



Rootstock-specific responses of ‘Rojo Brillante’ persimmon grafted onto *Diospyros lotus* and *Diospyros virginiana* to irrigation dose and planting layout, with implications for water status, fruit abscission and irrigation water productivity

Armand Román^{1,2} · Pau Martí¹ · Pablo González-Altozano² · Luis Bonet³ · Eduardo Badal³ · María Amparo Martínez-Gimeno³

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Abstract

The ‘Rojo Brillante’ persimmon (*Diospyros kaki*) is gaining relevance as an alternative to citrus in Mediterranean semiarid regions. This study evaluated the effects of irrigation dose (100% and 115% of a baseline irrigation dose, BID), planting layout (2.5 × 5 m and 3.5 × 5 m), and rootstock (*Diospyros lotus* and *Diospyros virginiana*) on midday stem water potential (Ψ_s , a plant-based indicator of tree water status), yield, vegetative growth, irrigation water productivity (IWP), and fruit abscission during the juvenile to mature transition (4 to 7-year-old trees) in southeast Spain. Across 2012–2014, Ψ_s in 100% and 115% treatments generally remained above -1.30 MPa, whereas dense spacing under 100% BID caused transient severe summer stress ($\Psi_s < -1.30$ MPa) in trees, coinciding with reduced productivity in *D. lotus*. Yield was largely unaffected by increasing irrigation dose, and *D. virginiana* induced greater vigour than *D. lotus* without a consistent yield advantage, partly associated with lower crop load and greater physiological fruit drop. At the hectare scale, the denser layout tended to improve productivity. To optimise irrigation for *D. virginiana*, a 2015 study compared two irrigation strategies, 110% BID and sustained deficit irrigation at 70% BID, against a *D. lotus* control receiving 100% BID, all under the standard 3.5 × 5 m planting layout. SDI reduced abscission relative to flowering by about 14%, maintained yield, and maximised IWP. Fruit quality was not assessed. Overall, the results support rootstock-specific irrigation scheduling and identify deficit-based strategies as promising for improving water productivity without compromising yield.

Introduction

Persimmon (*Diospyros kaki* L.f.) has traditionally been cultivated in Asia, particularly in regions of China and Korea, where abundant rainfall ensures that water availability is not a limiting factor (Ballester et al. 2022). In recent decades,

declining citrus profitability in southeast Spain has encouraged growers to explore alternative crops better suited to the region’s specific soil and climatic conditions (Buesa et al. 2013; Martínez-Gimeno et al. 2017). One such alternative is the persimmon cultivar Rojo Brillante, valued for its productivity, fruit quality, and ease of astringency removal (Arnal and Del Río 2003; Llácer and Badenes 2009). This cultivar has also been successfully established in the Mediterranean (Badal et al. 2013) and in other persimmon-producing countries such as Australia (Oag 2017) and Indonesia (Asmy et al. 2024).

The success of persimmon orchards in semiarid Mediterranean areas depends on climatic adaptability and appropriate rootstock selection. *D. kaki*, *D. lotus* L. and *D. virginiana* L. are deciduous species adapted to temperate climates (Mowat and George 1996). While most cultivars derive from *D. kaki*, *D. lotus* and *D. virginiana* are widely used as commercial rootstocks (Intrigliolo et al. 2018). In

✉ Pablo González-Altozano
pgaltozano@agf.upv.es

¹ Departament d’Enginyeria Industrial i Construcció, Àrea d’Enginyeria Agroforestal, Universitat de les Illes Balears, Carretera de Valldemossa km 7.5, 07122 Palma, Spain

² Departament d’Enginyeria Rural i Agroalimentària, Universitat Politècnica de València, c/Camí de Vera s/n, 46022 València, Spain

³ Irrigation Advisory Service, Valencian Institute for Agricultural Research (STR-IVIA), Moncada, Valencia, Spain

southeast Spain, ‘Rojo Brillante’ is predominantly grafted onto *D. lotus*, typically at 3.5×5 m spacing (Intrigliolo et al. 2018). However, despite its widespread adoption in the region, *D. lotus* is highly susceptible to chloride phytotoxicity due to poor irrigation water quality and limited soil drainage. *D. virginiana* offers greater tolerance to such conditions, but its agronomic performance with ‘Rojo Brillante’ remains poorly studied. Transitioning to *D. virginiana* may expand the range of soil and water conditions suitable for sustainable cultivation, though challenges linked to compatibility and management persist (Bellini and Giordani 2002; Intrigliolo et al. 2018).

Unlike other persimmon-producing regions, in the semi-arid Mediterranean area of eastern Spain, limited rainfall makes irrigation essential to achieve profitable yields that meet quality standards (Ballester et al. 2022). In these Mediterranean areas, irrigation is the main external factor influencing productivity (Intrigliolo et al. 2018), and its efficient management is critical due to the increasing water scarcity (Puerto et al. 2021). Irrigation scheduling is commonly based on FAO crop coefficients (Allen et al. 1998), with recent updates for woody crops in Mediterranean and warm temperate conditions (Pereira et al. 2024). However, available persimmon K_c information still derives mostly from studies on adult trees grafted onto *D. lotus* (Badal et al. 2013; Buesa et al. 2013). Ballester et al. (2022) recently quantified the transpiration coefficients of mature ‘Rojo Brillante’ persimmon trees grafted onto *D. lotus* under Mediterranean conditions in Spain, providing a reference framework for orchard water use under local climate. In contrast, Kanety et al. (2014) evaluated irrigation levels and derived ET_0 -based baseline crop factors for ‘Triumph’ persimmon grafted onto *D. virginiana* in northern Israel, a different cultivar, production environment, and management context. Taken together, these studies support irrigation scheduling in mature orchards but do not provide information for young orchards and, critically, do not address the irrigation requirements of ‘Rojo Brillante’ grafted onto *D. virginiana* under semiarid Mediterranean conditions in southeastern Spain.

Previous studies suggest that deficit irrigation can modify fruit size, drop, and yield. For example, in mature orchards of ‘Rojo Brillante’ grafted onto *D. lotus*, deficit irrigation did not reduce yield compared with fully irrigated controls, but decreased fruit weight and economic return (Buesa et al. 2013). Similarly, moderate water deficits applied late in spring reduced fruit abscission and improved yield (Badal et al. 2013). However, in young orchards, vegetative growth is strongly linked to future yield potential; therefore, excessive early water restriction may slow tree establishment (Parra et al. 2021). These considerations are particularly relevant given the greater vigour of *D. virginiana* compared to *D. lotus* (Kanety et al. 2014).

In this context, the present study aimed to evaluate the influence of planting layout on the agronomic responses of the Rojo Brillante persimmon cultivar under two irrigation regimes, grafted onto *D. lotus*, the predominant commercial rootstock, and *D. virginiana*, a potential alternative in the study area. The study also sought to characterise the onset of production in young orchards and to analyse fruit drop patterns under different irrigation conditions to optimise irrigation management strategies.

Methods

Experimental plot

The experiment was conducted over four years (2012–2015) in a commercial orchard of Rojo Brillante persimmon (*D. kaki*) cultivar trees, located in Liria ($39^\circ 42'N$, $0^\circ 38'W$, elevation 300 m), Valencia (Spain), under typical Mediterranean conditions. The local climate is characterised by hot, dry summers and mild winters and can be classified as Csa according to the Koppen-Geiger system. The trees were grafted onto two widely used persimmon rootstocks, *D. lotus* (DL) and *D. virginiana* (DV). Initially, the average canopy-covered area and trunk diameter were 1.1 ± 0.3 m² and 17.5 ± 1.0 cm for DL and 1.3 ± 0.3 m² and 14.2 ± 1.4 cm for DV. Trees were planted in 2008 and were in the juvenile-to-mature transition during the study period (2012–2015). Orchard management followed standard commercial practices for the region under conventional farming, and these practices were applied uniformly across treatments. Winter pruning was performed annually during dormancy to maintain balanced vegetative growth and adequate bearing capacity, in accordance with published recommendations (Yamada 2008). Fruit thinning was not performed during the study period to avoid confounding the assessment of fruit abscission. Fertilisation was applied under drip irrigation in accordance with regional technical guidelines for the training period (Badenes et al. 2015). Trees received 30 to 40 g N, 15 to 20 g P₂O₅, and 25 to 30 g K₂O per tree per year, multiplied by the number of years after planting; therefore, during the study period (4 to 7-year-old trees), applications ranged from 120 to 280 g N, 60 to 140 g P₂O₅, and 100 to 210 g K₂O per tree annually.

Trees were planted at two spacings: 2.5 m x 5 m (25-layout) and 3.5 m x 5 m (35-layout). Irrigation water was supplied through two drip lines per tree. In the 25-layout, each line carried five pressure-compensating emitters (4 L h⁻¹ per emitter), resulting in a total nominal discharge of 40 L h⁻¹ per tree. In the 35-layout, each line carried seven pressure-compensating emitters (4 L h⁻¹ per emitter), resulting in a total nominal discharge of 56 L h⁻¹ per tree. Irrigation

volumes were recorded using volumetric water meters installed at the inlet of each treatment plot within each block. The irrigation system underwent routine preventive and corrective maintenance, including leak repair, replacement of defective emitters, periodic line flushing, and filter cleaning based on pressure loss and visual inspection; additionally, chemical flushing with phosphoric acid was performed at the start of each irrigation season to mitigate calcium carbonate precipitation and emitter clogging. The water had an average electrical conductivity (EC) of 1.1 dS m^{-1} and an average chloride (Cl^-) concentration of 122 mg L^{-1} . The soil in the study area was classified as sandy loam, with a particle-size distribution of 56% sand, 29% silt, and 15% clay; a stone content of 32% by weight; and an effective depth of 0.8 m. Bulk density ranged from 1.35 to 1.45 t m^{-3} , and fertility levels were low, with an organic matter content of 0.66% and a total nitrogen concentration of 0.05%. Given the soil texture and organic matter content, the SPAW model (Saxton and Rawls 2006) was applied to estimate volumetric water content at field capacity and at the wilting point, which were 21% and 9.4%, respectively. Within the effective root zone (0–0.8 m), the total available water (TAW) was estimated as the difference between the volumetric water content at field capacity and the wilting point, yielding $0.116 \text{ m}^3 \text{ m}^{-3}$, equivalent to approximately 93 mm of plant-available water, indicating a moderate capacity for water retention.

Irrigation treatments

Irrigation water needs were calculated using the FAO methodology described by Allen et al. (1998), in which ET_c was

Table 1 Seasonal irrigation dose applied per treatment during 2012 to 2014, expressed as volume per tree and equivalent irrigation depth

	Irrigation level (relative to BID, %)	Irrigation applied, $\text{m}^3 \text{ tree}^{-1}$ (mm)		
		2012	2013	2014
DL25-HI	115	4.70 (376)	5.68 (454)	8.51 (681)
DL25-FI	100	4.10 (328)	4.85 (388)	7.33 (586)
DL35-HI	115	4.70 (268)	5.68 (325)	8.51 (486)
DL35-FI (rootstock control)	100	4.10 (234)	4.85 (277)	7.33 (419)
DV25-HI	115	4.70 (376)	5.68 (454)	8.51 (681)
DV25-FI	100	4.10 (328)	4.85 (388)	7.33 (586)
DV35-HI	115	4.70 (268)	5.68 (325)	8.51 (486)
DV35-FI (rootstock control)	100	4.10 (234)	4.85 (277)	7.33 (419)

BID baseline irrigation dose computed from ET_c . *DLD*, *lotus*; *DVD*, *virginiana*. 25 and 35 denote planting layouts $2.5 \times 5 \text{ m}$ and $3.5 \times 5 \text{ m}$, respectively. FI and HI denote full irrigation (100% of BID) and high irrigation (115% of BID), respectively. Values in parentheses are irrigation depth (mm) calculated from the ground area per tree for each layout

determined as $\text{ET}_c = \text{ET}_0 \times K_c$. ET_0 values were obtained from the automatic weather station near the orchard, which is part of the Sistema de Información Agroclimática para el Regadío (SIAR) of the Spanish Ministry of Agriculture. Table 1 summarises annual ET_0 and rainfall during the study period. Irrigation scheduling followed the approach proposed by Buesa et al. (2013) for ‘Rojo Brillante’ trees grafted onto DL rootstock. Site-specific operational crop coefficients were used for irrigation management. During the 2012–2014 period, corresponding to the juvenile-to-mature transition, K_c values ranged from 0.12 to 0.31 in 2012, 0.29 to 0.60 in 2013, and 0.22 to 0.72 in 2014, with the highest values coinciding with the seasonal maximum in canopy development. In 2015, when trees had reached maturity, K_c values ranged from 0.20 to 0.91. Because these coefficients were used as operational, site-specific values for irrigation scheduling within this experiment, they are not intended as transferable standard K_c values.

The experimental design initially spanned three years (2012 to 2014) and evaluated two irrigation regimes defined relative to a baseline irrigation dose (BID) for each combination of planting layout (25 and 35) and rootstock (DL and DV). The BID was computed from ET_c and used as the operational baseline dose. The daily BID (L tree^{-1}) was obtained by multiplying ET_c (mm d^{-1}) by the ground area assigned per tree according to planting layout ($\text{m}^2 \text{ tree}^{-1}$), assuming $1 \text{ mm} = 1 \text{ L m}^{-2}$, and the annual BID was calculated by summing daily values over the irrigation period. Treatments received either 100% of BID (hereafter referred to as full irrigation, FI) or 115% of BID (hereafter referred to as high irrigation, HI). This additional 15% irrigation input was included as a moderate supra-baseline irrigation level to evaluate whether a moderately higher irrigation dose than the reference dose could improve tree water status and agronomic performance, while also providing a safety margin against possible underestimation of crop water requirements under the site conditions. This factorial configuration resulted in four treatments per rootstock. In this first scenario, DL35-FI and DV35-FI were established as the control treatments, representing the standard planting layout ($3.5 \times 5 \text{ m}$) and receiving 100% of BID. For DV35-FI, irrigation scheduling followed the same ET_c -based framework used to calculate BID for DL. Under HI, both planting layouts (25 and 35) received 115% of BID per rootstock, whereas the 25-FI treatments used a higher-density planting layout ($2.5 \times 5 \text{ m}$) while maintaining 100% of BID relative to their respective 35-FI controls. Seasonal irrigation doses for each treatment are summarised in Table 1.

Based on the findings from the previous scenario, the trial was extended by one year (2015) to compare the performance of DL and DV rootstocks under modified irrigation strategies using only the standard planting layout

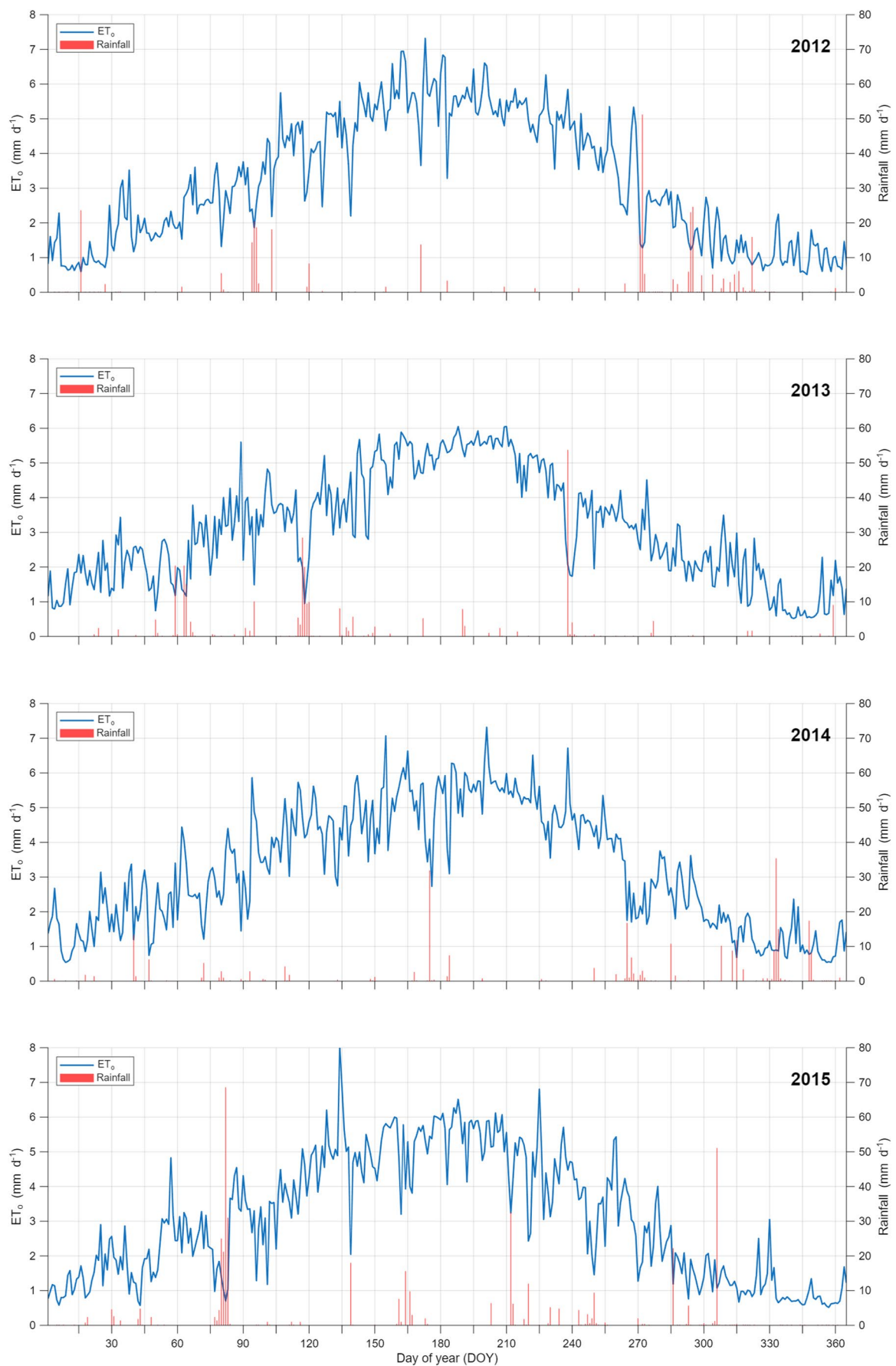


Fig. 1 Seasonal evolution of reference evapotranspiration (ET_0 , blue line) and rainfall (red bars) during 2012–2015. Data is shown at daily resolution by day of year (DOY), with one panel per season. ET_0 is plotted on the left y-axis (mm d^{-1}) and rainfall on the right y-axis (mm d^{-1})

(3.5×5 m). Accordingly, DL-FI (100% of BID) was designated as the control treatment, whereas DV-110 received 110% of BID. In addition, a sustained deficit irrigation treatment (DV-SDI) was introduced, in which DV trees received 70% of BID throughout the growing season.

The experimental orchard was arranged as a randomised complete block design (RCBD) with three blocks. Within each block, each treatment was represented by a plot consisting of three adjacent rows, with seven trees per row (21 trees per plot). To minimise border effects and potential lateral water movement between adjacent plots under drip irrigation, perimeter trees served as guards and measurements were restricted to internal trees. Specifically, the five interior trees of the middle row were used for the primary agronomic assessments ($n=15$ trees per treatment). Tree water status was monitored on two central trees per treatment plot within each block, selected from the central row of each plot to ensure consistent sampling ($n=6$ trees per treatment).

Field determinations

Tree water status

Tree water status was monitored weekly by measuring mid-day stem water potential (Ψ_S) at solar noon (McCutchan and Shackel 1992) during the growing season and less frequently during the winter, using a Scholander pressure chamber (Soil Moisture Equip. Corp. mod. 5100 A), following the procedures described by Turner (1981). Measurements were taken from two mature, northern-facing bagged leaves per tree, with two trees per treatment plot within each block (six trees per treatment). In 2012–2013, Ψ_S was measured only for 35-layout treatments. In subsequent years, Ψ_S was measured across all treatments. These Ψ_S measurements were used as a physiological check to confirm that the FI control treatments for each rootstock remained adequately irrigated and did not experience sustained water stress.

Vegetative growth

Vegetative growth was assessed in May of each season by measuring the trunk circumference of five trees per treatment plot within each block (15 control trees per treatment). The trunks of the sampled trees were marked at 0.25 m above ground level, above the graft union, and measurements were taken with a tape measure. The trunk cross-sectional area (TCA) and its annual increment (ΔTCA) were calculated for

each tree. Additionally, canopy volume was determined at the end of each growing season, defined as the post-harvest period after the onset of leaf fall and prior to winter pruning. Canopy volume was estimated from canopy height and diameter measurements.

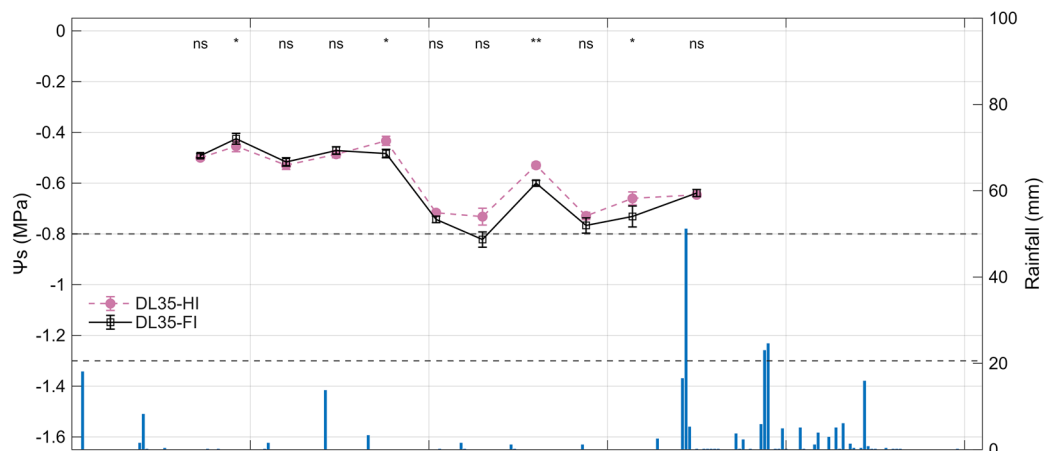
Yield and derived productivity indices

At harvest, yield and number of fruits per tree were determined for five trees per treatment plot within each block. Harvest was conducted on 20 November 2012, 4 December 2013, 4 December 2014, and 14 November 2015. Fruits were harvested at commercial maturity, following regional practice, using external skin colour as a non-destructive harvest index, and picking was carried out when fruits were fully developed and exhibited the cultivar's characteristic uniform orange-to-orange-red colouration (Badenes et al. 2015). Average fruit weight was then calculated as the ratio between yield and fruit number. Yield efficiency was assessed for each measured tree in all treatments ($n=15$ trees per treatment) and expressed as the ratio of yield to TCA ($\text{kg fruit per unit TCA}$). Additionally, the yield-to- ΔTCA ratio was calculated, as this ratio is commonly used to express resource partitioning between vegetative and productive growth (Ebel et al. 1995). Finally, irrigation water productivity (IWP) was calculated for each measured tree in all treatments as the ratio of yield to the volume of irrigation water applied (Pereira et al. 2012).

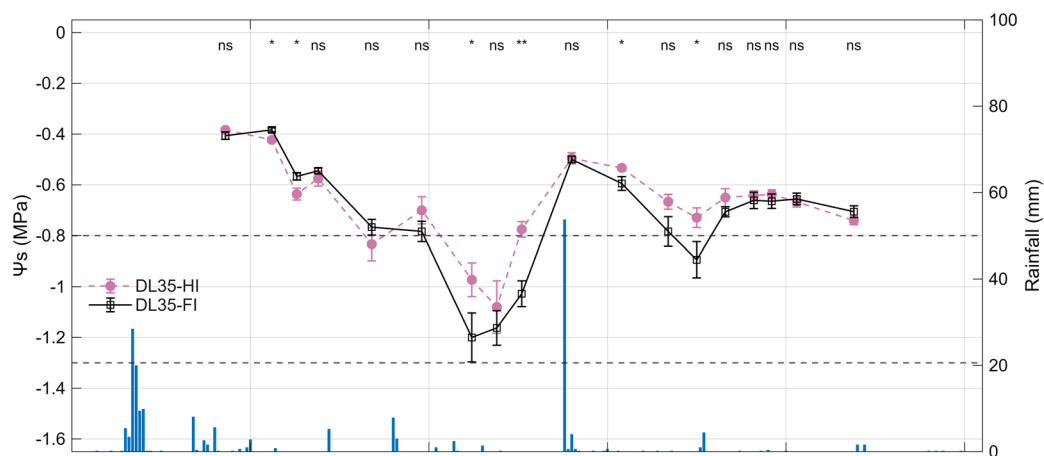
Fruit drop

As part of the additional year conducted in 2015 to extend the study, fruit drop was quantified by counting, on a weekly basis, the abscised reproductive organs (flowers and developing fruits) collected beneath the canopy of three randomly selected trees per treatment plot within each block ($n=9$ trees per treatment). Crop load was not regulated during the experiment; no flower bud or fruit thinning was performed, in accordance with common regional practice for persimmon and to avoid confounding fruit abscission dynamics (Badenes et al. 2015). This approach enabled evaluation of yield and fruit quality under unthinned crop-load conditions representative of commercial practice. These measurements were conducted in the DL-FI, DV-110, and DV-SDI treatments from late April through September–October, until abscission ceased. Because ‘Rojo Brillante’ produces only female flowers and fruit development occurs via parthenocarp, no distinction between pollinated and seedless fruits was applicable. Sampled trees were selected from the central area of each plot and were surrounded by guard trees, thereby minimising any potential interference from neighbouring plots. Additionally, the fruit drop-to-flowering ratio

2012



2013



2014

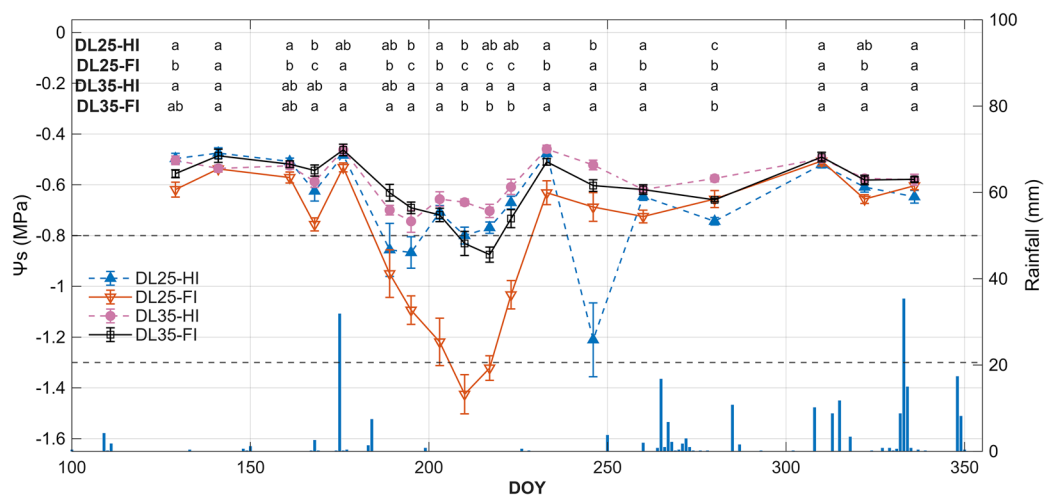


Fig. 2 Rainfall (blue bars) and midday stem water potential, Ψ_s (colour lines), during the growing season for the different irrigation treatments in *Diospyros lotus* rootstock in 2012, 2013 and 2014. Points represent means $\pm$ standard error ($n=12$ per treatment and sampling date). Horizontal dotted lines at -0.80 MPa and -1.30 MPa indicate thresholds for mild and severe water stress, respectively. Treatment abbreviations are defined as follows: DL, *D. lotus*; 25 and 35 denote planting layouts 2.5×5 m and 3.5×5 m, respectively; FI and HI denote full irrigation (100% of BID) and high irrigation (115% of BID), respectively; BID is the baseline irrigation dose computed from ET_c . Statistical differences among treatments at each sampling date were assessed using linear mixed-effects models with block as a random effect. When significant effects were detected, pairwise comparisons were performed using model-based contrasts with Holm adjustment. In 2014, different lowercase letters indicate significant differences among treatments ($p < 0.05$), whereas in 2012 and 2013, where only two treatments were compared, significance is indicated as ns, * ($p < 0.05$) or ** ($p < 0.01$)

was calculated as the percentage of fallen flowers and fruits relative to total flowering, where total flowering was defined as the sum of harvested fruits and the cumulative number of fallen flowers and developing fruits per tree.

Data analysis

Data quality assurance and quality control (QA/QC)

Prior to statistical analysis, all datasets underwent quality assurance and quality control procedures. Records flagged as anomalous in the experimental database were excluded. Data completeness and internal consistency were assessed for all variables, and missing values were treated as missing rather than imputed. For tree-based measurements, guard trees were excluded, and analyses were restricted to the predefined sampled trees. In addition, duplicate records for the same treatment, year, block, and tree were removed, retaining a single observation per unique experimental unit. Weather and irrigation datasets were checked for completeness and consistency prior to computing derived variables. All QA/QC steps were applied consistently across years and variables before model fitting.

Statistical analysis

Statistical data analysis was performed using MATLAB (The MathWorks Inc. 2023). Results are expressed as the mean $\pm$ standard error, and the significance level was established at $p < 0.05$ for all statistics. The normality of the data distribution was evaluated using the Kolmogorov–Smirnov test. To examine the robustness and temporal stability of treatment effects, statistical analyses were performed both for each season and across all years combined. For the 2012–2014 period, statistical analyses were performed separately for each rootstock. Within each rootstock, linear mixed-effects models (LMMs) were fitted with treatment, defined as the combination of irrigation regime and planting layout,

as a fixed effect and block as a random effect. In addition, an analysis across seasons was conducted within each rootstock using a mixed-effects model with treatment as a fixed effect and year and block as random effects. Accordingly, the design allowed within-rootstock comparisons among treatment combinations, but did not allow formal estimation of a rootstock $\times$ irrigation interaction across the full set of treatments. In 2015, when the study was extended to compare selected treatments across rootstocks (DL-FI, DV-110, DV-SDI), differences among these treatments were analysed using a mixed-effects model with treatment as a fixed effect and block as a random effect. Because irrigation levels were not shared across rootstocks in 2015, irrigation-by-rootstock interaction was not estimable. When significant fixed effects were detected, post hoc pairwise comparisons among treatments were conducted using model-based estimates from the mixed-effects models, with p -values adjusted using the Holm procedure to control the family-wise error rate for multiple comparisons.

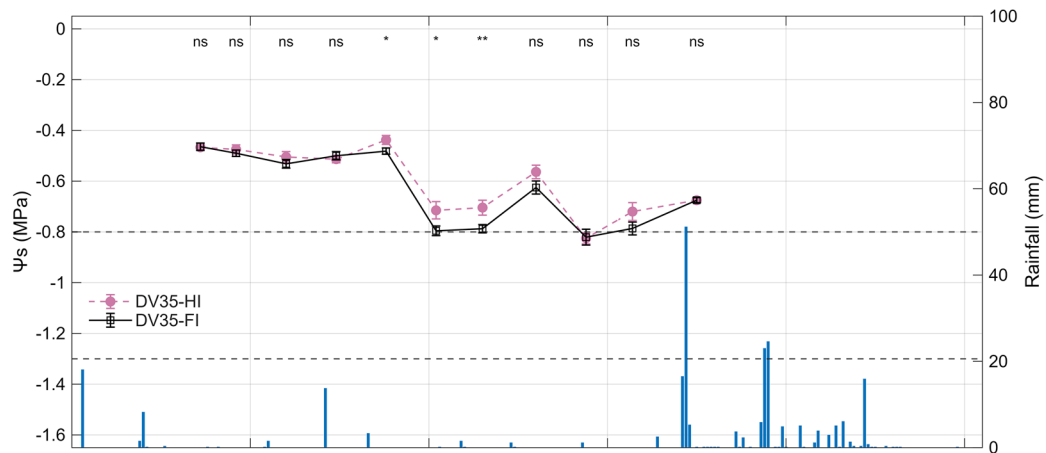
Results

Amount of water applied and water status of persimmon trees in the 2012–2014 period

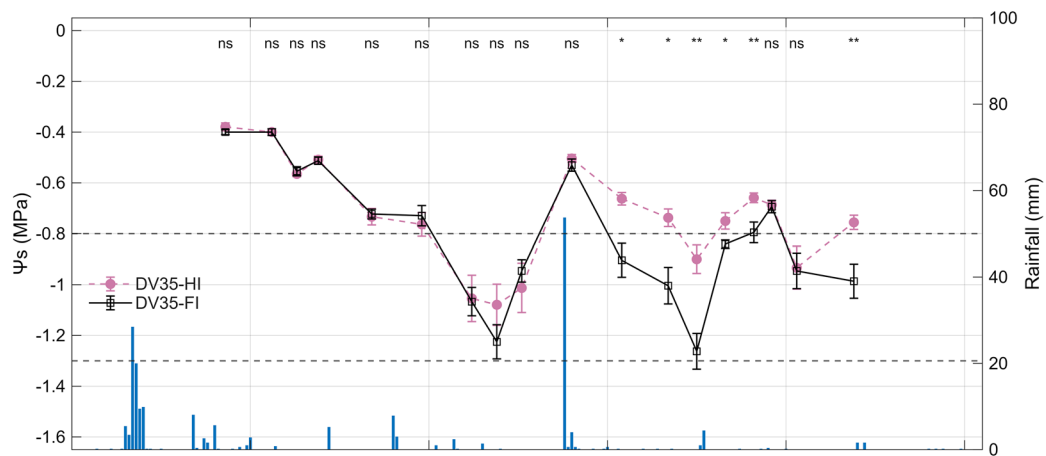
During this period, 2014 recorded the highest ET_o (1,197 mm) and the lowest rainfall (275 mm), whereas 2012 showed the highest rainfall (335 mm) and 2013 the lowest ET_o (1,142 mm). Daily dynamics for each year are shown in Fig. 1. Seasonal irrigation volumes increased markedly over the study period. From 2012 to 2014, the applied irrigation volume increased by approximately 80% under both FI and HI, with similar increases across both rootstocks. By design, 25-layout treatments received the same seasonal irrigation volume per tree as their corresponding 35-layout treatments; however, because the ground area per tree was smaller in the 2.5×5 m layout, this resulted in an approximately 40% higher irrigation depth per unit ground area compared with the 3.5×5 m layout (Table 1).

In the DL rootstock, Ψ_s under the FI control treatment (DL35-FI, 100% BID) remained generally above the severe stress threshold of -1.30 MPa across seasons, with a seasonal range of -0.42 to -0.82 MPa in 2012, -0.38 to -1.20 MPa in 2013, and -0.46 to -0.88 MPa in 2014 (Fig. 2). In 2014, DL25-HI showed a less negative Ψ_s seasonal minimum (-1.17 MPa) than DL25-FI (-1.43 MPa), indicating partial mitigation of the most pronounced water stress episodes. By contrast, in the 35-layout treatments, the seasonal Ψ_s minima were less negative (DL35-HI: -0.74 MPa, DL35-FI: -0.88 MPa), particularly during the mid-season period of highest evaporative demand, consistent with a more

2012



2013



2014

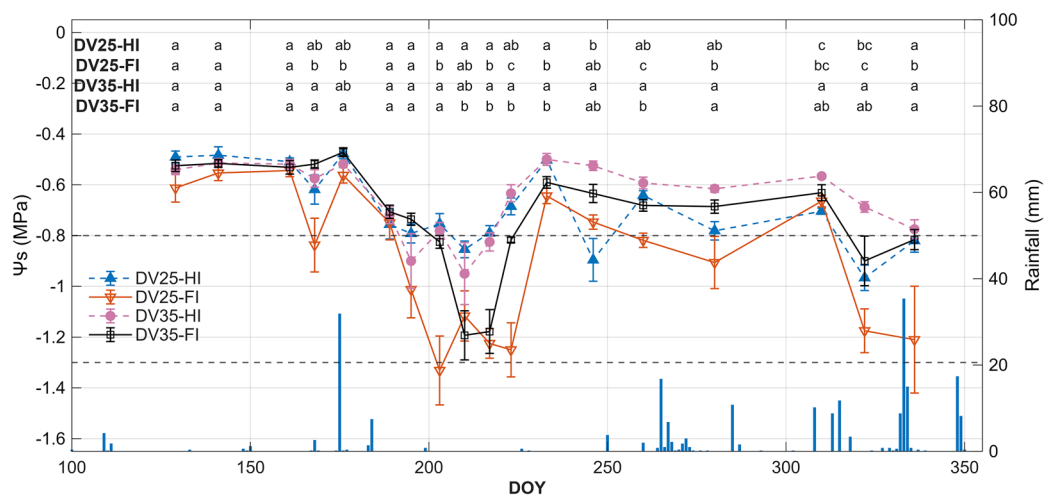


Fig. 3 Rainfall (blue bars) and midday stem water potential, Ψ_s (colour lines), during the growing season for the different irrigation treatments in *Diospyros virginiana* rootstock in 2012, 2013 and 2014. Points represent means $\pm$ standard error ($n=12$ per treatment and sampling date). Horizontal dotted lines at -0.80 MPa and -1.30 MPa indicate thresholds for mild and severe water stress, respectively. Treatment abbreviations are defined as follows: DV, *D. virginiana*; 25 and 35 denote planting layouts 2.5×5 m and 3.5×5 m, respectively; FI and HI denote full irrigation (100% of BID) and high irrigation (115% of BID), respectively; BID is the baseline irrigation dose computed from ET_c . Statistical differences among treatments at each sampling date were assessed using linear mixed-effects models with block as a random effect. When significant effects were detected, pairwise comparisons were performed using model-based contrasts with Holm adjustment. In 2014, different lowercase letters indicate significant differences among treatments ($p < 0.05$), whereas in 2012 and 2013, where only two treatments were compared, significance is indicated as ns, * ($p < 0.05$) or ** ($p < 0.01$)

buffered water status under the wider planting layout. Overall, HI tended to be associated with less negative Ψ_s values than the corresponding FI treatments during the mid-season peak in evaporative demand, but treatment contrasts were sampling-date-dependent rather than reflecting a uniform seasonal shift. Occasional reversals were observed on specific dates and are discussed in the context of subsequent agronomic responses in the next section.

In the DV rootstock, Ψ_s values followed comparable seasonal dynamics across years, with the FI control (DV35-FI, 100% BID) remaining generally above the severe stress threshold of -1.30 MPa, although short stress episodes were recorded in 2013 (seasonal range: -0.40 to -1.26 MPa) (Fig. 3). In 2012, Ψ_s in DV35-FI ranged from -0.46 to -0.82 MPa, and in DV35-HI from -0.44 to -0.83 MPa. In 2014, the 25-layout FI treatment showed the most negative minimum (DV25-FI: -1.33 MPa), crossing the -1.30 MPa threshold, whereas DV25-HI exhibited a less negative minimum (-0.99 MPa), indicating partial attenuation of peak stress. In the 35-layout treatments, seasonal minima were less negative (DV35-HI: -0.95 MPa; DV35-FI: -1.19 MPa), consistent with a more buffered water status under the wider planting layout, particularly during the mid-season period of highest evaporative demand. Consistent with the within-rootstock patterns described above, differences between DV-HI and DV-FI were primarily evident around mid-season and varied across sampling dates rather than persisting as a constant seasonal offset.

Comparing rootstock Ψ_s values, paired differences in midday stem water potential were quantified as $\Delta\Psi_s = \Psi_s$ (DV) - Ψ_s (DL) for each sampling day after matching rootstocks within the same planting layout and irrigation regime, as shown in Fig. 4. In agreement with the overall rootstock means, midday Ψ_s was, on average, less negative in DL than in DV (mean Ψ_s : -0.68 MPa in DL vs. -0.77 MPa in DV), indicating a more buffered water status in DL across the dataset. Mixed model estimates of $\Delta\Psi_s$ were negative across

all planting layouts by irrigation combinations (Fig. 4A), showing that, under equivalent management conditions, DV tended to exhibit more negative midday Ψ_s values than DL. Effect sizes were modest, ranging from -0.017 to -0.119 MPa. The only difference that remained statistically significant after Holm adjustment was observed in the 35 HI treatment, where $\Delta\Psi_s$ was -0.119 MPa (95% CI, -0.190 to -0.047 ; p -Holm = 0.005). In the 25 HI treatment, $\Delta\Psi_s$ was -0.082 MPa (-0.157 to -0.007 ; p -Holm = 0.095). Under FI, estimated differences were small and not significant in either planting layout (25 FI: -0.017 MPa, -0.092 to 0.059 , p -Holm = 0.856 ; 35 FI: -0.029 MPa, -0.100 to 0.042 , p -Holm = 0.854), suggesting that rootstock-related contrasts in midday Ψ_s were less pronounced under the full irrigation regime.

The distribution of paired $\Delta\Psi_s$ values across sampling dates (Fig. 4B) revealed substantial day-to-day variability within each group, with both positive and negative deviations from zero. This indicates that the direction of the DV-DL contrast was not constant across the season and that transient reversals occurred on specific dates. Nevertheless, the central tendency remained negative across all groups, consistent with the mixed-model estimates and reinforcing the conclusion that DL generally sustained a higher, less negative, Ψ_s value than DV when compared under matched planting layouts and irrigation conditions.

Yield components and irrigation water productivity in 2012–2014

Yield increased steadily with tree growth, reaching values close to maturity levels in 2014, characterised by yields equivalent to about 50 t ha^{-1} (Puerto et al. 2021). In the DL rootstock, yield per tree showed limited treatment differentiation in 2012 and no significant differences in 2013 (Table 2). In 2012, DL35-HI recorded a higher yield per tree than DL25-FI (22.2 vs. $17.5 \text{ kg tree}^{-1}$), whereas DL25-HI and DL35-FI displayed intermediate values. In 2014, treatment effects became pronounced: DL25-FI produced significantly less ($64.8 \text{ kg tree}^{-1}$) than the other three treatments, which did not differ from one another and ranged from 85.7 to $87.1 \text{ kg tree}^{-1}$. When data were pooled for 2012–2014, DL25-FI again showed the lowest mean yield per tree ($40.9 \text{ kg tree}^{-1}$), whereas DL25-HI, DL35-HI, and DL35-FI exhibited comparable values of approximately 50 kg tree^{-1} . Expressing yield on an area basis revealed a consistent advantage of the denser planting layout (2.5×5 m) over the 3.5×5 m layout across seasons (Table 2). In 2012, yield per hectare was higher in DL25-HI than in both 35-layout treatments (16.2 vs. 12.7 – 10.9 t ha^{-1}), with DL25-FI showing intermediate values (14.0 t ha^{-1}). In 2013, both 25-layout treatments outperformed the

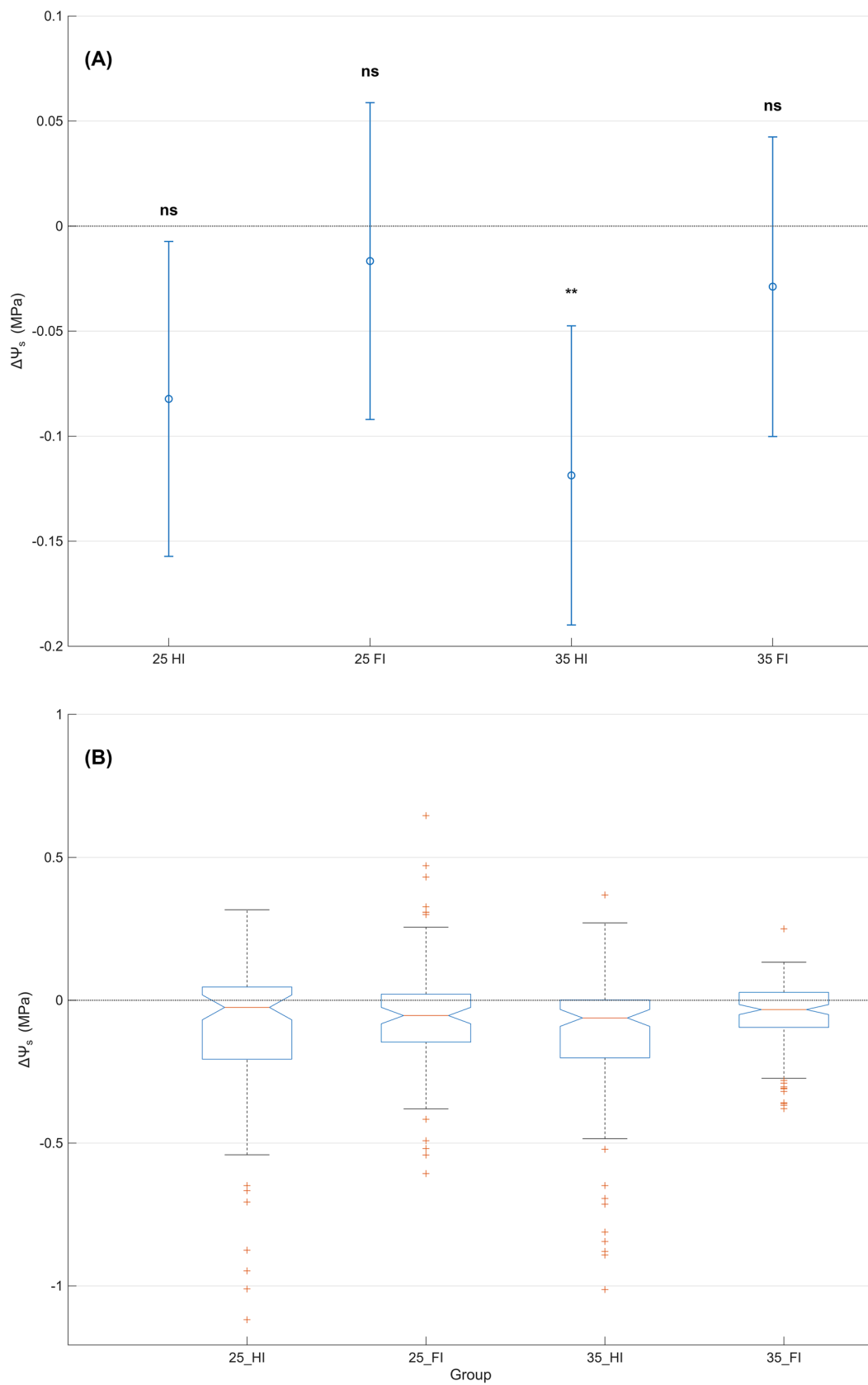


Fig. 4 Paired differences in midday stem water potential, $\Delta\Psi_s = \Psi_s(\text{DV}) - \Psi_s(\text{DL})$, computed for each sampling day of the year (DOY) within the year after matching rootstocks under the same planting layout and irrigation regime. Panel **A** shows mixed-model estimates of $\Delta\Psi_s$ for each combination of planting layout and irrigation regime with 95% confidence intervals; significance of the deviation from zero is indicated as ns, * ($p < 0.05$) or ** ($p < 0.01$) after Holm adjustment across the four groupwise contrasts. Panel **B** shows the distribution of paired $\Delta\Psi_s$ values by group (boxplots with notches). Treatment abbreviations are defined as follows: DV, *D. virginiana*; DL, *D. lotus*; 25 and 35 denote planting layouts 2.5×5 m and 3.5×5 m, respectively; HI and FI denote high irrigation (115% of BID) and full irrigation (100% of BID), respectively; BID is the baseline irrigation dose computed from ET_c

35-layout treatments ($32.3\text{--}34.0$ vs. $24.8\text{--}25.2$ t ha⁻¹). In 2014, DL25-HI achieved the highest yield per hectare (69.7 t ha⁻¹), significantly exceeding DL25-FI (51.8 t ha⁻¹) and both 35-layout treatments (49.0 to 49.8 t ha⁻¹), which did not differ from each other. During 2012–2014, the 25-layout maintained higher mean yields per hectare, with DL25-HI (40.1 t ha⁻¹) leading, followed by DL25-FI (32.7 t ha⁻¹), whereas both 35-layout treatments showed lower yields (28.4 to 29.3 t ha⁻¹).

In the DV rootstock, yield per tree did not differ significantly among treatments in any individual season or when data were pooled across 2012 to 2014 (Table 3). By contrast, expressing yield on an area basis revealed clear treatment effects driven primarily by planting layout. In 2012, DV25-FI achieved the highest yield per hectare (7.6 t ha⁻¹), significantly exceeding DV35-HI (1.3 t ha⁻¹), while DV25-HI and DV35-FI showed intermediate values. In 2013, both 25-layout treatments substantially outperformed the 35-layout treatments (DV25-HI and DV25-FI: $23.9\text{--}25.7$ t ha⁻¹ vs. DV35-HI and DV35-FI: $13.2\text{--}13.3$ t ha⁻¹). In 2014, DV25-HI and DV25-FI again recorded the highest yields per hectare (53.0 and 54.3 t ha⁻¹), significantly higher than DV35-HI (41.5 t ha⁻¹), whereas DV35-FI (42.9 t ha⁻¹) showed intermediate values. When averaged across 2012–2014, the 25-layout treatments maintained higher mean yields per hectare than the 35-layout treatments (26.9 to 29.2 vs. 17.2 to 19.9 t ha⁻¹), confirming a consistent advantage of the denser planting layout in DV rootstock.

Regarding fruit number, treatment effects were limited in the DL rootstock (Table 2). Differences were only apparent in 2014, when DL25-HI showed the highest fruit number (348 fruits tree⁻¹), exceeding DL25-FI and DL35-FI (270 to 274 fruits tree⁻¹), while DL35-HI was intermediate (293 fruits tree⁻¹). When averaged across 2012–2014, fruit number did not differ among DL treatments. In DV, fruit number per tree was generally similar among treatments across seasons (Table 3). In 2013, fruit number tended to be higher under the 25-layout than under the 35-layout, and across 2012–2014, DV25-FI showed the highest mean value (162 fruits tree⁻¹) and DV35-HI the lowest (133 fruits tree⁻¹),

with the remaining treatments being intermediate. Fruit weight showed clearer treatment patterns (Tables 2 and 3). In DL, fruit weight varied across all seasons. In 2012, DL25-HI produced the heaviest fruit (388 g), whereas DL25-FI and DL35-HI were lower (360 to 365 g), and DL35-FI was intermediate (371 g). In 2013, DL25-HI produced the largest fruit (263 g) and DL25-FI the smallest (205 g), with the 35-layout treatments intermediate ($219\text{--}239$ g). In 2014, both 35-layout treatments produced heavier fruit ($302\text{--}316$ g) than the 25-layout treatments ($251\text{--}254$ g). During 2012–2014, DL25-FI again showed the lowest mean fruit weight (276 g), whereas the other treatments converged at $303\text{--}306$ g. In DV, fruit weight differences were concentrated in 2013 and in the pooled analysis. In 2013, DV25-HI produced heavier fruit than DV25-FI (278 vs. 214 g), with the 35-layout treatments intermediate ($239\text{--}254$ g). Over 2012–2014, DV25-FI maintained a lower mean fruit weight (254 g) than DV25-HI and DV35-HI (287 and 281 g), while DV35-FI was intermediate (275 g).

Finally, IWP differed among treatments in both rootstocks. In DL, IWP was similar among treatments in 2012, but differences emerged in 2013 and 2014, when DL35-FI consistently achieved the highest values (8.95 and 11.70 kg m⁻³), while DL25-FI showed the lowest IWP in 2014 (8.83 kg m⁻³) (Table 2). Over 2012–2014, DL35-FI maintained the highest mean IWP (8.43 kg m⁻³), whereas the remaining treatments were similar (7.07 to 7.56 kg m⁻³). In DV rootstock, IWP differences were already apparent in 2012 and remained evident thereafter. DV25-FI showed the highest IWP in 2012 and 2013 (2.33 and 6.55 kg m⁻³), while DV35-HI recorded the lowest values (0.48 and 3.98 kg m⁻³) (Table 3). In 2014, DV35-FI reached the highest IWP (10.32 kg m⁻³), whereas DV25-HI reached the lowest (7.92 kg m⁻³). Across 2012–2014, the mean IWP was greatest in DV25-FI (6.05 kg m⁻³), with DV25-HI and DV35-HI remaining lower and comparable (4.58 to 4.77 kg m⁻³).

Vegetative growth of persimmon trees in the 2012–2014 period

In both rootstocks, canopy volume and TCA increased over time, with larger increments during the earlier seasons. In DL, canopy volume differed by treatment in 2012 and 2014, whereas canopy volume was similar across treatments in 2013 (Table 4). In 2014, DL25-FI showed the lowest canopy volume (4.60 m³ tree⁻¹), whereas the remaining treatments ranged from 5.23 to 5.33 m³ tree⁻¹. When averaged across 2012–2014, DL25-FI maintained a lower mean canopy volume than the other DL treatments. In DV, canopy volume did not differ among treatments in any season or in the 2012–2014 mean, with 2014 values ranging from 6.12 to 6.76 m³ tree⁻¹ (Table 5).

Table 2 Effect of irrigation treatments and planting layout on yield, number of fruits at harvest, fruit weight and irrigation water productivity per season in *Diospyros lotus* rootstock

	Year	DL25-HI	DL25-FI	DL35-HI	DL35-FI	<i>p</i> -value
Yield (kg tree ⁻¹)	2012	20.3±1.8 ab	17.5±1.7 b	22.2±2.4 a	19.1±2.5 ab	0.033
	2013	42.5±2.0	40.3±1.2	44.1±1.9	43.5±1.9	0.407
	2014	87.1±2.9 a	64.8±2.0 b	87.1±3.3 a	85.7±3.2 a	<0.001
	2012–2014	50.1±4.5 a	40.9±3.0 b	51.3±4.4 a	49.7±4.6 a	<0.001
Yield (T ha ⁻¹)	2012	16.2±1.5 a	14.0±1.4 ab	12.7±1.3 b	10.9±1.4 b	<0.001
	2013	34.0±1.6 a	32.3±0.9 a	25.2±1.1 b	24.8±1.1 b	<0.001
	2014	69.7±2.3 a	51.8±1.6 b	49.8±1.9 b	49.0±1.8 b	<0.001
	2012–2014	40.1±3.6 a	32.7±2.4 b	29.3±2.5 c	28.4±2.6 c	<0.001
No. fruits tree ⁻¹	2012	53±5	50±5	63±8	53±8	0.083
	2013	167±12	202±10	192±15	203±14	0.154
	2014	348±17 a	270±19 b	293±16 ab	274±14 b	0.004
	2012–2014	190±20	172±15	183±16	176±16	0.378
Fruit weight (g)	2012	388±4 a	360±7 b	365±7 b	371±9 ab	0.011
	2013	263±10 a	205±8 c	239±10 ab	219±8 bc	<0.001
	2014	254±7 b	251±10 b	302±10 a	316±7 a	<0.001
	2012–2014	303±10 a	276±10 b	304±9 a	306±11 a	<0.001
IWP (kg m ⁻³)	2012	4.30±0.37	4.32±0.43	4.72±0.51	4.70±0.64	0.412
	2013	7.42±0.37 b	8.27±0.24 ab	7.74±0.41 ab	8.95±0.47 a	0.025
	2014	10.31±0.44 b	8.83±0.26 c	10.22±0.33 b	11.70±0.46 a	<0.001
	2012–2014	7.34±0.44 b	7.07±0.34 b	7.56±0.42 b	8.43±0.54 a	0.001

Results are expressed as mean±standard error. DL, *D. lotus* rootstock. 25 and 35 denote planting layouts 2.5×5 m and 3.5×5 m, respectively. FI and HI denote full irrigation (100% of BID) and high irrigation (115% of BID), respectively. BID, baseline irrigation dose computed from ET_c. IWP, irrigation water productivity. P-values correspond to the fixed treatment effect (irrigation regime × planting layout) from a linear mixed-effects model. For each individual season (2012, 2013 and 2014), treatment was included as a fixed effect and block as a random effect. For the combined 2012–2014 analysis, treatment was included as a fixed effect, and year and block were treated as random effects. When a significant treatment effect was detected ($p < 0.05$), pairwise comparisons among treatments were performed using model-based contrasts, and p -values were adjusted for multiple testing using the Holm method. Different lowercase letters (a, b, c) within a row indicate statistically significant differences among treatments within the same season or for the combined 2012 to 2014 analysis. Bold values indicate statistically significant differences ($p < 0.05$)

TCA in DL differed consistently across treatments and seasons, as well as in the pooled 2012–2014 mean (Table 4). Across years, DL25-FI tended to show the lowest TCA, reaching 35.5 cm² in 2012, 45.3 cm² in 2013, and 52.8 cm² in 2014, whereas HI treatments and DL35-FI exhibited higher values, particularly in 2013 and 2014 (approximately 51.7–52.0 cm² in 2013 and 61.4–64.0 cm² in 2014). The pooled 2012–2014 mean confirmed this pattern, with DL25-FI at 44.5 cm², compared with 49.2–52.0 cm² in the remaining treatments. In DV rootstock, TCA was similar among treatments in 2012 and 2013, but differences became apparent in 2014, when DV35-HI reached 56.0 cm² and exceeded DV25-FI (46.6 cm²), while DV25-HI and DV35-FI remained intermediate (51.7 and 52.1 cm², respectively); the pooled 2012–2014 mean showed the same ordering (Table 5). Annual Δ TCA in DL did not differ among treatments in 2012 or 2013, whereas in 2014 DL35-FI showed the largest increase (28.6%) and DL25-FI the smallest (16.7%), with HI treatments showing intermediate values (18.9% in DL25-HI and 23.7% in DL35-HI) (Table 4). Mean Δ TCA across 2012–2014 was similar among DL treatments (34.7–38.8%). In DV, Δ TCA differed among treatments within

each season and in the pooled analysis, with DV25-FI consistently showing lower relative growth than the HI treatments, particularly in 2013 (25.6% vs. 38.1 to 45.0%) and in the pooled 2012–2014 mean (40.8% vs. 50.1 to 55.2%), while DV35-FI remained intermediate (Table 5).

Production efficiency increased over time in both rootstocks. In DL, treatment differences were evident in 2014, with DL25-FI showing lower production efficiency (1.23 kg cm⁻²) than the other treatments (1.36 to 1.42 kg cm⁻²), whereas in 2012, 2013 and in the pooled 2012–2014 mean values, treatments were similar (Table 4). In DV, production efficiency was comparable among treatments within individual seasons, with 2014 values ranging from 1.28 to 1.47 kg cm⁻²; however, the pooled 2012–2014 mean indicated higher production efficiency in DV25-FI (0.88 kg cm⁻²) than in DV35-HI (0.71 kg cm⁻²), with DV25-HI and DV35-FI remaining intermediate (0.75 and 0.68 kg cm⁻², respectively) (Table 5). The yield-to-annual- Δ TCA ratio showed limited separation among DL treatments across seasons and in the pooled analysis (Table 4). In DV, this ratio differed among treatments in 2013, 2014 and in the pooled 2012–2014 mean. In 2013, DV25-FI showed the highest value

Table 3 Effect of irrigation treatments and planting layout on yield, number of fruits at harvest, fruit weight and irrigation water productivity per season in *Diospyros virginiana* rootstock

	Year	DV25-HI	DV25-FI	DV35-HI	DV35-FI	<i>p</i> -value
Yield (kg tree ⁻¹)	2012	6.7±2.1	9.5±2.4	2.3±0.9	4.8±2.0	0.066
	2013	29.9±3.4	32.2±3.6	23.1±3.0	23.3±3.6	0.122
	2014	66.3±5.6	67.9±3.3	72.6±4.2	75.0±2.5	0.465
	2012–2014	33.7±4.4	36.5±4.0	34.8±4.7	30.1±4.9	0.591
Yield (T ha ⁻¹)	2012	5.4±1.7 ab	7.6±2.0 a	1.3±0.5 b	2.7±1.1 ab	0.014
	2013	23.9±2.7 a	25.7±2.9 a	13.2±1.7 b	13.3±2.0 b	<0.001
	2014	53.0±4.5 a	54.3±2.6 a	41.5±2.4 b	42.9±1.4 ab	0.003
	2012–2014	26.9±3.5 a	29.2±3.2 a	19.9±2.7 b	17.2±2.8 b	<0.001
No. fruits tree ⁻¹	2012	21±7	33±10	7±3	15±6	0.068
	2013	117±15 a	158±18 a	99±16 a	102±17 a	0.041
	2014	261±27	295±26	268±19	271±21	0.723
	2012–2014	130±18 ab	162±19 a	133±18 b	115±19 ab	0.026
Fruit weight (g)	2012	333±9	317±12	333±8	324±9	0.554
	2013	278±20 a	214±11 b	254±14 ab	239±8 ab	0.004
	2014	261±7	249±18	279±8	285±12	0.138
	2012–2014	287±9 a	254±10 b	281±8 a	275±8 ab	0.005
IWP (kg m ⁻³)	2012	1.40±0.43 ab	2.33±0.61 a	0.48±0.18 b	1.18±0.49 ab	0.040
	2013	5.24±0.59 ab	6.55±0.72 a	3.98±0.51 b	4.82±0.75 ab	0.045
	2014	7.92±0.73 b	9.26±0.43 ab	8.51±0.54 ab	10.32±0.39 a	0.034
	2012–2014	4.77±0.53 b	6.05±0.55 a	4.58±0.55 b	4.93±0.68 ab	<0.001

Results are expressed as mean±standard error. DV, *D. virginiana* rootstock. 25 and 35 denote planting layouts 2.5×5 m and 3.5×5 m, respectively. FI and HI denote full irrigation (100% of BID) and high irrigation (115% of BID), respectively. BID, baseline irrigation dose computed from ET_c. IWP, irrigation water productivity. P-values correspond to the fixed treatment effect (irrigation regime × planting layout) from a linear mixed-effects model. For each individual season (2012, 2013 and 2014), treatment was included as a fixed effect and block as a random effect. For the combined 2012 to 2014 analysis, treatment was included as a fixed effect and year and block were treated as random effects. When a significant treatment effect was detected ($p < 0.05$), pairwise comparisons among treatments were performed using model-based contrasts, and *p*-values were adjusted for multiple testing using the Holm method. Different lowercase letters (a, b, c) within a row indicate statistically significant differences among treatments within the same season or for the combined 2012 to 2014 analysis. Bold values indicate statistically significant differences ($p < 0.05$).

(4.34 kg cm⁻²), whereas DV35-HI and DV35-FI had lower values (1.56 and 2.30 kg cm⁻²); DV25-HI was intermediate (2.93 kg cm⁻²). In 2014, DV25-FI again reached the highest ratio (9.86 kg cm⁻²), exceeding DV35-HI (6.17 kg cm⁻²), while DV25-HI and DV35-FI were intermediate (7.58 and 7.26 kg cm⁻²). Over 2012–2014, DV25-FI maintained the highest mean ratio (4.99 kg cm⁻²), whereas the remaining treatments clustered at lower values (2.82 to 3.63 kg cm⁻²) (Table 5).

Comparison between *D. lotus* and *D. virginiana* rootstock control treatments

To provide a direct rootstock comparison under identical management, yield and growth variables were contrasted between *D. lotus* and *D. virginiana* under full irrigation and the standard planting layout (DL35-FI vs. DV35-FI) across 2012 to 2014 (Table 6). Under this matched-reference condition, DL consistently produced higher yields per tree than DV in each season and in the pooled 2012–2014 mean. Yield differences were pronounced in the first two seasons (2012: 19.1 vs. 4.8 kg tree⁻¹; 2013: 43.5 vs. 23.3 kg tree⁻¹)

and persisted in 2014 (85.7 vs. 75.0 kg tree⁻¹), resulting in a higher average yield over the experimental period in DL than in DV (49.7 vs. 30.1 kg tree⁻¹). Differences in fruit number largely paralleled the yield response. DL showed higher fruit number than DV in 2012 (53 vs. 15 fruits tree⁻¹) and 2013 (203 vs. 102 fruits tree⁻¹), whereas in 2014 both rootstocks reached similar fruit numbers (274 vs. 271 fruits tree⁻¹). When averaged across 2012–2014, fruit number remained higher in DL (176 fruits tree⁻¹) than in DV (115 fruits tree⁻¹). Fruit weight differed between rootstocks in all seasons and in the pooled analysis, although the direction was year-dependent. DL produced heavier fruit than DV in 2012 (371 vs. 324 g) and 2014 (316 vs. 285 g), whereas DV produced heavier fruit than DL in 2013 (239 vs. 219 g). Over 2012–2014, mean fruit weight remained higher in DL than in DV (306 vs. 275 g).

IWP was consistently higher in DL than in DV across all seasons, with marked differences in 2012 (4.70 vs. 1.18 kg m⁻³) and sustained separation in 2013 and 2014 (8.95 vs. 4.82 kg m⁻³; 11.70 vs. 10.32 kg m⁻³). The pooled 2012–2014 mean confirmed this pattern (8.43 vs. 4.93 kg m⁻³). In contrast, DV showed higher vegetative vigour indicators

Table 4 Influence of irrigation treatments and planting layout on vegetative and reproductive growth parameters of ‘Rojo Brillante’ grafted onto *Diospyros lotus* per season

	Year	DL25-HI	DL25-FI	DL35-HI	DL35-FI	<i>p</i> -value
Canopy ($\text{m}^3 \text{ tree}^{-1}$)	2012	2.82±0.16 ab	2.41±0.17 b	2.92±0.18 a	2.49±0.13 ab	0.008
	2013	4.73±0.12	4.17±0.23	4.58±0.16	4.67±0.20	0.110
	2014	5.33±0.16 a	4.60±0.18 b	5.23±0.21 ab	5.30±0.19 a	0.012
	2012–2014	4.29±0.15 a	3.73±0.19 b	4.24±0.18 a	4.15±0.18 a	<0.001
TCA (cm^2)	2012	41.0±1.1 a	35.5±1.2 b	40.1±1.5 a	37.9±1.1 ab	0.007
	2013	51.7±1.2 a	45.3±1.3 b	52.0±2.0 a	48.0±1.1 ab	0.004
	2014	61.4±1.4 a	52.8±1.6 b	64.0±2.1 a	61.7±1.6 a	<0.001
	2012–2014	51.3±1.3 a	44.5±1.4 b	52.0±1.9 a	49.2±1.3 a	<0.001
Annual Δ TCA (%)	2012	65.6±4.2	59.4±2.9	56.7±5.0	60.5±1.8	0.263
	2013	26.4±1.5	28.2±1.9	29.7±2.1	27.2±1.6	0.558
	2014	18.9±1.4 bc	16.7±1.6 c	23.7±2.3 ab	28.6±2.0 a	<0.001
	2012–2014	37.0±2.4	34.7±2.1	36.7±3.1	38.8±1.8	0.326
Production efficiency (kg cm^{-2})	2012	0.51±0.05	0.51±0.06	0.58±0.07	0.53±0.08	0.578
	2013	0.83±0.05	0.90±0.03	0.87±0.06	0.91±0.05	0.611
	2014	1.42±0.04 a	1.23±0.03 b	1.36±0.05 ab	1.40±0.05 a	0.006
	2012–2014	0.92±0.06	0.88±0.05	0.94±0.06	0.95±0.07	0.237
Ratio Yield/Annual Δ CTA (kg cm^{-2})	2012	1.35±0.17	1.47±0.17	1.79±0.30	1.44±0.23	0.236
	2013	4.13±0.33	4.31±0.31	4.05±0.39	4.42±0.33	0.856
	2014	9.84±0.93 a	10.13±1.25 a	8.38±1.12 a	6.53±0.48 a	0.050
	2012–2014	5.02±0.63	5.07±0.66	4.67±0.58	4.00±0.39	0.138

Results are expressed as mean±standard error. DL, *D. lotus* rootstock. 25 and 35 denote planting layouts 2.5×5 m and 3.5×5 m, respectively. FI and HI denote full irrigation (100% of BID) and high irrigation (115% of BID), respectively. BID, baseline irrigation dose computed from ET_c . Canopy, canopy volume. TCA, trunk cross-sectional area. Annual Δ TCA (%), annual relative increment in TCA expressed as a percentage of the initial seasonal TCA. P-values correspond to the fixed treatment effect (irrigation regime $\times$ planting layout) from linear mixed-effects models. For each individual season (2012, 2013 and 2014), treatment was included as a fixed effect and block as a random effect. For the combined 2012 to 2014 analysis, treatment was included as a fixed effect and year and block were treated as random effects. When a significant treatment effect was detected ($p < 0.05$), pairwise comparisons among treatments were performed using model-based contrasts, and *p*-values were adjusted for multiple testing using the Holm method. Different lowercase letters within a row indicate statistically significant differences among treatments within the same season or for the combined 2012 to 2014 analysis. Bold values indicate statistically significant differences ($p < 0.05$)

than DL. Canopy volume was greater in DV from 2013 onwards (2013: 5.66 vs. 4.67 $\text{m}^3 \text{ tree}^{-1}$; 2014: 6.12 vs. 5.30 $\text{m}^3 \text{ tree}^{-1}$), and the pooled mean canopy volume remained higher in DV (4.93 vs. 4.15 $\text{m}^3 \text{ tree}^{-1}$). Similarly, annual Δ TCA was higher in DV in 2012 and 2013 (96.8 vs. 60.5%; 33.2 vs. 27.2%), and across 2012–2014 (52.2 vs. 38.8%). Finally, yield relative to annual Δ TCA was higher in DL in 2012 and 2013 (1.44 vs. 0.38; 4.42 vs. 2.30 kg cm^{-2}) and in the pooled mean (4.00 vs. 2.98 kg cm^{-2}), whereas values converged in 2014 (6.53 vs. 7.26 kg cm^{-2}). Taken together, this matched-control comparison highlights contrasting patterns in vegetative growth and reproductive performance between rootstocks under the same irrigation dose and the standard planting layout. This comparison was based on a common reference treatment and does not represent a full factorial assessment of the rootstock $\times$ irrigation interaction.

Optimising irrigation strategies of *D. virginiana* rootstock

Following the 2012–2014 evaluation period, a new experimental stage was conducted in 2015 including three

treatments under the standard planting layout (3.5×5 m): DL-FI as the reference control (100% BID) and two *D. virginiana* treatments, DV-110 (110% BID) and DV-SDI (70% BID), to assess the response of *D. virginiana* to contrasting irrigation doses. Seasonal ET_c and rainfall in 2015 were 1,124 mm and 422 mm, respectively (Fig. 1). Consequently, the irrigation dose applied was 8.77 $\text{m}^3 \text{ tree}^{-1}$ in DL-FI, 9.62 $\text{m}^3 \text{ tree}^{-1}$ in DV-FI, and 6.18 $\text{m}^3 \text{ tree}^{-1}$ in DV-SDI (Table 7). The evolution of Ψ_s throughout the 2015 season is shown in Fig. 5. DL-FI and DV-110 maintained comparable water status, with Ψ_s ranging from -0.73 to -0.44 MPa in DL-FI and from -0.72 to -0.43 MPa in DV-110. By contrast, the sustained deficit irrigation imposed on DV-SDI resulted in consistently lower Ψ_s values, with a seasonal range from -1.49 to -0.51 MPa, reaching the minimum during the final stage of fruit development and ripening (Fig. 5).

The influence of irrigation dose on the pattern of physiological flower and fruit drop varied between rootstocks, as shown in Fig. 6. Two distinct waves of fruit drop were observed in DL-FI, whereas the *D. virginiana* treatments showed a less pronounced second wave, particularly under

Table 5 Influence of irrigation treatments and planting layout on vegetative and reproductive growth parameters of ‘Rojo Brillante’ grafted onto *Diospyros virginiana* per season

	Year	DV25-HI	DV25-FI	DV35-HI	DV35-FI	<i>p</i> -value
Canopy (m ³ tree ⁻¹)	2012	3.01±0.23	3.24±0.17	2.80±0.17	3.01±0.25	0.484
	2013	5.81±0.27	5.66±0.27	5.65±0.34	5.66±0.35	0.979
	2014	6.76±0.31	6.42±0.26	6.29±0.34	6.12±0.37	0.564
	2012–2014	5.19±0.27	5.11±0.23	4.91±0.28	4.93±0.32	0.684
TCA (cm ²)	2012	30.9±1.5	31.1±0.9	30.9±2.0	31.0±1.6	0.994
	2013	41.9±1.4	38.9±0.9	44.0±2.2	41.1±1.7	0.118
	2014	51.7±1.8 ab	46.6±1.3 b	56.0±3.2 a	52.1±2.4 ab	0.002
	2012–2014	41.5±1.6 ab	38.8±1.0 b	43.6±2.5 a	41.4±1.9 ab	0.004
Annual ΔTCA (%)	2012	89.0±3.7 a	76.8±3.7 a	91.7±4.7 a	96.8±9.1 a	0.034
	2013	38.1±4.5 a	25.6±2.0 b	45.0±5.0 a	33.2±2.1 ab	0.045
	2014	23.3±1.9 ab	20.0±2.0 b	29.0±1.6 a	26.7±1.9 ab	0.004
	2012–2014	50.1±3.4 a	40.8±2.6 b	55.2±3.8 a	52.2±4.4 a	<0.001
Production efficiency (kg cm ⁻²)	2012	0.27±0.09	0.31±0.08	0.09±0.03	0.17±0.07	0.122
	2013	0.72±0.08	0.84±0.10	0.57±0.07	0.58±0.09	0.078
	2014	1.28±0.10	1.47±0.08	1.35±0.09	1.47±0.07	0.333
	2012–2014	0.75±0.09 ab	0.88±0.09 a	0.71±0.09 b	0.68±0.10 ab	0.020
Ratio Yield/Annual ΔCTA (kg cm ⁻²)	2012	0.60±0.21	0.76±0.20	0.19±0.07	0.38±0.16	0.078
	2013	2.93±0.46 ab	4.34±0.58 a	1.56±0.18 b	2.30±0.41 b	<0.001
	2014	7.58±1.08 ab	9.86±0.97 a	6.17±0.56 b	7.26±0.59 ab	0.014
	2012–2014	3.63±0.59 b	4.99±0.68 a	2.82±0.46 b	2.98±0.52 b	<0.001

Results are expressed as mean±standard error. DV, *D. virginiana* rootstock. 25 and 35 denote planting layouts 2.5×5 m and 3.5×5 m, respectively. FI and HI denote full irrigation (100% of BID) and high irrigation (115% of BID), respectively. BID, baseline irrigation dose computed from ET_c. Canopy, canopy volume. TCA, trunk cross-sectional area. Annual ΔTCA (%), annual relative increment in TCA expressed as a percentage of the initial seasonal TCA. P-values correspond to the fixed treatment effect (irrigation regime × planting layout) from linear mixed-effects models. For each individual season (2012, 2013 and 2014), treatment was included as a fixed effect and block as a random effect. For the combined 2012 to 2014 analysis, treatment was included as a fixed effect and year and block were treated as random effects. When a significant treatment effect was detected ($p < 0.05$), pairwise comparisons among treatments were performed using model-based contrasts, and *p*-values were adjusted for multiple testing using the Holm method. Different lowercase letters within a row indicate statistically significant differences among treatments within the same season or for the combined 2012 to 2014 analysis. Bold values indicate statistically significant differences ($p < 0.05$)

DV-SDI. Differences among treatments were mainly associated with the second wave, with DL-FI showing higher fruit drop than the *D. virginiana* treatments, and DV-SDI showing a localised reduction of fruit drop during this period. No clear treatment differences were observed during the first wave. By the end of the season, cumulative fruit drop curves showed high variability and limited separation among treatments (Fig. 7). Nevertheless, the fruit drop to flowering ratio differed among treatments (Table 7), being highest in DV-110 (86.95%), intermediate in DL-FI (79.91%), and lowest in DV-SDI (72.84%).

Yield components and growth responses to irrigation strategy in 2015 are summarised in Table 7. Yield per tree was similar among treatments, with values of 77.9 kg in DL-FI, 75.1 kg in DV-SDI, and 66.4 kg in DV-110. Fruit number was higher in DV-SDI (338 fruits tree⁻¹) and DL-FI (299 fruits tree⁻¹) than in DV-110 (222 fruits tree⁻¹). As expected, mean fruit weight followed the opposite ranking, with the highest value in DV-110 (306 g), intermediate in DL-FI (264 g), and the lowest in DV-SDI (223 g). As a result, IWP differed among treatments, reaching its

highest value in DV-SDI (12.11 kg m⁻³), followed by DL-FI (8.94 kg m⁻³) and DV-110 (6.88 kg m⁻³).

Additionally, canopy volume was significantly greater in DV-110 (7.83 m³ tree⁻¹) than in DL-FI (6.49 m³ tree⁻¹), while DV-SDI (7.24 m³ tree⁻¹) showed intermediate values. Yield efficiency was similar among treatments. By contrast, annual relative ΔTCA differed among irrigation strategies, with the highest value in DV-110 (28.34%), the lowest in DL-FI (16.11%), and DV-SDI intermediate (20.23%). The ratio Yield/ΔTCA was higher in DL-FI (8.79 kg cm⁻²) than in DV-110 (4.53 kg cm⁻²), with DV-SDI again showing intermediate values (7.74 kg cm⁻²).

Discussion

Ψ_s patterns show that control and 115% BID treatments remained above the severe stress threshold of −1.30 MPa throughout the study period (Badal et al. 2010; Martínez-Gimeno et al. 2017). Under the dense 2.5 m spacing at 100% BID (25-FI), Ψ_s occasionally fell below this threshold during summer, as observed in DL25-FI and DV25-FI in 2014,

Table 6 Comparison of *Diospyros lotus* and *Diospyros virginiana* rootstocks under full irrigation at the standard planting layout (3.5 × 5 m) during 2012 to 2014

	Year	DL35-FI	DV35-FI	<i>p</i> -value
Yield (kg tree ⁻¹)	2012	19.1 ± 2.5 a	4.8 ± 2.0 b	<0.001
	2013	43.5 ± 1.9 a	23.3 ± 3.6 b	<0.001
	2014	85.7 ± 3.2 a	75.0 ± 2.5 b	0.020
	2012–2014	49.7 ± 4.6 a	30.1 ± 4.9 b	<0.001
No. fruits tree ⁻¹	2012	53 ± 8 a	15 ± 6 b	<0.001
	2013	203 ± 14 a	102 ± 17 b	<0.001
	2014	274 ± 14	271 ± 21	0.887
	2012–2014	176 ± 16 a	115 ± 19 b	<0.001
Fruit weight (g)	2012	371 ± 9 a	324 ± 9 b	<0.001
	2013	219 ± 8 b	239 ± 8 a	<0.001
	2014	316 ± 7 a	285 ± 12 b	0.020
	2012–2014	306 ± 11 a	275 ± 8 b	<0.001
IWP (kg m ⁻³)	2012	4.70 ± 0.64 a	1.18 ± 0.49 b	<0.001
	2013	8.95 ± 0.47 a	4.82 ± 0.75 b	<0.001
	2014	11.70 ± 0.46 a	10.32 ± 0.39 b	0.035
	2012–2014	8.43 ± 0.54 a	4.93 ± 0.68 b	<0.001
Canopy (m ³ tree ⁻¹)	2012	2.49 ± 0.13	3.01 ± 0.25	0.052
	2013	4.67 ± 0.20 b	5.66 ± 0.35 a	0.018
	2014	5.30 ± 0.19 b	6.12 ± 0.37 a	0.034
	2012–2014	4.15 ± 0.18 b	4.93 ± 0.32 a	<0.001
Annual ΔTCA (%)	2012	60.5 ± 1.8 b	96.8 ± 9.1 a	<0.001
	2013	27.2 ± 1.6 b	33.2 ± 2.1 a	0.021
	2014	28.6 ± 2.0	26.7 ± 1.9	0.476
	2012–2014	38.8 ± 1.8 b	52.2 ± 4.4 a	0.001
Ratio Yield/Annual ΔCTA (kg cm ⁻²)	2012	1.44 ± 0.23 a	0.38 ± 0.16 b	<0.001
	2013	4.42 ± 0.33 a	2.30 ± 0.41 b	<0.001
	2014	6.53 ± 0.48	7.26 ± 0.59	0.320
	2012–2014	4.00 ± 0.39 a	2.98 ± 0.52 b	0.008

Results are expressed as mean ± standard error. DL and DV denote *D. lotus* and *D. virginiana* rootstocks, respectively. 35 denotes the standard planting layout (3.5 × 5 m). FI denotes full irrigation (100% of BID), where BID is the baseline irrigation dose computed from ET_c. IWP, irrigation water productivity. P-values correspond to the fixed rootstock effect (DL35-FI vs. DV35-FI) from a linear mixed-effects model. For each season, rootstock was included as a fixed effect, and block was included as a random effect. For the combined 2012–2014 analysis, rootstock was included as a fixed effect, and year and block were treated as random effects. When a significant effect was detected ($p < 0.05$), pairwise comparisons were based on model estimates and *p*-values were adjusted using the Holm method. Different lowercase letters (a, b) within a row indicate statistically significant differences between rootstocks within the same season or for the combined 2012 to 2014 analysis. Bold values indicate statistically significant differences ($p < 0.05$)

likely reflecting increased within-row competition together with the prevailing atmospheric demand. As expected, 115% BID treatments tended to maintain less negative Ψ_s values than 100% BID, although significant differences appeared only under the 2.5 m planting layout treatments in 2014. Under matched planting layout and irrigation regime, the paired analysis of Ψ_s showed a negative central tendency

Table 7 2015 comparison among selected treatment combinations (rootstock × irrigation strategy) in ‘Rojo Brillante’ persimmon: vegetative growth, yield components, fruit drop, and irrigation water productivity

	DL-FI (Control 100% BID)	DV-110 (110% BID)	DV-SDI (70% BID)	<i>p</i> -value
Irrigation doses applied (m ³ tree ⁻¹) [mm]	8.77 [501]	9.62 [550]	6.18 [353]	-
Yield (kg tree ⁻¹)	77.9 ± 2.7	66.4 ± 5.2	75.1 ± 3.8	0.111
No. fruits tree ⁻¹	299 ± 15 a	222 ± 20 b	338 ± 17 a	<0.001
Fruit drop to flowering (%)	79.91 ± 1.43 b	86.95 ± 1.54 a	72.84 ± 2.33 c	<0.001
Fruit weight (g)	264 ± 6 b	306 ± 7 a	223 ± 6 c	<0.001
IWP (kg m ⁻³)	8.94 ± 0.39 b	6.88 ± 0.52 c	12.11 ± 0.61 a	<0.001
Canopy (m ³ tree ⁻¹)	6.49 ± 0.24 b	7.83 ± 0.40 a	7.24 ± 0.39 ab	0.032
TCA (cm ²)	71.5 ± 1.7	65.3 ± 3.7	66.9 ± 3.6	0.328
ΔTCA (%)	16.11 ± 1.69 b	28.34 ± 1.17 a	20.23 ± 2.41 b	0.001
Yield efficiency (kg cm ⁻²)	1.09 ± 0.04	1.02 ± 0.08	1.17 ± 0.07	0.242
Ratio Yield/ΔTCA (kg cm ⁻²)	8.79 ± 1.03 a	4.53 ± 0.55 b	7.74 ± 0.79 a	0.008

Results are expressed as mean ± standard error. Treatments represent the combination of rootstock and irrigation strategy in 2015: DL-FI, *D. lotus* under full irrigation (100% of BID); DV-110, *D. virginiana* receiving 110% of BID; and DV-SDI, *D. virginiana* under sustained deficit irrigation (70% of BID). BID, baseline irrigation dose computed from ET_c. Values in brackets are irrigation depth (mm) calculated from the ground area per tree for the 3.5 × 5 m planting layout. P-values correspond to the fixed treatment effect from linear mixed-effects models, with block treated as a random effect. When a significant treatment effect was detected ($p < 0.05$), pairwise comparisons among treatments were performed using model-based contrasts, and *p*-values were adjusted for multiple testing using the Holm method. Different lowercase letters within a row indicate statistically significant differences among treatments in 2015. Bold values indicate statistically significant differences ($p < 0.05$)

across all management combinations, indicating that *D. virginiana* generally operated at more negative midday Ψ_s than *D. lotus*. However, effect sizes were modest, and the signal was not uniform across groups, being most evident under HI in the 3.5 × 5 m layout, whereas differences were weaker under full irrigation. The distribution of paired $\Delta\Psi_s$ values further highlighted substantial day-to-day variability and transient reversals, suggesting that rootstock differences in plant water status reflect a dynamic balance between hydraulic regulation and canopy demand rather than a fixed seasonal offset.

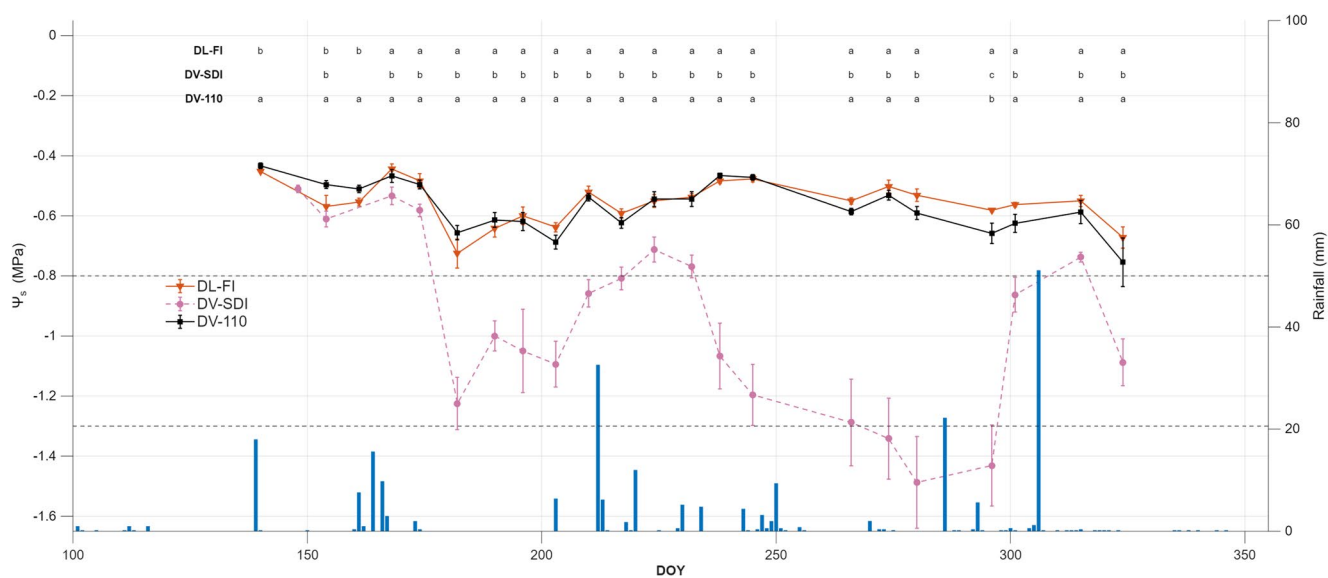


Fig. 5 Rainfall (blue bars) and midday stem water potential, Ψ_s (coloured lines), during the 2015 growing season for the three treatments included in the extended trial: DL-FI, DV-110 and DV-SDI. Points represent means $\pm$ standard error ($n=6$ trees per treatment). Horizontal dashed lines at -0.80 MPa and -1.30 MPa indicate thresholds for mild and severe water stress, respectively. Treatment abbreviations are defined as follows: DL and DV denote *D. lotus* and *D. virginiana* rootstocks, respectively; FI denotes full irrigation at 100% of the baseline irrigation dose (BID); DV-110 denotes *D. virginiana*

receiving 110% of BID; SDI denotes sustained deficit irrigation at 70% of BID. Differences among treatments at each sampling date were assessed using linear mixed-effects models with block as a random effect. When significant effects were detected ($p < 0.05$), pairwise comparisons were performed using model-based contrasts, with p -values adjusted using the Holm procedure; different lowercase letters indicate statistically significant differences among treatments within the same sampling date

By 2014, yields in both rootstocks reached maturity levels of 70 to 100 kg tree⁻¹, equivalent to about 50 t ha⁻¹, consistent with previous reports for ‘Rojo Brillante’ (Badal et al. 2010; Fernandez-Zamudio et al. 2020; Parra et al. 2021; Puerto et al. 2021). Yet, in *D. lotus*, the yield depression observed in DL25-FI in 2014 coincided with the period when Ψ_s fell below -1.30 MPa, supporting the interpretation that severe stress episodes can translate into reduced productivity under this rootstock. In *D. virginiana*, a comparable summer decline in Ψ_s in DV25-FI did not coincide with a clear reduction in yield per tree, suggesting that yield formation may be less tightly coupled to short severe-stress excursions in this rootstock under the conditions tested. This pattern suggests that, under the conditions of this study, yield in *D. lotus* may be more tightly coupled to episodes in which Ψ_s drops below the severe-stress threshold of -1.30 MPa, whereas in *D. virginiana*, yield appeared less responsive to comparable short-term declines in Ψ_s . From a practical perspective, this raises the possibility that the -1.30 MPa benchmark, originally proposed as a severe-stress reference in *D. lotus*, may be conservative when directly applied to *D. virginiana*, at least when threshold crossings are transient and occur under the tested conditions, in line with recent evidence reported for mature ‘Rojo Brillante’ orchards under spring-regulated deficit irrigation (Román et al. 2026). However, this apparent decoupling should not be

interpreted as a straightforward drought advantage, because *D. virginiana* also tended to operate at more negative midday Ψ_s under matched management; rather, it likely reflects rootstock-specific interactions among vegetative vigour, crop load, and whole-tree water use. Root architectural differences may contribute to this behaviour, since *D. lotus* is often described as having a fibrous, predominantly shallow root system, whereas *D. virginiana* is associated with a more developed taproot, traits that may influence the spatial pattern of soil water uptake and whole-tree hydraulics under drip irrigation (Visconti et al. 2017). Overall, these results indicate that the agronomic response to planting density and irrigation dose depends on the extent to which severe stress is avoided and, on the rootstock-specific balance between vegetative growth and reproductive performance. At the hectare scale, planting layout produced contrasting responses depending on rootstock and irrigation regime. In *D. lotus*, layout increased yield per hectare under both irrigation doses, with the advantage being most evident under 100% BID in 2012 and under 115% BID in 2013 and 2014, whereas yields under the 3.5 $\times$ 5 m layout remained consistently lower across seasons. Conversely, in *D. virginiana*, the denser layout also increased yield per hectare under 100% BID and maintained an advantage under 115% BID in the pooled 2012–2014 comparison, indicating that closer

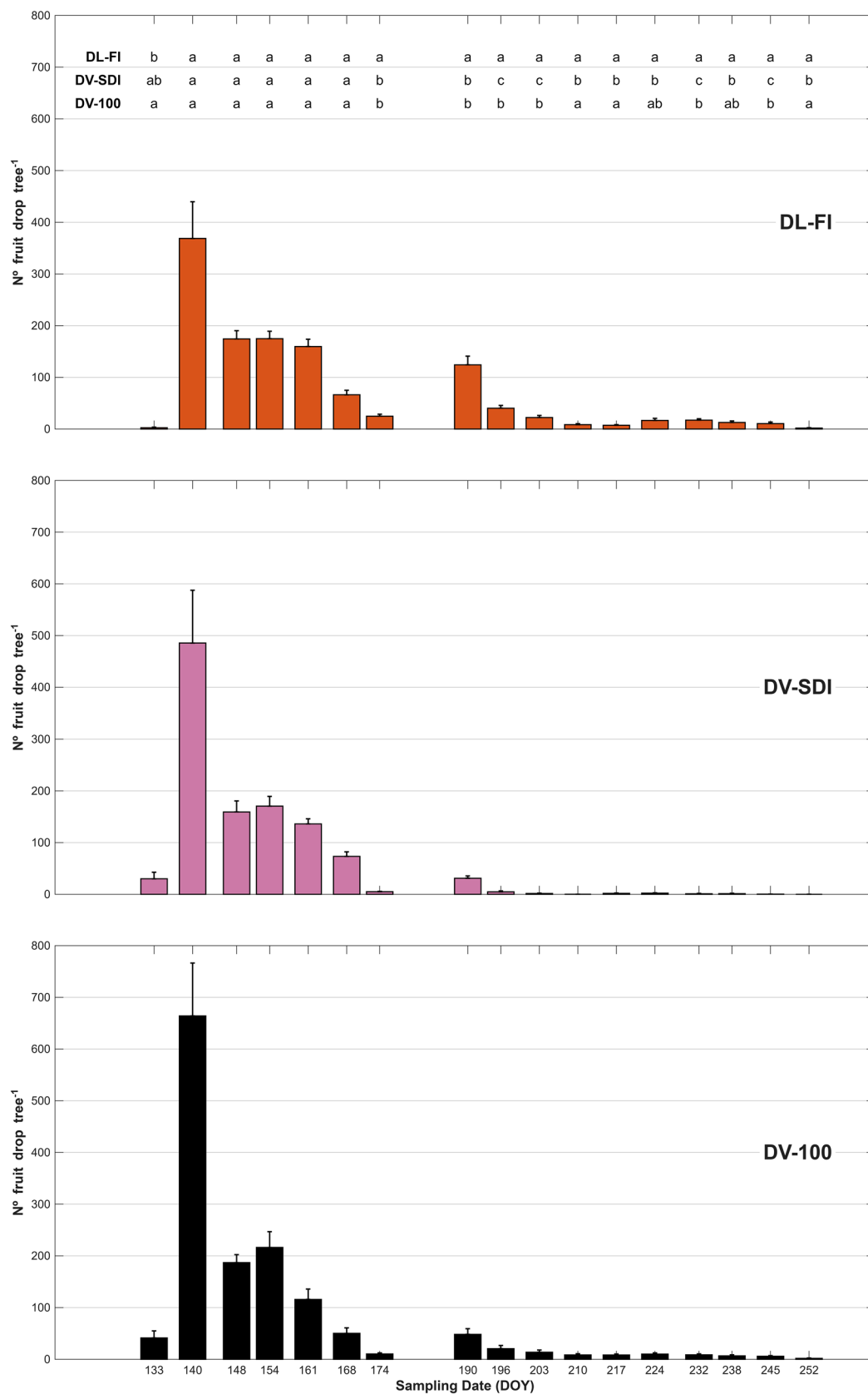


Fig. 6 Weekly fruit drop dynamics during the 2015 season for the three treatments included in the extended trial, per tree at each sampling date. Data are presented for DL-FI, DV-110 and DV-SDI, with bars representing means $\pm$ standard error ($n=9$ trees per treatment). The x-axis denotes sampling date (DOY). Treatment abbreviations are defined as follows: DL and DV denote *D. lotus* and *D. virginiana* rootstocks, respectively; FI denotes full irrigation at 100% of the baseline irrigation dose (BID); DV-110 denotes *D. virginiana* receiving 110% of BID; SDI denotes sustained deficit irrigation at 70% of BID. At each sampling date, differences among treatments were evaluated using linear mixed-effects models with block as a random factor. When a significant treatment effect was detected ($p < 0.05$), pairwise comparisons were performed using model-based contrasts with Holm adjustment. Different lowercase letters above the panels indicate statistically significant differences among treatments within the same sampling date

spacing generally improved hectare-scale productivity in this rootstock.

These hectare-scale patterns should be interpreted together with the paired rootstock comparison of water status and the matched control comparison under full irrigation and standard spacing. Although the present design did not allow formal estimation of the rootstock $\times$ irrigation interaction across the full set of treatments, these matched comparisons provide direct evidence of contrasting agronomic behaviour between *D. lotus* and *D. virginiana* under equivalent management conditions. Therefore, the differences discussed here should be interpreted as rootstock-dependent responses under the management scenarios evaluated, rather than as a complete factorial quantification of interaction effects. Under matched planting layout and irrigation regime, midday Ψ_s was generally more negative in *D. virginiana* than in *D. lotus*, although the magnitude of the contrast was modest and sampling-date dependent. This supports the idea that rootstocks differ in their regulation of water status under the same irrigation dose, rather than implying a simple difference in irrigation requirement. Although *D. virginiana* is often described as relatively drought-tolerant (Gil-Muñoz et al. 2020), a more negative midday Ψ_s does not necessarily indicate higher water demand and may instead reflect a distinct physiological strategy of water use and hydraulic regulation. Analogous behaviour has been reported for other drought-adapted fruit tree species, in which baseline water potentials can be more negative even under adequate water supply due to conservative stomatal regulation and hydraulic traits, as described in olive (Shackel et al. 2021; Sánchez-Piñero et al. 2023) or almond (Fernandes de Oliveira et al. 2023).

Because irrigation in this trial was scheduled according to the requirements traditionally adopted for *D. lotus* under commercial practice, it remains plausible that the same BID-based scheduling was not equally optimal for *D. virginiana*. In this context, the lower Ψ_s values observed in DV treatments should be viewed as evidence that *D. virginiana* operates under a different water-status set-point, rather than

as a direct indication of higher water demand. Importantly, applying an irrigation dose calibrated to *D. lotus* may have resulted in relative over-irrigation of *D. virginiana* in some periods, which could contribute to excessive vegetative sink strength and potentially exacerbate physiological flower and fruit drop, ultimately reducing productive performance (Badal et al. 2013). Therefore, evaluating irrigation dose specifically for ‘Rojo Brillante’ grafted onto *D. virginiana* is essential to determine whether the applied irrigation strategy is agronomically optimal for this rootstock. This rationale directly motivated the 2015 irrigation optimisation stage, in which DV-110 and DV-SDI were contrasted against the DL-FI reference control under the standard planting layout to test whether adjusting the irrigation strategy could improve agronomic performance in *D. virginiana*.

Fruit load and weight further illustrate the balance between reproductive demand and vegetative growth, with vegetative tissues being particularly sensitive to resource availability (Badal et al. 2010; Buesa et al. 2013). In ‘Rojo Brillante’, the relevant production goals are not limited to maximising yield per tree, but include achieving stable yield per hectare, maintaining a commercially preferred fruit size distribution, limiting excessive physiological fruit drop, and improving irrigation water productivity while avoiding unnecessary stimulation of vegetative vigour. In this context, the trade-off was evident in *D. lotus*, where the planting layout influenced resource competition, but not in *D. virginiana*. Importantly, large persimmons are not a commercial target, as consumers prefer smaller fruits (Puerto et al. 2021). Thus, the reduced fruit weight observed under the 25-layout with *D. lotus* aligns with desirable production goals, especially in the DL25-HI treatment, where yields remained unaffected by stress. The absence of a consistent effect of planting layout or irrigation dose on yield suggests that applying 115% BID is not justified, since it fails to increase tree yield while not improving IWP. Moreover, in *D. virginiana*, IWP values were consistently lower than in *D. lotus*, despite *D. virginiana*’s greater vigour (Kanety et al. 2014; Intrigliolo et al. 2018), reinforcing the need to define irrigation management targets and operational thresholds in a rootstock-specific framework.

Canopy volume and TCA increased progressively in both rootstocks as the orchard approached the onset of full production, with larger increments early in the period and smaller relative gains thereafter. Winter pruning was performed annually during dormancy and applied uniformly across treatments to maintain balanced canopy structure. Across seasons, *D. virginiana* consistently developed a larger canopy than *D. lotus*, confirming its greater vigour, a trait that can be advantageous for rapid canopy establishment but may increase pruning and harvesting requirements at maturity (Parra et al. 2021). Despite higher vegetative

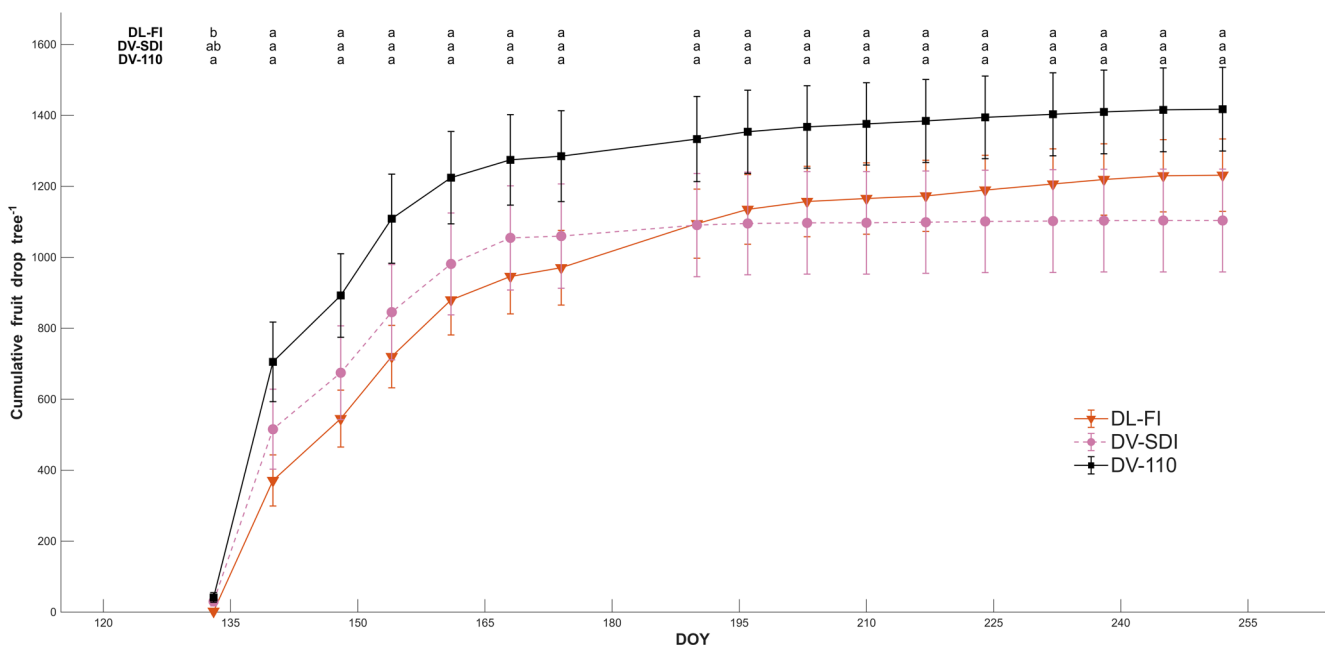


Fig. 7 Cumulative fruit drop in ‘Rojo Brillante’ persimmon during the 2015 season for the DL-FI, DV-110 and DV-SDI treatments. Values represent means $\pm$ standard error ($n=9$ trees per treatment). Treatment abbreviations are defined as follows: DL, *Diospyros lotus*; DV, *Diospyros virginiana*; FI, full irrigation (100% of the baseline irrigation dose, BID); DV-110, *D. virginiana* receiving 110% of BID; SDI, sustained deficit irrigation (70% of BID); BID, baseline irrigation dose

growth, the larger canopy in *D. virginiana* did not translate into higher yield per tree, suggesting that reproductive performance was constrained by factors beyond canopy size alone. Within rootstocks, canopy volume showed limited treatment separation overall, although in *D. lotus* the dense layout under full irrigation (DL25-FI) tended to show lower canopy volume by 2014 and in the pooled mean, consistent with stronger intra-row competition. TCA provided a clearer signal in *D. lotus*, where DL25-FI repeatedly showed the lowest values across seasons and in the pooled mean, whereas HI treatments and DL35-FI remained higher, indicating that dense spacing coupled with the FI regime constrained vegetative growth. In *D. virginiana*, TCA differences were weaker early in the period but became apparent by 2014, with higher values under DV35-HI and lower values under DV25-FI in the pooled mean. Annual Δ TCA declined with maturation and, when treatment contrasts emerged, they were most evident in later years, consistent with the dependence of vegetative growth on turgor-driven cell expansion under adequate water status (Hsiao 1973).

Production efficiency indicated that, as trees matured, yield increased relative to vegetative structure in both rootstocks, consistent with the progressive shift from canopy establishment to reproductive investment. In *D. lotus*, this balance was clearly influenced by water availability, as resource partitioning shifted under conditions of stress. By

computed from ET_c . Statistical differences among treatments at each sampling date (DOY) were assessed using linear mixed-effects models with block as a random effect. When significant effects were detected, pairwise comparisons were performed using model-based contrasts with Holm adjustment. Different lowercase letters indicate significant differences among treatments within the same sampling date ($p < 0.05$)

contrast, *D. virginiana* maintained stable efficiency across treatments despite its higher vigour, suggesting greater resilience in assimilate partitioning. The more extensive and denser root system of *D. virginiana* has been reported to enhance performance in heavy and dry soils (Badenes et al. 2015), which may help buffer vegetative growth against water limitations. In this context, ‘Rojo Brillante’ grafted onto *D. virginiana* may represent a viable option under these experimental conditions, as by 2014 its yields were already closely aligned with the expected standard of 50 t ha⁻¹ (Badal et al. 2010), although the irrigation doses applied according to the requirements of *D. lotus* appear insufficient for *D. virginiana* to reach its maximum yield potential.

The previous results highlighted that *D. virginiana* exhibited greater vigour than *D. lotus* without a parallel increase in yield, associated with lower fruit number per tree and a tendency towards higher physiological fruit drop under a common irrigation regime, as discussed. Previous studies have suggested that both reduced flowering and increased abscission may explain these patterns (Badal et al. 2013; Porras-Jorge et al. 2025). To explore whether irrigation management could mitigate these constraints, the 2015 trial evaluated two contrasting strategies for *D. virginiana* under the standard 3.5 $\times$ 5 m layout: an increased dose (DV-110, 110% BID) and sustained deficit irrigation (DV-SDI, 70% BID), using DL-FI (100% BID) as the reference control.

Raising allocation improved water status to levels comparable to those of the DL-FI control, whereas DV-SDI operated under a markedly lower Ψ_s range, with episodes of severe stress late in the season. This response indicates that Ψ_s in *D. virginiana* is highly sensitive to irrigation dose, but these effects do not necessarily translate into proportional changes in yield. The temporal dynamics of fruit abscission revealed patterns broadly consistent with previous descriptions in persimmon, where one to multiple waves of drop can occur, often involving seedless fruit in early events under pollination-limited conditions (Otani 1961; Bargioni et al. 1979; Kitajima et al. 1990; Badal et al. 2013). In this study, pollination was not possible because the Rojo Brillante cultivar produces only female flowers, so all fruits developed parthenocarpically, making it impossible to distinguish between pollinated and seedless fruits (Badal et al. 2013). In addition, crop load was not adjusted by hand thinning during the study, so the observed abscission dynamics reflect the trees' intrinsic physiological regulation of flowering and fruit retention under the imposed irrigation strategies.

In our 2015 trial, cumulative fruit drop patterns suggested a clear hierarchy among treatments: DV-110 had the highest number of fruits abscised, followed by DV-SDI, and both exceeded DL-FI, although these differences were not statistically significant. By contrast, when expressed relative to flowering, the data revealed a marked shift: *D. virginiana* showed a greater tendency to flower and fruit abscission than *D. lotus* under fully irrigated treatments, yet the implementation of SDI substantially mitigated this effect, resulting in a lower percentage of drop than in *D. lotus*. This pattern is consistent with the notion that moderate water stress can reduce abscission, possibly by reducing vegetative competition and favouring early fruit set (Choi et al. 2010). These results align with those of Badal et al. (2013), who reported that moderate early-season water stress reduced fruit drop in *D. lotus* under a regulated deficit irrigation. From a production standpoint, the lower number of fruits harvested in DV-110 must be explicitly acknowledged, since it implies a shift in yield formation: yield per tree was maintained through a compensatory increase in mean fruit weight, rather than through crop load. This compensation may be agronomically acceptable if fruit size distribution remains within the commercial target, but it also suggests that excessive abscission under fully irrigated *D. virginiana* can constrain fruit number and potentially limit yield stability across seasons. Despite these contrasting abscission and crop-load responses, yield per tree remained similar among treatments, indicating strong compensation between fruit number and mean fruit weight. From an efficiency perspective, DV-SDI maximised IWP, consistent with the general evidence that deficit irrigation can improve

water productivity in fruit crops (Feres and Soriano 2006; Buesa et al. 2013; Porras-Jorge et al. 2025).

Although higher irrigation enhanced vegetative growth, as reflected in the trunk increment, this investment did not translate into higher yield or improved yield-to-growth efficiency. In fact, the yield-to- ΔTCA ratio indicated that the increased irrigation strategy in *D. virginiana* promoted vegetative growth disproportionately relative to productive output, whereas sustained deficit irrigation maintained a more favourable balance between yield formation and annual trunk increment. This highlights a strategy-dependent coupling between water supply, growth and reproduction in *D. virginiana*, where additional irrigation did not increase productive efficiency and may have shifted assimilate allocation towards vegetative sinks. Rather than indicating a simple drought advantage, these responses are consistent with rootstock-specific differences in vigour, crop load regulation and whole-tree resource partitioning, potentially influenced by traits linked to rooting and hydraulic behaviour (Badal et al. 2010; Badenes et al. 2015).

Conclusions

This study provides the first integrated evaluation of irrigation strategy and planting layout in 'Rojo Brillante' persimmon grafted onto *D. lotus* and *D. virginiana* rootstocks under Mediterranean conditions. The results demonstrate that, by the end of the juvenile stage, yield per tree was largely unaffected by either a 15% increase in irrigation dose or denser spacing, except when Ψ_s crossed the -1.30 MPa threshold in *D. lotus*, confirming its sensitivity to severe water stress. At the hectare scale, closer spacing tended to improve productivity, but responses depended on rootstock and irrigation regime, suggesting that orchard intensification is a viable option under the studied conditions, though its long-term implications in mature orchards require further assessment. A central finding is the contrasting agronomic behaviour of the two rootstocks. However, the experimental design did not include a fully crossed set of common irrigation levels across both rootstocks, so the rootstock $\times$ irrigation interaction could not be quantified explicitly across the full experiment. *D. virginiana* combined greater vigour with consistently lower Ψ_s values, yet sustained yields, indicating that its root system confers resilience to moderate deficits. However, higher irrigation doses, when scheduled according to *D. lotus* requirements, did not enhance yield in *D. virginiana* and may even have promoted excessive fruit drop. In contrast, a sustained deficit irrigation (SDI) regime reduced abscission while maintaining yield and maximising irrigation water productivity. To our knowledge, this is the first evidence that SDI can be used as

a targeted management strategy for *D. virginiana*, offering practical potential to optimise fruit set and water-use efficiency in this rootstock.

Overall, these results highlight the importance of tailoring irrigation management to rootstock physiology rather than applying uniform schedules. While conventional irrigation dose levels appear adequate for *D. lotus*, *D. virginiana* requires specific calibration, with reduced irrigation dose emerging as a promising alternative. Both SDI and regulated deficit irrigation should be further evaluated to determine their potential for optimising fruit set and water-use efficiency in this rootstock. Multi-year trials will be essential to validate these patterns and assess their relevance once orchards reach full maturity.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no competing interests.

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