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Abstract

Aims To elucidate how deep irrigation regulates root-zone water supply, seasonal water-source use and citrus production in a hilly region with red soils.

Methods We conducted a field experiment in a 15-year-old Nanfeng mandarin (*Citrus reticulata* Blanco) orchard in a hilly red-soil region of Jiangxi, China. Irrigation was applied at 25, 50 and 100 cm and at 50%, 75% and 100% of full irrigation, producing nine treatments. Soil water content, root dry mass, yield, fruit quality and irrigation water-use efficiency (IWUE) were measured; water-source contributions were estimated using δ^2H, $\delta^{18}O$ and MixSIAR.

Results Month, treatment and soil layer significantly affected soil water content (all $P < 0.001$). Roots were concentrated in the 0–40 cm layer (58.20% of total root dry mass), whereas irrigation mainly altered vertical allocation. Under severe deficit irrigation, citrus relied predominantly on shallow water. Under mild deficit and full irrigation, shallow water dominated in July and August, whereas deeper-soil contributions increased from September to October. Irrigation depth, amount and their interaction significantly affected yield and IWUE (all $P < 0.001$). The 50-cm mild-deficit treatment (D2W2) produced the highest yield (78.50 kg tree^{-1}) and IWUE (14.66 kg m^{-3}), with high soluble sugar, ascorbic acid and total soluble solids. PCA and entropy-weighted TOPSIS ranked D2W2 first.

Conclusions Under the conditions tested, 50-cm irrigation combined with mild deficit irrigation best coordinated root-zone water supply, seasonal water-source use and citrus production.

Keywords Citrus; Red-soil hilly region; Irrigation depth; Stable isotopes; MixSIAR model

Introduction

Root water uptake links soil water supply with plant transpiration and orchard productivity, governing the efficiency with which soil water is transferred to trees for transpiration, photosynthesis, and growth (Boursiac et al., 2022). In perennial fruit trees, root water uptake is governed not by irrigation amount alone but also by the spatial and temporal distribution of soil water within the profile (Mehra et al., 2023; Wendel et al., 2022). In subtropical red-soil hilly orchards, uneven seasonal rainfall, limited effective soil water storage, and high evaporative demand further intensify vertical heterogeneity in root-zone water availability (Segovia-Cardozo et al., 2022; Tu et al., 2021). Accordingly, the key to water-saving orchard irrigation lies not only in how much water is applied, but also in the soil depth at which it is supplied and whether the resulting wetted zone overlaps with the active root zone.

This issue first concerns the coupling between root distribution and soil water availability. Citrus fine roots are commonly concentrated in shallow soil layers, although rootstock, soil conditions, and water management can alter their allocation to deeper layers (Adriano et al., 2017; Simpson et al., 2020; Zheng et al., 2024). Studies of deficit irrigation have shown that moderate water deficits can maintain fruit-tree yield, improve fruit quality, and enhance irrigation water-use efficiency under certain conditions. These responses, however, depend jointly on deficit severity, timing, and soil water status (Chen et al., 2022; Chen et al., 2025; Cui et al., 2024; Saitta et al., 2021; Silveira et al., 2020). Irrigation amount describes the total water input but does not determine where water enters the soil profile. Applying the same amount of water at different depths may generate distinct wetted zones, root–soil contact patterns, and water-retention durations, thereby leading to different root-growth and water-use responses.

Irrigation depth may therefore be a key regulator linking the location of water inputs to root

water uptake. Studies of subsurface and localised irrigation have shown that the position of water application can alter soil wetting patterns, root distribution, and crop water-uptake depth (Aguzzoni et al., 2022; Cai et al., 2021). In apple orchards, deficit irrigation can increase the use of water from deeper soil layers, indicating that irrigation regimes can modify fruit-tree water-source selection (Brighenti et al., 2024). Nevertheless, most previous studies have considered irrigation amount or irrigation depth separately. It remains unclear whether these two factors interact and whether shifting the depth of irrigation-water inputs can consistently alter the actual water-uptake depth of mature citrus trees. Put differently, water delivered to deeper soil does not necessarily mean that trees can effectively use deep soil water, and field-based quantitative evidence for this process remains limited.

Combined hydrogen and oxygen stable-isotope analysis and Bayesian mixing models provide a valuable approach for identifying plant water sources and their seasonal dynamics (Rothfuss and Javaux, 2017; Sprenger et al., 2016). In recent years, this approach has been used to resolve the use of water from different soil layers by apple, grapevine, and other fruit trees, revealing dynamic shifts in root water-uptake depth with phenology, water stress, and irrigation regimes (Aguzzoni et al., 2022; Brighenti et al., 2024; Penna et al., 2021). However, water-source studies have generally focused on tree water uptake, whereas integrated assessments of soil water distribution, vertical root configuration, and production performance remain scarce. Source-contribution estimates alone cannot determine whether a given irrigation regime genuinely improves root-zone water supply and translates into advantages in yield, fruit quality, or irrigation water-use efficiency. Integrating isotopic evidence with soil water dynamics, root distribution, and fruit production is therefore necessary to clarify how irrigation regulates water use in citrus orchards.

Here, we conducted a two-factor field experiment in a 15-year-old mandarin orchard in the subtropical red-soil hilly region. The experiment included three irrigation depths (25, 50, and 100 cm) and three irrigation amount (full irrigation, 75% of full irrigation, and 50% of full irrigation). We monitored soil water content throughout the 0–200 cm profile, quantified the vertical distribution of root dry mass, and used δ^2H, $\delta^{18}O$, and the MixSIAR model to estimate the relative contributions of water from different soil layers. These process-based indicators were linked with tree yield, fruit quality, and irrigation water-use efficiency, and principal component analysis and entropy-weighted TOPSIS were used for integrated evaluation. We tested three hypotheses: (1) irrigation depth and irrigation amount interact, and deep irrigation enhances the use of water from middle and deep soil layers only when the wetted zone sufficiently overlaps with the active root zone; (2) as shallow soil water is depleted over the growing season, citrus shifts water uptake from shallow to middle and deeper soil layers, although the extent of this shift depends on soil water distribution and root spatial configuration; and (3) an intermediate irrigation depth combined with moderate deficit irrigation achieves a favourable balance among root-zone water supply, water-source switching, yield, fruit quality, and irrigation water-use efficiency. By testing these hypotheses, this study aimed to clarify how the location and amount of irrigation-water inputs jointly regulate soil water dynamics, root distribution, and water-use strategies in citrus orchards.

Materials and methods

Study site

The field experiment was conducted in 2025 in a commercial Nanfeng mandarin orchard located in Chating Village, Baishe Town, Nanfeng County, Jiangxi Province, China (27°05′ N,

116°27′ E). The study area has a subtropical monsoon climate, with a mean annual temperature of 18.5 °C, mean annual precipitation of approximately 1,845.5 mm, and a frost-free period of approximately 285 days. The climate is generally warm and humid and is well suited to citrus production. The experimental orchard consisted of 15-year-old mandarin trees planted at a spacing of 4 m × 3 m. The trees exhibited uniform vigour and were managed consistently throughout the experiment. The soil was classified as a typical acidic red soil, and its principal physicochemical properties are presented in Table 1.

Because soil bulk density was not measured in the 120–200 cm soil layers, it was estimated to convert gravimetric soil water content into volumetric soil water content. A relationship between bulk density and soil depth was fitted using measurements obtained at depths of 20, 40, 60, 80, and 100 cm (Sequeira et al., 2014). Bulk density increased with soil depth, but the rate of increase gradually declined. A saturating exponential model was therefore fitted as follows:

$$\rho_b = 2.0968 - 0.9368 * e^{-0.008635D} \quad (1)$$

The model provided an excellent fit to the measurements collected at depths of 20–100 cm (R^2 = 0.9997;RMSE = 0.0023 g·cm^{-3}) and was subsequently used to estimate bulk density in the 120–200 cm soil layers. Here, ρ_b is soil bulk density (g·cm^{-3}), and (D) is soil depth (cm).

Field capacity in the unmeasured soil layers was estimated by scaling total porosity according to the mean ratio between measured field capacity and total porosity (Hong et al., 2013):

$$\theta = 0.7163 * \left(1 - \frac{\rho_b}{2.65}\right) \quad (2)$$

where (θ) is volumetric water content at field capacity (m^3·m^{-3}), and 2.65 g·cm^{-3} is the assumed soil particle density.

Experimental design

Each treatment consisted of seven trees, of which the three central trees were selected for measurements. The irrigation system comprised a water reservoir, pump, filtration unit, mainline, lateral lines and field emitters (Fig. 1). The emitters were designed and installed as follows. At four cardinal directions, east, south, west and north, 1 m from the trunk, holes were drilled with a soil auger to the preset irrigation depths of 25, 50 and 100 cm. After the soil was removed, PVC pipes with a diameter of 5 cm were inserted vertically, with the bottom of each pipe positioned at the target irrigation depth. Four emitters, each with a flow rate of 8 L h^{-1}, were installed on the lateral line surrounding each tree and connected to the PVC pipes with flexible tubing, allowing water to be delivered directly to the designated soil layer.

For soil-moisture monitoring, a time-domain reflectometry (TDR) sensor was installed vertically 0.5 m west of the trunk and aligned with the centre of the PVC pipe. Volumetric soil water content was measured at depths of 0.2, 0.4, 0.6, 0.8 and 1.0 m. Irrigation water was obtained from a shallow well within the orchard. The well was recharged by the infiltration of regional precipitation, and the water was clean and met the quality standards for agricultural irrigation, making it suitable for subsurface drip irrigation in the citrus orchard. A plastic film was laid over the soil surface in the experimental area to prevent direct infiltration of natural rainfall. Consequently, rainfall did not contribute to soil-water replenishment during the experiment.

A soil-water content of 65% θ_f was used as the common lower irrigation threshold for all treatments. When soil water content fell below this threshold, the reference irrigation amount for the fully irrigated treatment (W3) was calculated using the following equation:

$$I_3 = P \times H \times A \times \left(\theta_f - 0.65\theta_f\right) \quad (3)$$

where (I_3) is the irrigation amount per tree (m^3), (P) is the planned wetting ratio (0.3), (H) is the planned wetted-soil depth (1 m), (A) is the area controlled by an individual tree (12 m^2, calculated as 4 × 3 m), and (θ_f) is the upper irrigation limit, corresponding to field capacity. The W3 treatment was irrigated to (θ_f), whereas the W2 and W1 treatments received 0.75(θ_f) and 0.50(θ_f), respectively. Thus, all treatments shared the same irrigation trigger threshold, and the differences among treatments were defined by the irrigation amount applied during each irrigation event.

Based on this equation, the single-irrigation amount for W3 was 1.890 m^3 $tree^{-1}$. The W2 and W1 treatments received 0.75 and 0.50 of the W3 amount, corresponding to 1.42 and 0.95 m^3 $tree^{-1}$, respectively. Six irrigation events were conducted during the experiment, resulting in total irrigation amounts of 11.34, 8.52 and 5.70 m^3 $tree^{-1}$ for W3, W2 and W1, respectively.

Soil-water sampling and measurement

Soil samples were collected on representative clear days from July to October 2025 at monthly intervals. A soil auger was used to collect samples from the 0–200 cm soil profile at 20 cm intervals. Samples from each depth were divided into two portions. One portion was placed in pre-weighed aluminium tins and transported to the laboratory, where it was oven-dried at 105 °C to a constant mass to determine gravimetric soil water content. The other portion was immediately transferred to sealed glass vials and stored at −20 °C for stable-isotope analysis of soil water. Volumetric soil water content was calculated using Eq. (4):

$$\theta = \theta_m * r \quad (4)$$

where (θ) is volumetric soil water content (m^3 m^{-3}), (θ_m) is gravimetric soil water content, and (r) is soil bulk density (g cm^{-3}).

Root sampling and measurement

Root samples were collected during fruit maturation in October 2025. An 85-mm-diameter soil auger was used to collect root samples from the 0–200 cm soil profile at a radial distance of 1 m from the trunk, with sampling intervals of 20 cm. Three replicates were collected for each treatment and soil layer.

The collected root samples were transported to the laboratory and gently washed with clean water to remove adhering soil and debris. Intact fine roots with diameters ≤2 mm were selected and placed in pre-labelled kraft paper bags or aluminium containers. The samples were heat-killed at 105 °C for 30 min in a forced-air drying oven and then dried at 75 °C to a constant mass, usually for approximately 48 h. The samples were immediately transferred to a desiccator containing indicating silica gel and cooled to room temperature. Each sample was weighed using an analytical balance with a precision of 0.0001 g. The measured mass was recorded as the fine-root dry mass of the sample. The three replicates from each soil layer were measured separately, and the results were expressed as fine-root dry mass for each soil layer.

Measurement of yield, fruit quality and irrigation water-use efficiency

Three central citrus trees were selected from each plot, and all fruits were harvested. The fruits were graded according to the Chinese standard NY/T 1190-2006, *Citrus Grades and Specifications*. Fruits weighing less than 80 g or having a transverse diameter smaller than 50 mm and failing to meet the criteria for marketable fruit were classified as non-standard fruits. Fruits with mechanical damage covering more than 5% of the peel area, pest or disease damage, or decay were classified as defective fruits. Each fruit was inspected and classified individually at harvest, and the weights of non-standard and defective fruits were excluded from the calculation of yield per tree.

Fruit-quality measurements were conducted with three biological replicates. Soluble sugar content was determined using a commercial assay kit and a microplate reader (BioTek, USA). Vitamin C (ascorbic acid, AsA) content was measured using a reduced-ascorbic-acid assay kit and the same microplate reader. Titratable acidity was determined by NaOH titration and expressed as citric acid equivalents. Total soluble solids were measured using a handheld refractometer (AK002B). Irrigation water-use efficiency (IWUE) was calculated using Eq. (5):

$$IWUE = \frac{Y}{I_i} \tag{5}$$

where ($IWUE$) is irrigation water-use efficiency (kg m^{-3}), (Y) is yield per tree (kg tree^{-1}), and (I_i) is the total irrigation water applied per tree (m^3 tree^{-1}).

Collection and measurement of stable-isotope samples

Xylem samples were collected at noon on the days when soil samples were collected from July to October 2025. For each monitored tree, current-year shoots were collected from the east, south, west and north sides. Shoots from the four orientations were treated as subsamples of the same tree and were not considered independent biological replicates. The bark and phloem were removed immediately after sampling. The processed xylem samples were placed in sealed glass vials and stored at −20 °C.

Precipitation samples were collected throughout the experimental period. Immediately after each rainfall event, the samples were transferred to sealed glass vials and stored at low temperature to minimise evaporative fractionation during storage.

Soil water and xylem water were extracted using cryogenic vacuum extraction. After thawing, an appropriate amount of each frozen sample was weighed and placed in a pre-cleaned extraction tube, where it was secured with quartz wool. The extraction tube was connected to a vacuum system and evacuated to below 1 Pa, followed by heating at 205 °C for 25 min. The evaporated water was condensed in a collection vial cooled with liquid nitrogen. Water-extraction efficiency was calculated using Eq. (6):

$$\alpha = \frac{n_2 - n_1}{m_5 - m_2} \times 100\% \tag{6}$$

where (α) is extraction efficiency (%); (n_1) and (n_2) are the masses of the collection vial before and after extraction, respectively (g); and (m_2) and (m_5) are the masses of the sample tube before extraction and after oven-drying, respectively (g). Samples with extraction efficiencies between 98% and 102% were considered acceptable.

The δ^2H and δ^{18}O values of soil-water and precipitation samples were measured using a liquid-water isotope analyser (LWIA-45EP, Los Gatos Research, USA), with measurement precisions of ±1‰ and ±0.2‰, respectively. Xylem-water isotopes were measured using an isotope-ratio mass spectrometer, with precisions of ±2‰ for (δ^2H) and ±0.3‰ for (δ^{18}O). All samples were calibrated against reference waters traceable to Vienna Standard Mean Ocean Water (VSMOW). Isotopic composition was calculated using Eq. (7):

$$\delta = \frac{R_{Sample} - R_{Stand}}{R_{stand}} \times 1000 \tag{7}$$

where (δ) is isotopic composition (‰), (R_{Sample}) is the measured isotope ratio of the sample, and (R_{Stand}) is the isotope ratio of the VSMOW reference standard.

Soil water from the 0–40, 40–120 and 120–200 cm layers was defined as the potential water sources, and xylem water was treated as the mixture. The relative contributions of water from the

three soil layers to citrus water uptake were estimated separately for each treatment and month using the MixSIAR model.

Data analysis and processing

Data were organised using Microsoft Excel 2021. Statistical analyses and plotting were performed using R 4.5.1 and Origin 2021, with statistical significance set at $P < 0.05$. Soil water content was analysed using three-way analysis of variance (ANOVA). Root dry mass was analysed using a Gamma generalised linear model. Total root dry mass, yield and fruit-quality variables were analysed using two-way ANOVA. Multiple comparisons among treatments were performed using Sidak's test. Principal component analysis and entropy-weighted TOPSIS were used for comprehensive evaluation. MixSIAR outputs were post-processed in R to visualise water-source contributions and their temporal dynamics.

Results and analysis

Temporal dynamics of soil water content

As shown in Table 2, month, irrigation treatment, and soil layer significantly affected soil water content in the citrus orchard ($P < 0.001$). Soil layer had the largest effect size, indicating that vertical stratification was the dominant feature of soil water variation. The interactions between month and irrigation treatment and between irrigation treatment and soil layer were significant. By contrast, the month × soil layer interaction and the three-way interaction were not significant. These results indicate that soil water status varied among treatments across months and soil depths, whereas the overall vertical distribution pattern remained relatively consistent among months.

Across all treatments, soil water content was generally lower in the surface layer and increased with soil depth (Fig. 2). Soil water content was relatively low in the 0–40 cm layer and gradually increased below 40 cm. The 120–200 cm layer generally maintained higher water content, indicating that soil water was mainly distributed in the middle and deeper layers during the experimental period. Similar vertical distribution patterns were observed across months, consistent with the non-significant interaction between month and soil layer.

Soil water content also showed pronounced month-to-month variation (Fig. 3). The overall mean soil water content across all treatments decreased from 21.62% on 24 July to 16.85% on 29 September, representing a decline of 22.1%. It subsequently increased to 17.64% on 30 October, which was 4.7% higher than the September value. In July, the mean soil water contents in the 0–40, 40–120, and 120–200 cm layers were 10.73%, 20.94%, and 27.74%, respectively. These values decreased to 8.00%, 16.31%, and 21.81%, respectively, in September. Although soil water content varied among months in all soil layers, the overall pattern of lower surface-layer and higher deep-layer water content remained unchanged.

Differences among irrigation treatments were mainly observed in the middle and deeper soil layers. The mean soil water contents under W2, W1, and W3 were 21.13%, 19.67%, and 16.59%, respectively. The overall mean soil water content under D3 was 20.39%, exceeding the values under D1 and D2, which were 18.46% and 18.54%, respectively. Among the treatment combinations, D3W2 showed the highest profile-averaged soil water content in July, August, and October, with values of 26.34%, 27.60%, and 22.55%, respectively. In September, the highest value was observed under D3W1, reaching 24.17%. These results indicate that the effects of irrigation treatment were not consistent across months, consistent with the significant interaction between month and irrigation treatment.

Further comparison among soil layers showed that differences associated with irrigation depth were relatively small in the 0–40 cm layer but increased below 40 cm. D3W2 maintained relatively high soil water content in the middle and deeper layers during most months, suggesting that irrigation at 100 cm combined with moderate deficit irrigation promoted the downward distribution of water. By contrast, D3W3 showed a relatively pronounced decline in profile-averaged soil water content from August to October. Overall, soil water in the citrus orchard exhibited a pronounced deep-profile distribution. Month mainly affected the overall water level throughout the profile, whereas irrigation treatment exerted stronger effects on the middle and deeper layers and their month-to-month variation.

Vertical distribution of citrus roots

As shown in Table 3, irrigation amount and soil depth significantly affected citrus root dry mass ($P < 0.001$), whereas the main effect of irrigation depth was not significant ($P = 0.913$). The interactions between irrigation depth and irrigation amount (D × W), irrigation depth and soil depth (D × S), irrigation amount and soil depth (W × S), and among all three factors (D × W × S) were significant ($P < 0.05$). These results indicate that the effects of irrigation depth and deficit irrigation on root dry mass varied with soil depth, with treatment differences occurring mainly in the vertical distribution of roots.

Root dry mass generally decreased with increasing soil depth across all treatments, indicating a clear concentration of roots in the shallow soil layers (Fig. 4). The mean root dry masses across all treatments were 0.910 and 0.673 g in the 0–20 and 20–40 cm layers, respectively, decreasing to 0.310 g in the 40–60 cm layer. Root dry mass did not exceed 0.152 g in any layer below 60 cm. The depth profiles differed among irrigation treatments. Under severe deficit irrigation, roots in D1W1 were concentrated mainly in the 0–40 cm layer, whereas D3W1 showed a relatively greater root distribution in the middle and deep layers. Under full irrigation, D3W3 maintained relatively high root dry mass below 120 cm. Treatment differences therefore varied with soil depth, consistent with the significant D × S, W × S and D × W × S interactions shown in Table 3.

The total root dry mass in the 0–200 cm profile also differed numerically among treatments (Fig. 5a). D3W3 had the highest value at 4.30 g, whereas D2W1 had the lowest value at 1.68 g; the remaining treatments fell between these two values. However, two-way analysis of variance showed that the effects of irrigation depth, deficit irrigation and their interaction on total root dry mass were not significant ($P > 0.05$). The proportions of root dry mass allocated to different soil layers further illustrated the differences in vertical distribution among treatments (Fig. 5b). Across all treatments, roots in the 0–40, 40–120 and 120–200 cm layers accounted for 58.2%, 24.1% and 17.7% of total root dry mass, respectively. The D1W1 treatment had the highest proportion of roots in the 0–40 cm layer, reaching 80.2%, whereas roots in the 120–200 cm layer accounted for only 6.5%. In D3W1, the proportion of roots in the 0–40 cm layer decreased to 50.3%, while that in the 120–200 cm layer increased to 17.4%. D3W3 had the highest proportion of deep roots, with 27.6% of root dry mass distributed in the 120–200 cm layer. However, the shift towards deeper root distribution with increasing irrigation depth was not fully consistent across deficit-irrigation amount, further indicating that the effect of irrigation depth on vertical root distribution was contingent on deficit intensity.

Overall, citrus roots were concentrated mainly in the 0–40 cm soil layer. Irrigation treatments did not significantly alter total root dry mass within the 0–200 cm profile, but they changed the allocation of roots among soil layers. The effect of deep irrigation on the downward distribution of

roots varied with the intensity of deficit irrigation.

Contributions of different soil layers to citrus root water uptake

The proportional contribution of water from each soil layer to citrus root water uptake under different irrigation treatments was quantified using the MixSIAR model (Fig. 6). Under severe deficit irrigation (W1), citrus trees relied predominantly on water from the 0–40 cm soil layer. Its contribution ranged from 36.7% under D1W1 in September to 87.7% under D3W1 in October. This pattern indicated that the low irrigation amount did not provide a stable, available water source in the middle and deeper soil layers.

Under W2 and W3, the dominant water-uptake depth gradually shifted downwards as the growing season progressed. In July and August, the 0–40 cm layer remained the dominant water source, contributing between 42.5% under D3W3 in August and 87.7% under D2W2 in July. By September, the dominant water source had shifted to the 40–120 cm layer under D1W2, D3W2, D1W3, and D2W3. The corresponding contributions were 42.7%, 51.7%, 46.6%, and 46.0%, respectively. In contrast, trees under D2W2 and D3W3 predominantly used water from the 120–200 cm layer, which contributed 41.3% and 35.1%, respectively. In October, the 40–120 cm layer remained the dominant source only under D2W2, with a contribution of 35.4%. All other W2 and W3 treatments shifted towards predominant reliance on water from the 120–200 cm layer. Contributions from this layer ranged from 44.0% under D1W2 to 71.0% under D3W3.

Citrus yield and irrigation water-use efficiency

As shown in Fig. 7, irrigation depth (D) and deficit amount (W) both had highly significant effects on citrus yield, and their interaction was also highly significant ($P < 0.001$). Overall, yield was lowest under W1, with a mean of 34.60 kg tree^{-1}. Yields under W2 and W3 were 60.84 and 61.91 kg tree^{-1}, respectively, both significantly higher than that under W1. Among the nine treatment combinations, D2W2 produced the highest yield, at 78.50 kg tree^{-1}, which was significantly higher than those of the other eight treatments.

Under W1, the yield of D2W1 was 43.13 kg tree^{-1}, significantly higher than that of D3W1. The yield of D1W1 was intermediate and did not differ significantly from those of D2W1 or D3W1. Under W2, D2W2 produced a significantly higher yield than D1W2 and D3W2. Under W3, yields ranged from 57.23 to 64.60 kg tree^{-1} across D1W3, D2W3 and D3W3, with no significant differences among treatments.

When irrigation depth was considered separately, yields under W2 and W3 at D1 were both significantly higher than that under W1, whereas W2 and W3 did not differ significantly. At D2, yield followed the order W2 > W3 > W1, with significant differences among all irrigation amounts. At D3, yield increased with irrigation amount, following the order W3 > W2 > W1, and the differences among treatments were significant. These results indicate that the yield advantage of mild deficit irrigation occurred mainly at the 50 cm irrigation depth, with D2W2 representing the highest-yielding treatment combination in this experiment.

As shown in Fig. 8, irrigation depth (D), deficit amount (W) and their interaction had highly significant effects on citrus irrigation water-use efficiency (IWUE) ($P < 0.001$). Overall, IWUE was highest under W2, with a mean of 11.36 kg m^{-3}, representing increases of 25.6% and 40.4% relative to W1 and W3, which had mean values of 9.05 and 8.09 kg m^{-3}, respectively. Among the nine treatment combinations, D2W2 had the highest IWUE, at 14.66 kg m^{-3}, significantly exceeding that of the other eight treatments.

Under W1, IWUE under D2W1 was 11.28 kg m^{-3}, significantly higher than those under D1W1

and D3W1. Under W2, D2W2 had significantly higher IWUE than D1W2 and D3W2. Under W3, no significant differences were observed among irrigation depths.

When irrigation depth was considered separately, IWUE under W2 at D1 was significantly higher than that under W1 but did not differ significantly from W3. At D2, IWUE followed the order W2 > W1 > W3, with significant differences among all treatments. At D3, no significant differences were detected among the three deficit amount. These results indicate that the improvement in IWUE under mild deficit irrigation was constrained by irrigation depth, with D2W2 producing the highest IWUE.

Citrus fruit quality

Fruit quality attributes responded differently to irrigation depth and water-deficit severity (Fig. 9). Soluble sugar, ascorbic acid (AsA), and total soluble solids (TSS) showed similar response patterns. All three variables were primarily affected by water-deficit severity ($P < 0.001$), whereas neither irrigation depth nor its interaction with water-deficit severity had a significant effect ($P > 0.05$).

Mean soluble sugar content was highest under W2, reaching 86.01 mg g^{-1}, which was 6.07% and 10.35% higher than under W1 and W3, respectively. AsA content showed a similar pattern. Its mean value under W2 was 192.63 μg g^{-1}, compared with 124.56 μg g^{-1} under W1 and 171.91 μg g^{-1} under W3. The highest AsA content was recorded under D2W2, reaching 212.62 μg g^{-1}. These results showed that mild deficit irrigation favoured the accumulation of soluble sugars and AsA, whereas differences among irrigation depths were relatively small.

Mean TSS content was also highest under W2, reaching 15.24%, compared with 12.47% under W1 and 13.27% under W3. Among the treatment combinations, D2W2 had the highest TSS content, at 15.47%. In contrast to soluble sugar, AsA, and TSS contents, titratable acidity was significantly affected by irrigation depth, water-deficit severity, and their interaction ($P < 0.01$). Titratable acidity was highest under D2W3 (0.875%), significantly exceeding that under all other treatments ($P < 0.05$), whereas the lowest value was recorded under D2W2 (0.297%). However, the response of titratable acidity to water-deficit severity varied among irrigation depths, indicating the absence of a consistent response pattern.

Overall, mild deficit irrigation was associated with greater accumulation of soluble sugars, AsA, and soluble solids, whereas titratable acidity responded more complexly to irrigation depth and water-deficit severity. D2W2 had the highest soluble sugar, AsA, and TSS contents and the lowest titratable acidity among all treatment combinations.

Comprehensive evaluation of citrus yield, fruit quality and irrigation water-use efficiency

As shown in Table 4, principal component analysis (PCA) and entropy-weighted TOPSIS produced broadly consistent evaluation results. All three treatments at the W2 irrigation amount showed comparatively strong overall performance. In the PCA evaluation, D2W2 achieved the highest comprehensive score, followed by D1W2 and D3W2. In the TOPSIS evaluation, D2W2 had the highest closeness coefficient (1.000), with D1W2 and D3W3 ranking second and third, respectively. Both methods identified D2W2 as the best-performing treatment and ranked D3W1 last. Overall, D2W2 provided the most favourable balance among yield, fruit quality, and irrigation water-use efficiency and was therefore identified as the preferred irrigation combination under the conditions of this experiment.

Discussion

Effects of irrigation treatments on soil water content and root distribution

Irrigation depth and amount jointly determine the point at which water enters the soil profile and its subsequent redistribution. In this study, treatment effects on soil water content were mainly concentrated below 40 cm. D3W2 maintained relatively high profile-mean soil water content in July, August, and October, whereas D3W3 did not retain this advantage from August to October. These results suggest that deeper water delivery does not necessarily lead to greater water retention within the root zone, because irrigation amount also affects wetting-front expansion and water residence at different depths. In an apple orchard under subsurface drip irrigation, (Nazari et al., 2021) found that emitter depth, discharge rate, and irrigation duration jointly altered the root water uptake zone and the extent of downward water movement; a lower discharge rate combined with a longer irrigation duration reduced deep water penetration. In commercial citrus groves, moderate irrigation produced more favourable soil wetting patterns than high irrigation and improved tree water status and fibrous root growth (Atta et al., 2025). Because vertical soil-water fluxes were not measured in the present study, the fate of water associated with the late-season decline in soil water content under D3W3 cannot be determined from soil water content alone.

Root dry mass in the 0–40 cm layer accounted for 58.2% of the total within the 0–200 cm profile, indicating that roots of mature citrus trees remained concentrated in shallow soil, whereas irrigation treatments mainly altered their vertical allocation. Under severe deficit irrigation, 80.2% of root dry mass was distributed in the 0–40 cm layer under D1W1, compared with 50.3% under D3W1, accompanied by an increase in the proportion of roots in the 120–200 cm layer. D3W3 showed the highest proportion of deep roots, with 27.6% of total root dry mass occurring below 120 cm. These patterns corresponded to treatment-induced differences in root-zone water distribution. Continuous observations of citrus fine roots have shown that their vertical distribution and seasonal dynamics are jointly influenced by rootstock and soil environment, and the dominant rooting depth differs among plant materials (Zheng et al., 2024). (Atta et al., 2025) also reported that moderate irrigation increased fibrous root length density and root lifespan in commercial citrus groves on sandy soil. Total root dry mass did not differ significantly among treatments in the present study, suggesting that irrigation depth and amount may affect vertical root configuration before producing detectable changes in total root biomass. However, root dry mass represents standing biomass at the sampling time and cannot be used to infer root water uptake activity at different depths.

Notably, higher soil water content in the middle and deep soil layers should not be equated with a greater contribution of water from these layers to tree water use. Using stable isotopes in an apple orchard, Brighenti et al. found that deficit irrigation increased the use of deeper soil water, indicating that the depth of root water uptake can adjust in response to water supply conditions (Brighenti et al., 2024). A recent study in a pear orchard further showed that an appropriate combination of irrigation amount and lateral depth improved the root-zone environment at 30-60 cm and promoted root development (Wang et al., 2026b). However, that study was conducted in an arid, salinity-affected orchard, where soil water-salt conditions, tree species, and irrigation depths differed substantially from those in the present study. For mature citrus trees in the red-soil hilly region, the 40-120 cm layer may be regarded as a soil layer that is particularly sensitive to irrigation-induced changes in water distribution.

Seasonal shifts in citrus water sources under different irrigation treatments and their relationship to root distribution

Seasonal shifts in citrus water sources depend on whether water from each soil layer can enter the root water uptake pathway during a given phenological stage. Tracer experiments using deuterium have shown that irrigation location, emitter number, and irrigation amount can alter the proportion of irrigation water entering the aboveground organs of fruit trees (Giuliani et al., 2023). Irrigation water can also be absorbed by roots and transported to branches within several hours after application (Aguzzoni et al., 2022). In the present study, soil water from the 0–40 cm layer remained the dominant source under W1 from July to October, whereas W2 and W3 relied mainly on shallow soil water in July and August and progressively shifted towards water below 40 cm thereafter. This pattern was consistent with the progressive decline in shallow soil water content and the relatively higher water content maintained in the middle and deep soil layers during the experimental period. The seasonal change in water-source contributions therefore likely reflected adjustments in the root-zone water supply pattern under different irrigation treatments, rather than a large-scale reorganization of root biomass over a short period.

The vertical distribution of root dry mass provides a spatial basis for interpreting this shift, but standing root biomass cannot be used as a direct proxy for the water contribution of each soil layer. In the present study, 58.2% of total root dry mass was concentrated in the 0–40 cm layer, whereas the use of water from the middle and deep soil layers increased markedly under mild deficit and full irrigation during the later growth stages. Li et al. found that roots in the weathered-rock layer accounted for only 3–5% of total root biomass in an apple orchard, yet water from this layer contributed 33–34% of tree transpiration water consumption (Li et al., 2024a). Wang et al. further showed that the contribution of deep water to apple water use was jointly constrained by root distribution, soil physical properties, and water availability; when a weathered layer restricted root extension, its contribution to tree water use could remain limited even when its water content was relatively high (Wang et al., 2023). Long-term observations have also shown that fruit trees can adopt different cross-layer water uptake strategies under contrasting soil-profile conditions (Wang et al., 2026a). These studies indicate that a relatively small proportion of roots in the middle and deep layers does not preclude their contribution to tree water supply. However, root activity, root hydraulic traits, and sap flow were not measured in the present study, so the actual water uptake intensity of roots at different depths cannot be quantified.

Water deficit did not necessarily lead to greater dependence on deep soil water. (Brighenti et al., 2024) observed that deficit irrigation increased the proportion of deeper soil water used by apple trees, whereas the W1 treatment in the present study did not show a stable shift towards deep water. Although D3W1 had a higher proportion of roots below 120 cm, water from the 0–40 cm layer remained the dominant source. This discrepancy may be related to whether a sustained and accessible water source was formed in the middle and deep layers, and may also reflect differences in soil texture, irrigation location, and root–soil contact conditions. (Attou et al., 2025) found that contrasting drip-irrigation systems altered the isotope dynamics of soil water below 30 cm and xylem water in an olive orchard, indicating a persistent influence of irrigation method on root-zone water replenishment pathways. By comparison, D2W2 used mainly shallow soil water in July, shifted towards water from the 120–200 cm layer in September, and relied primarily on water from the 40–120 cm layer in October, indicating continuous adjustment of the dominant water-source layer.

Effects of irrigation treatments on citrus yield, fruit quality and irrigation water-use efficiency

In this study, citrus yield and irrigation water-use efficiency (IWUE) were significantly affected by irrigation depth, irrigation amount and their interaction. The D2W2 treatment produced the highest yield and IWUE, indicating that the benefit of a given irrigation amount depends on the depth at which water enters the soil profile. Although D3W2 maintained a relatively high soil water content in the deeper layers, this did not translate into a corresponding production benefit. Given that most roots were distributed in the 0–40 cm soil layer, irrigation at 50 cm was closer to the principal water-uptake zone and likely improved the spatial matching between irrigation water and functional roots. Studies of subsurface drip irrigation in citrus have shown that the burial depth and placement of drip lines should be considered together with root distribution, soil texture and the extent of water diffusion; increasing the depth of water application alone does not consistently improve yield or water productivity (Meshram et al., 2025). In citrus production, coordinated regulation of irrigation amount and timing is likewise considered important for balancing yield, fruit quality and water-use efficiency (Chen et al., 2023). Thus, the yield advantage of D2W2 in this study was likely associated with the combined effects of an appropriate water-supply position and moderate water deficit.

Irrigation amount was the main driver of changes in fruit quality. Soluble sugar, ascorbic acid (AsA) and total soluble solids (TSS) were generally higher under W2, whereas titratable acidity was affected jointly by irrigation depth, irrigation amount and their interaction and showed no consistent gradient. Previous studies have shown that the effects of water deficit on citrus fruit quality depend on both deficit intensity and timing. Moderate deficit can increase sugar components, AsA and TSS, whereas severe deficit may impair fruit expansion and quality development (Chen et al., 2022). At the molecular level, appropriate late-season deficit irrigation can enhance sucrose-, glucose- and fructose-related metabolic processes and thereby promote sugar accumulation in citrus fruit (Cui et al., 2024). In the present experiment, water supply under W2 remained sufficient to support fruit growth while possibly reducing solute dilution associated with excessive irrigation. The decline in AsA and TSS under W1 suggests that severe deficit exceeded the range within which yield and fruit quality could be maintained simultaneously. Studies of late-maturing mandarins have likewise shown that the duration and intensity of water deficit jointly determine responses in yield and IWUE (Berríos et al., 2023). Because fruit turgor, sugar transport and osmotic adjustment were not measured directly here, these quality responses do not by themselves establish a single physiological mechanism.

The integrated evaluation further showed that the advantage of D2W2 resulted from a balance among yield, fruit quality and IWUE. Similar multi-objective irrigation studies have found that moderately reducing irrigation amount while optimizing the timing of water supply can improve fruit quality and water productivity without reducing yield (Chen et al., 2023). In other citrus experiments, moderate soil-moisture management combined with rhizosphere regulation was associated with high yield, sugar content and water-use efficiency (Li et al., 2024b); applying 85% of evapotranspiration together with mulching saved irrigation water without significantly reducing yield (Al-Qthanin et al., 2024). A global meta-analysis of citrus studies further indicated that both insufficient and excessive irrigation can reduce yield, fruit quality and resource-use efficiency, and that the suitable range of water inputs depends on tree age, cultivar, soil and climate (Zhang et al., 2026). The present conclusion applies to the 15-year-old mandarin orchard, red-soil hilly region and growing-season water conditions represented in this experiment. Its stability across tree ages, soil

textures and multi-year climatic conditions requires further testing.

Conclusions

Irrigation depth and irrigation amount jointly regulated root-zone soil water distribution, seasonal water-source use, and production performance in the mature citrus orchard. Soil water content generally increased with soil depth, with treatment differences occurring primarily below 40 cm. Although irrigation treatments did not significantly affect total root dry mass, they altered its vertical distribution, with 58.20% of the total root dry mass concentrated in the 0–40 cm layer. Citrus trees under severe deficit irrigation relied predominantly on shallow soil water, whereas those under mild deficit and full irrigation progressively increased their use of middle and deep soil water from September to October. D2W2 exhibited the most pronounced seasonal adjustment in water-source use. Irrigation depth, irrigation amount, and their interaction significantly affected yield and irrigation water-use efficiency. D2W2 achieved the highest yield (78.50 kg $tree^{-1}$) and irrigation water-use efficiency (14.66 kg m^{-3}), while also maintaining high soluble sugar, ascorbic acid, and total soluble solids contents. Both principal component analysis and entropy-weighted TOPSIS ranked D2W2 first, with a TOPSIS closeness coefficient of 1.000. These findings indicate that matching irrigation depth with water supply can improve coordination among root-zone water availability, seasonal water-source switching, and fruit production. Under the conditions of this one-year field experiment, irrigation at a depth of 50 cm combined with mild deficit irrigation provided the most favourable overall performance in the red-soil hilly citrus orchard. Further multi-year and multi-site studies are required to evaluate the robustness of this irrigation strategy across climatic conditions, soil types, and orchard ages.

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Authorship contribution

Zhenjing Tan: Conceptualization, Methodology, Investigation, Formal analysis, Data curation, Visualization, Writing – original draft. **You Hu:** Conceptualization, Methodology, Supervision, Project administration, Funding acquisition, Resources, Writing – review and editing. **Min Li:**

Conceptualization, Methodology, Supervision, Project administration, Funding acquisition, Writing – review and editing. **Huaming Zhang:** Investigation, Data curation, Validation, Writing – review and editing. **Yao Peng:** Investigation, Resources, Validation, Writing – review and editing. **Jie Zhang:** Investigation, Data curation, Writing – review and editing. **Yao Jiang:** Investigation, Resources, Writing – review and editing.

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Data availability

Data will be made available on request.

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.

Figures and tables

Table 1. Physicochemical properties of soil in citrus orchard

Soil depth (cm)	Soil bulk density (g cm^{-3})	Field capacity θ_f (m^3 m^{-3})	pH	Soil particle-size composition		
				Sand (%)	Silt (%)	Clay (%)
20	1.31	0.301	5.60	63.98	27.88	8.13
40	1.43	0.300	5.44	57.73	31.51	10.76
60	1.54	0.295	4.85	59.58	31.12	9.30
80	1.63	0.284	4.65	55.51	33.38	11.10
100	1.70	0.320	4.64	57.26	30.24	12.50
120	1.76	0.241	4.61	54.13	35.10	10.77
140	1.82	0.224	4.50	51.38	37.86	10.75
160	1.86	0.214	4.54	50.73	37.81	11.45
180	1.90	0.203	4.50	52.16	37.25	10.60
200	1.93	0.195	4.74	61.51	30.33	8.16

Table 2. Analysis of variance of the effects of month, irrigation treatment and soil layer on soil moisture in citrus orchard

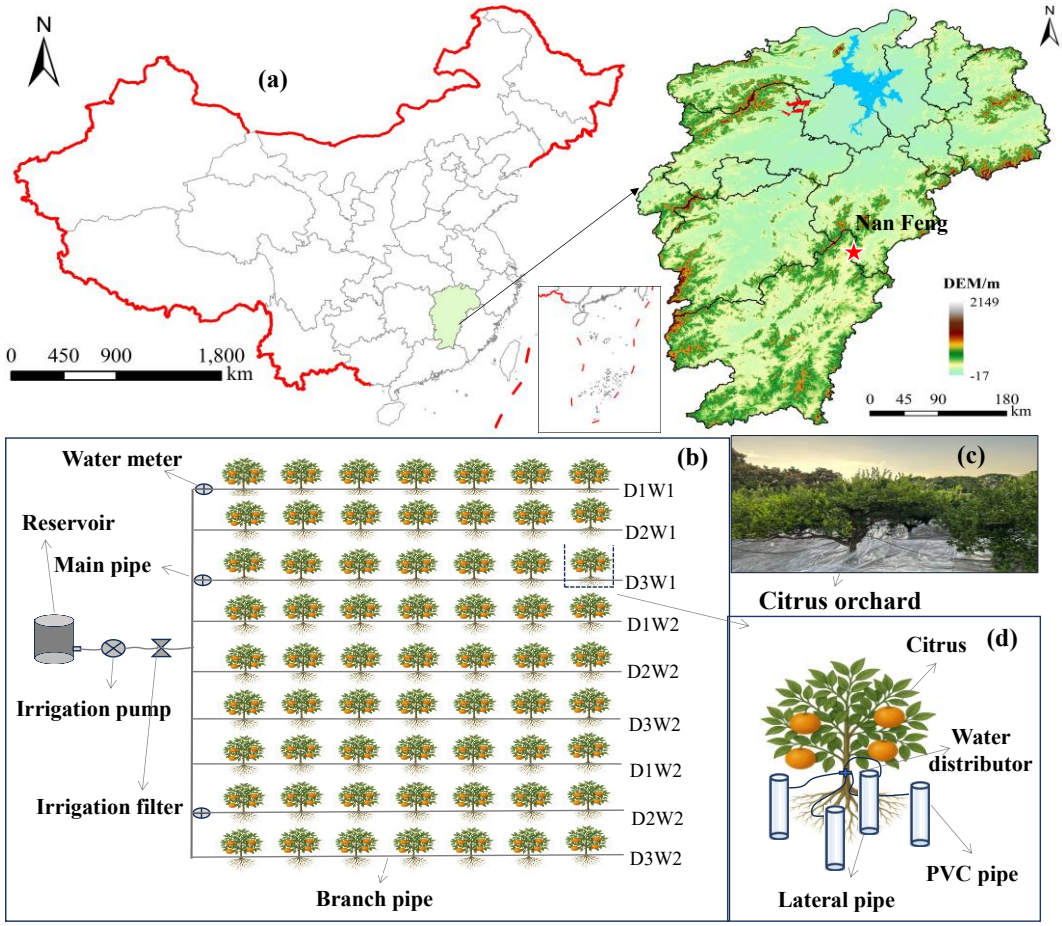
Source of variation	F	P	Partial η^2
Month (M)	26.93	<0.001	0.243
Treatment (T)	22.63	<0.001	0.418
Soil layer (S)	323.79	<0.001	0.720
M×T	2.15	0.002	0.170
M×S	1.69	0.124	0.039
T×S	8.34	<0.001	0.346
M×T×S	0.99	0.504	0.158

682 Table 3. Generalized linear mixed model analysis of the effects of irrigation depth, irrigation amount
683 and soil layer on citrus root dry mass

Source of variation	df	χ^2	*P*
Irrigation depth (D)	2	0.183	0.913
Irrigation amount (W)	2	54.640	＜0.001
Soil layer (S)	9	615.137	＜0.001
D×W	4	12.663	0.013
D×S	18	42.375	＜0.001
W×S	18	35.734	0.008
D×W×S	36	74.026	＜0.001

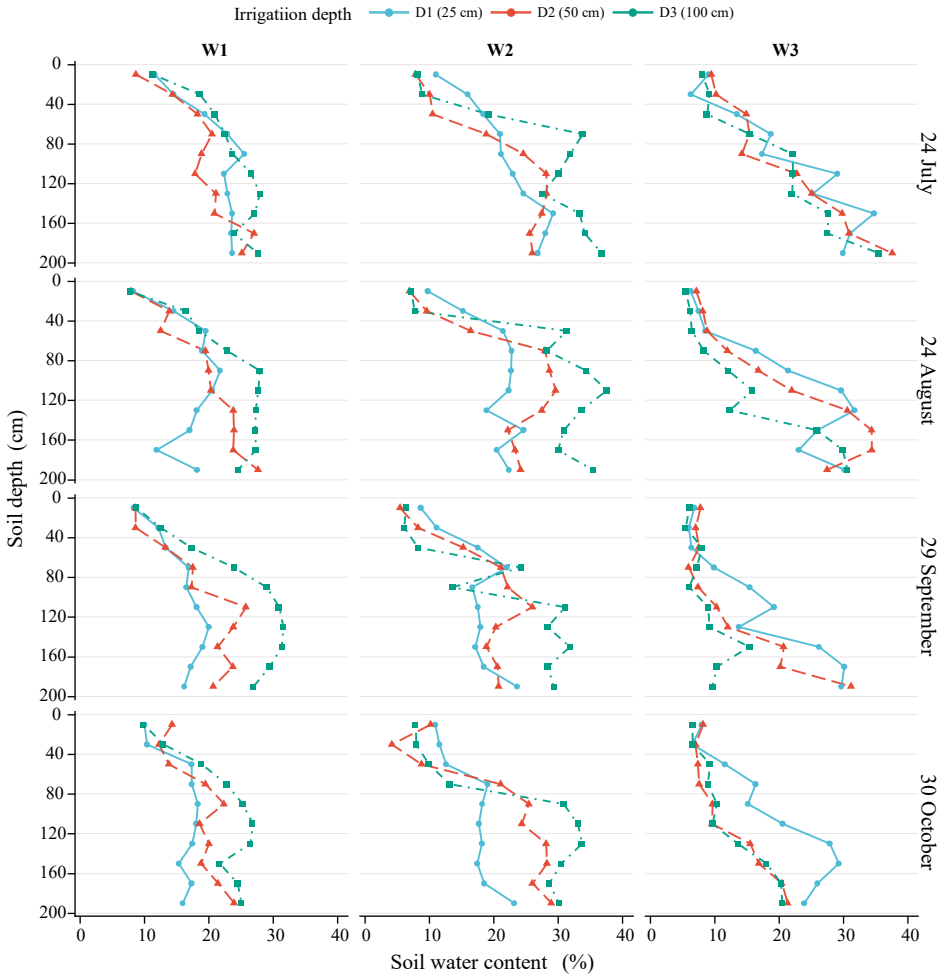
684 Note: D, irrigation depth; W, irrigation amount; and S, soil layer. Root dry mass was analysed using a Gamma
685 generalized linear mixed-effects model with a log link function, with D, W and S specified as fixed effects. The χ^2
686 and P values in the table are from Type III Wald tests. $P < 0.05$ indicates a statistically significant difference.
687 Table 4. Principal component analysis and entropy-weighted TOPSIS comprehensive evaluation
688 results of different irrigation treatments

Treatment	PCA score	PCA ranking	TOPSIS closeness coefficient	TOPSIS ranking
D2W2	2.573	1	1.000	1
D1W2	0.631	2	0.594	2
D3W3	0.063	5	0.452	3
D3W2	0.311	3	0.434	4
D2W3	-1.034	8	0.425	5
D2W1	-0.193	6	0.344	6
D1W3	0.135	4	0.293	7
D1W1	-0.723	7	0.181	8
D3W1	-1.763	9	0.080	9



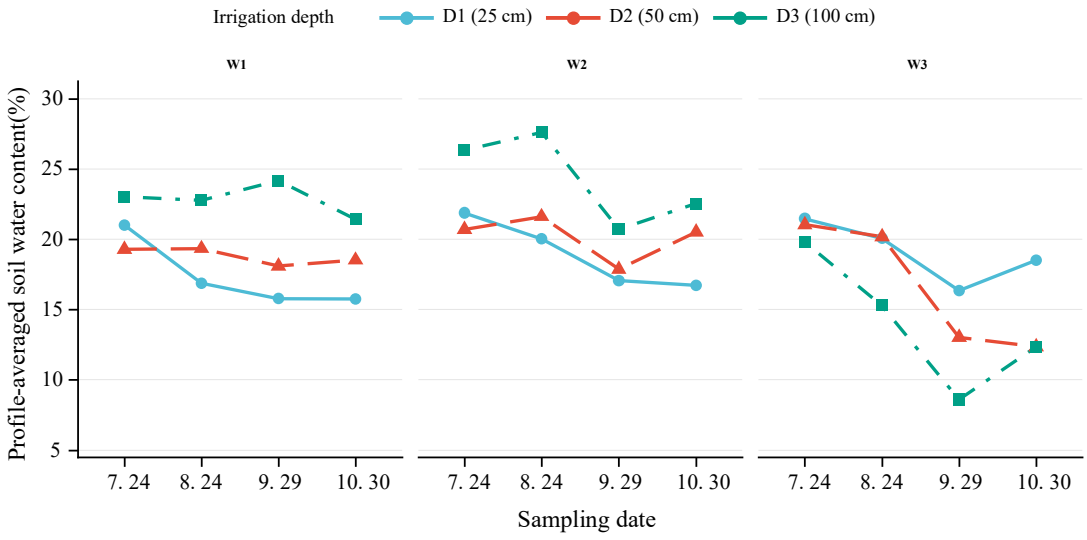
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690 Fig. 1 Schematic diagram of the study area location and deep irrigation system (a, location of the
691 study area; b, layout of irrigation systems for different treatments in the experimental plot; c,
692 schematic diagram of the citrus orchard; d, structural diagram of the irrigation emitter)



693

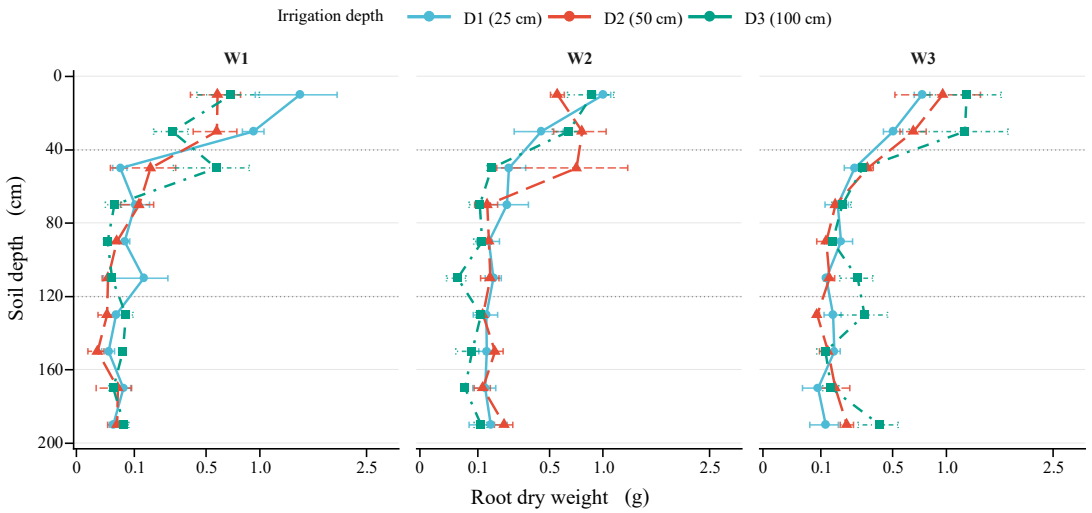
694 Fig. 2 Vertical distribution of soil moisture content under different irrigation treatments



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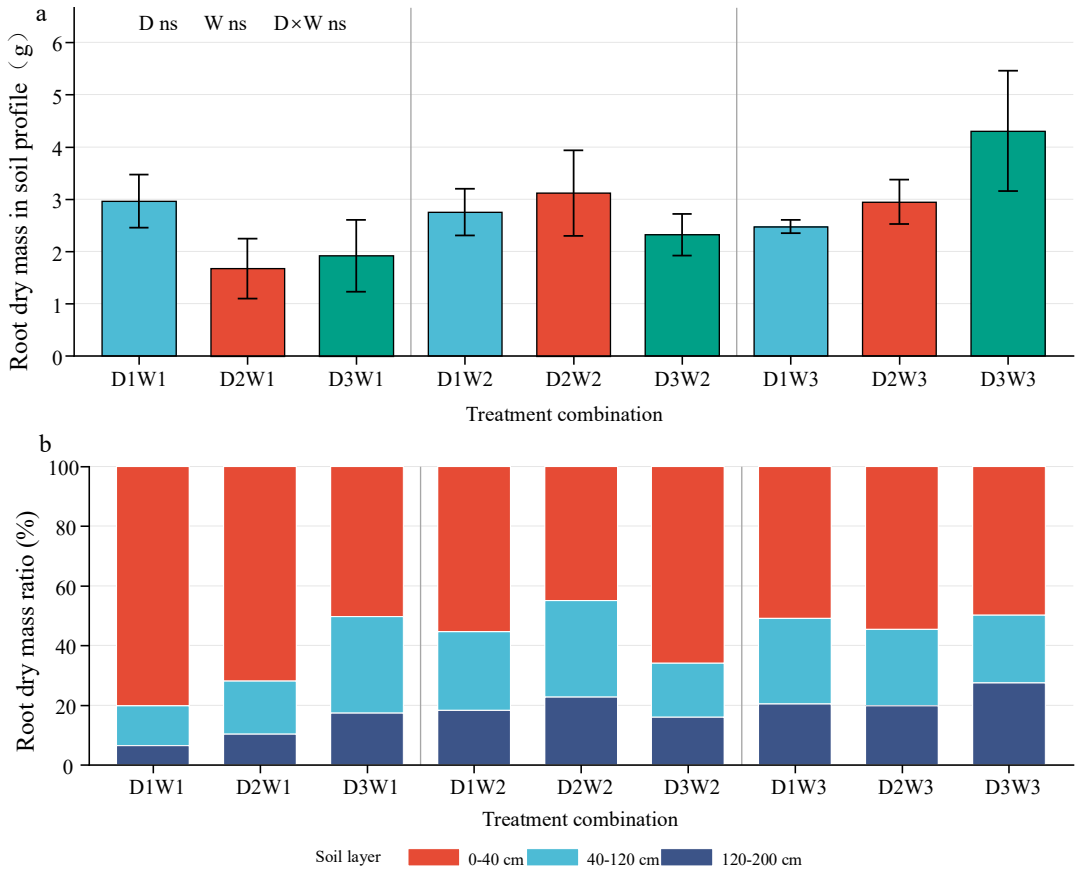
696 Fig. 3 Average soil moisture content in the soil profile under different irrigation treatments

697



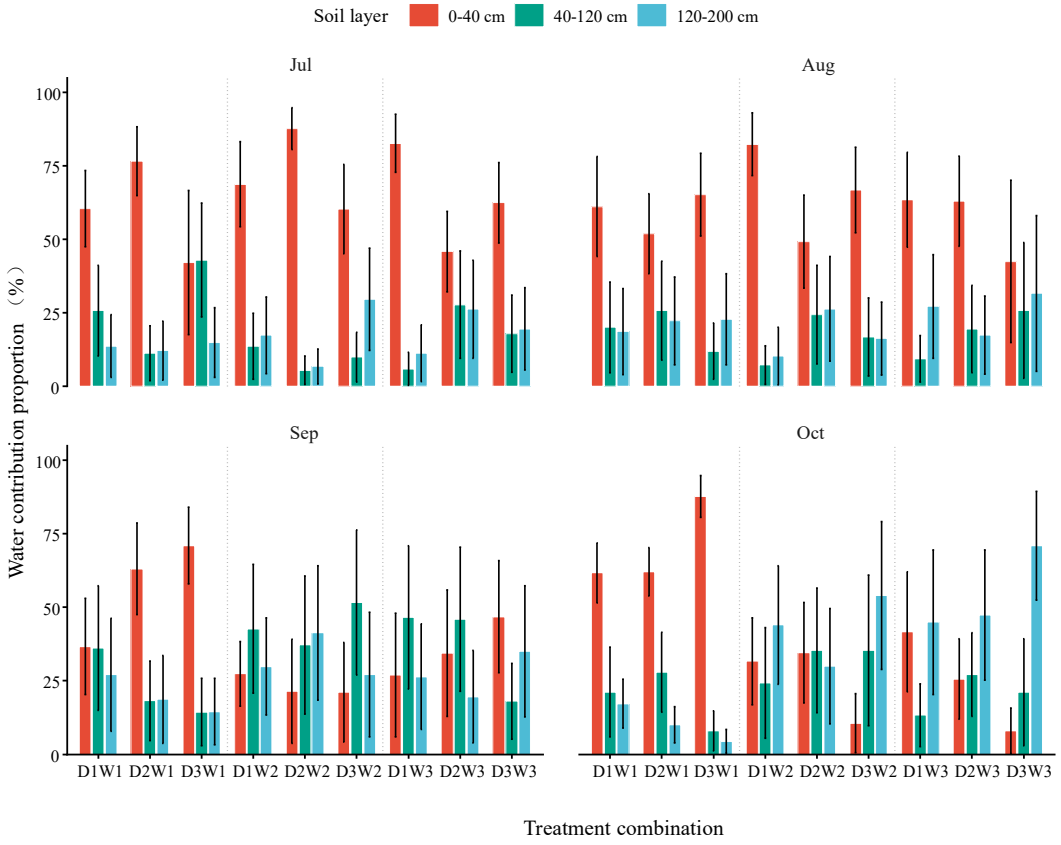
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699 Fig. 4 Vertical distribution of root dry mass under different irrigation treatments



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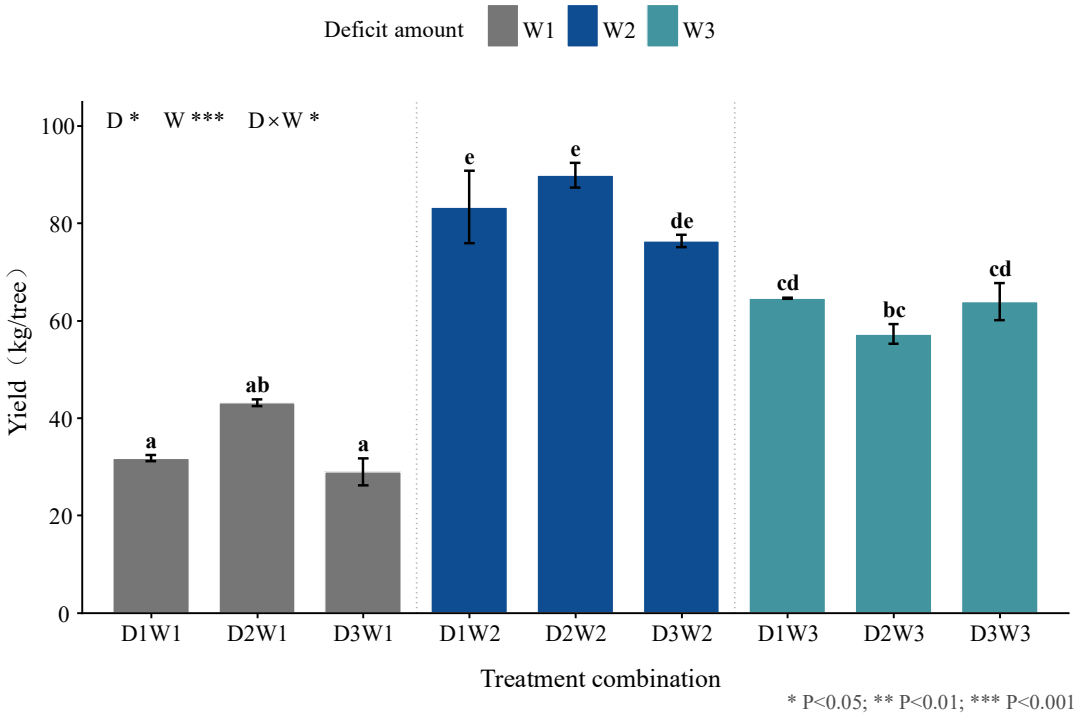
701 Fig. 5 Effects of different irrigation treatments on total root dry mass and distribution proportion
702 in soil layers. (a) Root dry mass in the 0–200 cm soil profile under each treatment combination. (b)
703 Proportional distribution of root dry mass among the 0–40, 40–120 and 120–200 cm soil layers. D1,
704 D2 and D3 represent irrigation depths of 25, 50 and 100 cm, respectively. W1, W2 and W3 represent
705 50%, 75% and 100% of full irrigation, respectively.



706

707 Fig. 6 Contribution rates of soil water in different soil layers (0–40 cm, 40–120 cm, 120–200 cm)

708 to root water uptake of citrus trees under different irrigation treatments



709

710 Fig. 7 Citrus yield under different irrigation treatments

711 Note: Different lowercase letters indicate significant differences among treatment combinations, whereas treatments

sharing the same letter do not differ significantly. D and W denote irrigation depth and deficit amount, respectively, and D × W denotes their interaction. *, ** and *** indicate $P < 0.05$, $P < 0.01$ and $P < 0.001$, respectively; ns indicates $P > 0.05$. The same notation applies below.

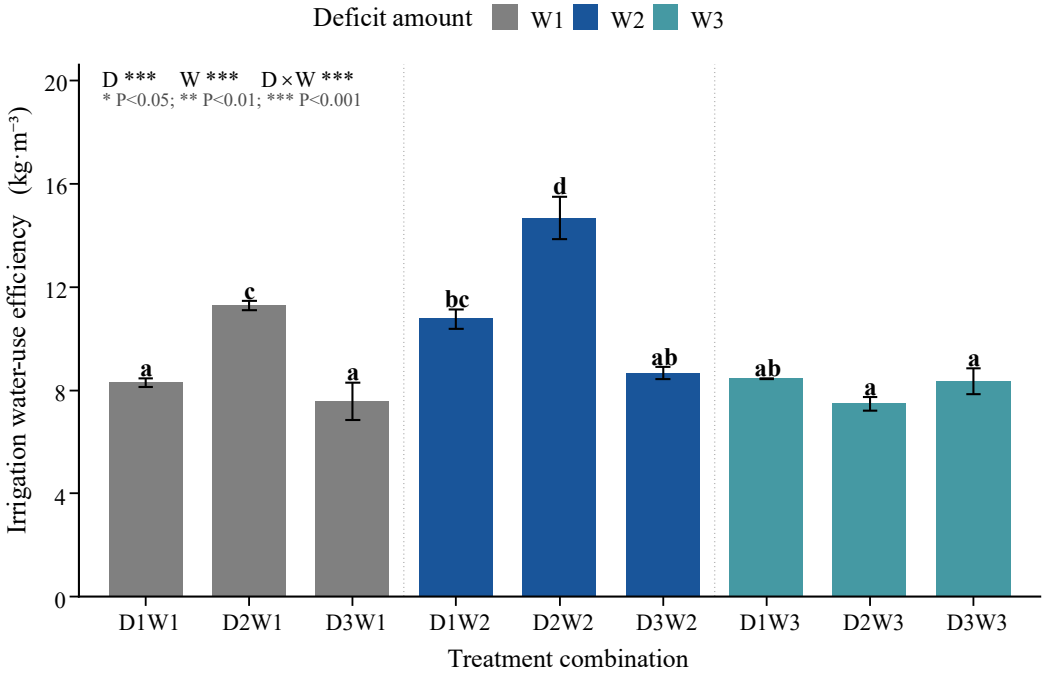


Fig. 8 Irrigation water use efficiency under different irrigation treatments

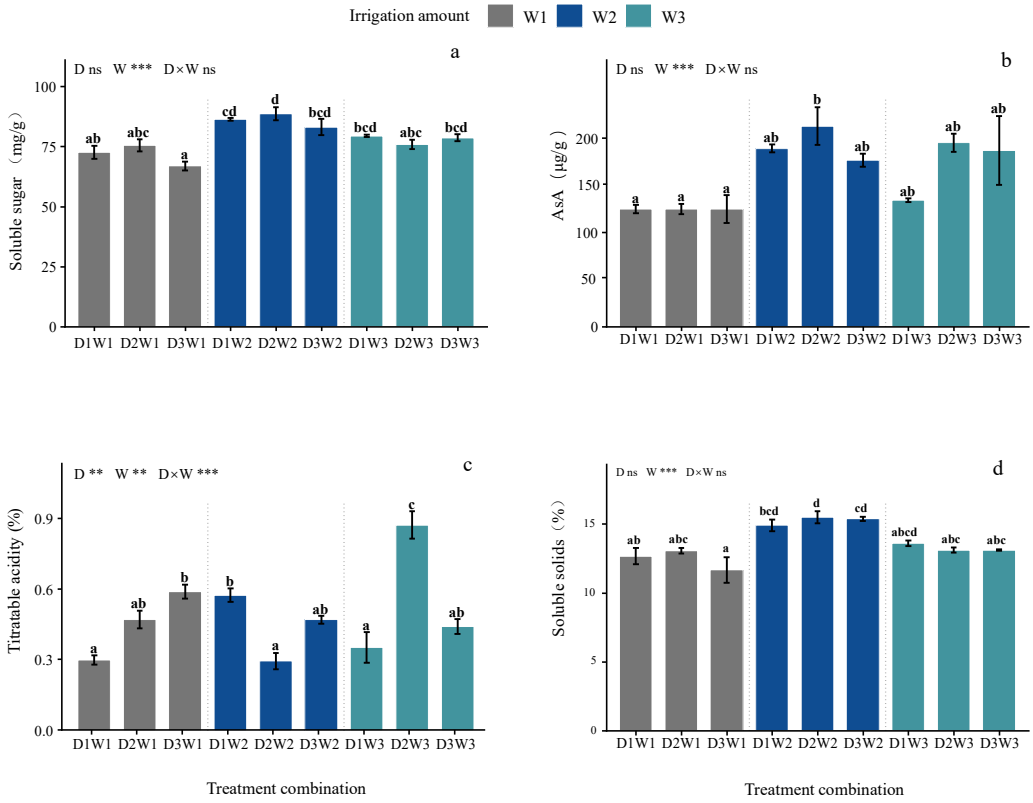


Fig. 9 Citrus fruit quality under different irrigation treatments. (a) Soluble sugar content. (b) Ascorbic acid (AsA) content. (c) Titratable acidity. (d) Total soluble solids content. D1, D2 and D3 represent irrigation depths of 25, 50 and 100 cm, respectively. W1, W2 and W3 represent 50%, 75% and 100% of full irrigation, respectively.