-term sustainability of cherry orchards in the Jerte Valley. Furthermore, the results underscore the importance of strategic investments in mountain irrigation infrastructure and governance programs, which are essential not only to ensure the economic viability of cherry production but also to promote generational renewal and sustain rural communities in Mediterranean mountain regions.

CRediT authorship contribution statement

Elena Nieto-Serrano: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Carlos Campillo:** Writing – review & editing, Project administration, Methodology, Investigation, Funding acquisition, Data curation. **Maria Henar Prieto:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Victor Blanco:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no personal, financial, professional, or institutional interests that could have influenced the results of this article.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.scienta.2026.114765.

Data availability

Data will be made available on request.

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