Agricultural Water Management 274 (2022) 107969

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Vegetative growth, yield, and crop water productivity response to different irrigation regimes in high density walnut orchards (Juglans regia L.) in a semi-arid environment in Argentina

Franco Emmanuel Calvo [a,b,*], Eduardo Rafael Trentacoste [c], Sonia Teresa Silvente [d]

[a] *Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Argentina*
[b] *Instituto de Agricultura Sostenible en el Oasis (IASO), Universidad Nacional de Chilecito (UNdeC), Av. Los Peregrinos s/n Chilecito, La Rioja, Argentina*
[c] *Estación Experimental Agropecuaria La Consulta, Instituto Nacional de Tecnología Agropecuaria, Ex Ruta 40 Km 96, San Carlos, Mendoza, Argentina*
[d] *Instituto de Ambiente de Montaña y Regiones Áridas (IAMRA), Universidad Nacional de Chilecito (UNdeC), Av. Los Peregrinos s/n Chilecito, La Rioja, Argentina*

ARTICLE INFO

Handling Editor - J.E. Fernández

Keywords:
Cv. Chandler
Kernel weight
Kernel oil concentration
Water productivity function

ABSTRACT

The area dedicated to walnut orchards has recently expanded in central-western Argentina. Nevertheless, studies on crop water demand are scarce and fundamental in semi-arid environments. This work aims to evaluate the effects on stem water potential (SWP) and stomatal conductance (gs), vegetative growth (trunk cross-sectional area, canopy volume, and canopy porosity), and water productivity in terms of yield of four water irrigation regimes T50, T75, T100, and T125. The plants were irrigated at 50%, 75%, 100%, and 125%, of crop evapotranspiration, respectively over two consecutive seasons (2018–2019 and 2019–2020). The experiment was carried out in a young walnut orchard cv. Chandler in a semiarid environment in La Rioja province, Argentina. SWP and gs had similar seasonal behavior in both seasons. T100 SWP remained between 0.5 and 0.8 MPa, like T75, while T50 reached minimum values of − 1.0 MPa. Stomatal conductance was less responsive than SWP to water deficit, showing significant differences only at 100 days after bloom. Vegetative growth and yield components did not differ among treatments. Compared to T100 and T50, crop water productivity (CWP) increased from 4.30 to 5.29 dry yield mm^{-1} ha^{-1} in 2018–2019 and from 5.25 to 7.28 kg dry yield mm^{-1} ha^{-1} in 2019–2020; while T75 CWP did not differ from the CWP of T100. Irrigation doses greater than crop requirements (T125) have no effect on yield if compared with T100, and in terms of the water productivity function, irrigation at 90% of T100 would have allowed for maximum productivity in both seasons.

1. Introduction

Since the 2000 s, in the central-western region of Argentina, there has been a significant increase in the walnut planted area (from 12,000 ha in 2002–16,000 ha in 2018: INDEC, 2020). After more than a century of traditional low-density (100 trees ha^{-1}) and surface-irrigated walnut orchards, new commercial orchards are now being established using technologies that combine localized irrigation and high tree density (>300 trees ha^{-1}) (Sibbett et al., 1997; Lemus, 2010). The central-western region of Argentina is characterized by low annual rainfall in the range of 200–600 mm concentrated in the summer months (Rubí Bianchi and Cravero, 2010), where walnut growing is only possible under irrigation. Despite the expansion of walnut in Argentina, local studies focused on crop water demands are scarce. The increasing limitations of water resources in cost and availability (Rivera et al., 2021) have led to a growing interest in knowing the walnut water needs and improving crop water productivity (CWP) to reduce costs and increase the planted area.

Crop evapotranspiration (ETc) varies according to the environment, variety, plant density, and crop age (Pereira et al., 2015). The main limitation for crop evapotranspiration estimation is the use of expensive equipment such as lysimeters and long-term studies. In Argentina, walnut farmers use the irrigation scheduling crop coefficients (Kc) estimated for California (USA) in agro-climatic conditions different from those of Argentina. The walnut's annual ETc is estimated in the range of 1000 mm ha^{-1} with a Kc range of 0.12–1.14 (Goldhamer et al., 1998; Steduto et al., 2012). In this context, applying different irrigation levels seems to be the best strategy for quantifying the walnut water

---

* Corresponding author at: Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Argentina.
E-mail address: fcalvo@undec.edu.ar (F.E. Calvo).

https://doi.org/10.1016/j.agwat.2022.107969
Received 8 July 2022; Received in revised form 19 September 2022; Accepted 28 September 2022

productivity function in order to define irrigation strategies leading to increased CWP.

In fruit crops, for the control of tree water status, the most widespread measurement is water potential, although other measures such as thermal sensing, stomatal conductance, and stem dendrometry are performed in conjunction (Parkash and Singh, 2020). In walnut, the midday stem water potential (SWP) threshold to avoid productive loss with vegetative growth control was estimated at − 0.8 MPa (Fulton et al., 2014), while stomatal conductance (gs) lower than 20 mmol m^{-2} s^{-1} has been associated with water deficit conditions (Rosati et al., 2006). Fulton and Buchner (2015) reviewed articles about the effect of the application of deficit irrigation strategies on walnut throughout the season in California agro-climatic conditions, categorizing strategies into: i) reduction in applied water of up to 20% of ETc (SWP from −0.4 to −0.8 MPa), which increases dark kernels and slightly lowers yield; ii) reduction in irrigation between 20% and 50% of ETc (SWP from −0.5 to −1 MPa). In this case, if the reduction occurs gradually between kernel filling and harvest, the effect can be a slight reduction in yield (i.e., the first strategy). If the reduction is close to 50%, not only will the percentage of dark kernels and yield reduction increase, but the yield of the following season might also be affected by an excessive reduction of vegetative growth. iii) Severe irrigation reductions above 50% of ETc (SWP of −0.8 to −1.2 MPa) have an inevitable negative effect on the quantity and quality of production, and the recovery period could take more than two seasons with regular irrigation. On the other hand, Cohen et al. (1997) applying surplus irrigation equivalent to 130% of ETc showed that yield and quality were not significantly higher than the control irrigated 100% of ETc and also promoted excessive vegetative growth.

We hypothesized that the negative effect on walnut production of deficit irrigation strategies throughout the growing season is of little significance in central-western Argentina since the summer rainfall regime of this region reduces water crop demand. Thus, the aim of this work is to study the effects of four irrigation regimes (at 50%, 75%, 100% and 125% of ETc) on stem water potential, stomatal conductance, vegetative growth indicators (trunk cross-sectional area, canopy volume, and canopy porosity), as well as yield and its components in order to quantify the water productivity function of a young walnut orchard cv. Chandler and contributing with more information to improve the irrigation scheduling decisions.

2. Materials and methods

2.1. Study site and orchard description

The experiment was conducted on a six years-old commercial Chandler walnut variety orchard in Guanchín (29° 10′ S; 67° 40′ W; 1750 MASL), La Rioja province, Argentina, over two seasons: 2018–2019 (Season 1, from October 1, 2018, to May 31, 2019) and 2019–2020 (Season 2, from October 1, 2019, to May 31, 2020). The orchard was established in 2012 with trees spaced at 7 m x 5 m (285 trees ha^{-1}) and irrigated with one microjet per tree. The region has a mean annual temperature of 13.5 °C and a mean annual rainfall of 534 mm (2010–2020), with the majority of rainfall falling during the summer months (December to March in the Southern Hemisphere). At a weather station near the experimental site, daily meteorological data such as, maximum and minimum air temperatures, relative humidity, solar radiation, wind speed, rainfall, and reference evapotranspiration (ET0), were collected. Soil physicochemical characteristics were analyzed at depths up to 1 m at the beginning of the experiment (Table 1). The soil was loam to 0.75 m and clay-loam from 0.75 to 1 m depth. The sodium absorption ratio was less than 0.16 mEq kg^{-1} and the organic matter decreased from 5% in the first 25 cm to 3.7% at 1.0 m depth; pH remained stable throughout the soil profile at values ranging from 8.5 to 8.8.

2.2. Experimental design

The experimental design was framed in randomized complete blocks, with four irrigation levels, each one with four replications. At the beginning of the study, total height, canopy volume, and trunk cross-sectional area (TCSA) at 50 cm aboveground were measured in 175 trees distributed in 5 contiguous rows to be used as blocking criteria. Sixteen experimental plots were selected, which consisted of 12 trees (3 rows x 4 trees per row), where two central trees (similar in height, canopy volume, and TCSA) from the central row were used for data collection and the remaining trees were "guard tree" borders. Of the central trees, one was kept unaltered until harvest, vegetative growth measurements were made on it, and yield at harvest was determined, while potentially destructive measurements such as water potential and nut sample collection were made on the other tree.

2.3. Irrigation treatments

The four irrigation treatments (regimes) were carried out between October 1, 2018, and May 15, 2020. The T100 treatment received a seasonal water amount equivalent to 100% of ETc. The T50, T75, and T125 treatments received seasonal water amounts equivalent to 50%, 75%, and 125% of T100. To replenish the water needs in each treatment, self-compensating microjets with different flow rates (T50: 20 L h^{-1}; T75: 30 L h^{-1}; T100: 40 L h^{-1}; and T125: 50 L h^{-1}) were used, allowing a similar spatial distribution of emitters and irrigation frequency to be maintained. The ETc was estimated according to the following equation:

$$ETc = ET0 * Kc * Kr$$

ET0 was estimated from weather station data subjected to the Penman-Monteith equation modified by FAO (Allen et al., 1998), while monthly values of Kc proposed by Goldhamer et al. (1998) are shown in Table 2. Kr is a reduction coefficient associated with crop cover percentage, estimated from the equation Kr = (2 *%Cover)/100, which can be assumed to have a maximum value of 1 (Fereres, 1982). In this case, since the trees had already covered more than 50% of the soil surface at the beginning of the experiment, Kr was equal to 1. The irrigation schedule considered the effective rainfall (eR) from daily rainfall (R) by applying the following equations (Puertas, 2009):

$$R < 12\ mm \rightarrow eR = 0$$

Table 1
Soil physicochemical characteristics at four depths in the experimental site.

Depth (m)	Textural class	pH	EC (µs cm^{-1})	SAR (mEq kg^{-1})	OM (%)	SWC at 10 KPa (%)	SWC at 1500 KPa (%)	AWC (%)
0–0.25	Loam	8.5	511	0.13	5.0	26.6	8.5	18.1
0.25–0.50	Loam	8.6	429	0.15	4.5	26.6	8.5	18.1
0.50–0.75	Loam	8.8	376	0.16	4.0	26.6	8.5	18.1
0.75–1.00	Clay loam	8.8	385	0.16	3.7	31.6	7.3	24.3

EC, Electrical conductivity; SAR, Sodium absorption ratio; OM, Organic matter; SWC, Soil water content; AWC, Available water capacity

Table 2
Crop coefficients (Kc) used for irrigation scheduling proposed by Goldhamer et al. (1998). Both study seasons (2018–2019 and 2019–2020) started on October 1 (Day 1 of the growing season) and finished on May 15 (Day 230 of the growing season).

Day of the season	Kc
1–19	0.4
20–34	0.6
35–49	0.7
50–64	0.9
65–144	1.1
145–174	1.0
175–189	0.8
190–204	0.7
205–230	0.6

$$R \geq 12\ mm \rightarrow eR = (R - 12) * 0.8$$

The interval between irrigation events from bloom to harvest was weekly, except if the eR was significant, then the interval was extended.

2.4. Measurements

2.4.1. Stem water potential and stomatal conductance

Stem water potential (SWP) and stomatal conductance (gs) were monthly measured on the same completely clear days from the beginning of sprouting (November) to harvest (March). Measurements of SWP were made between 12:00 and 13:00 h solar time using a Scholander-type pressure chamber (BioControl 0–4 MPa, Buenos Aires, Argentina) following the methodology proposed by McCutchan and Shackel (1992). Two apical leaflets of mature leaves from shoots close to the trunk were selected from the center tree of each replicate. The selected leaflets were placed in a reflective and waterproof plastic bag at least 90 min before measurement. Stomatal conductance was measured in two apical leaflets of two fully developed leaves on one tree per replicate during mid-morning (10:00–11:00 h solar time) with a previously calibrated stomatal diffusion porometer (Delta-T AP4, Cambridge, UK).

2.4.2. Trunk cross-sectional area, canopy volume, and canopy porosity

TCSA was estimated from the perimeter at 50 cm from the soil surface in one central tree of each replicate. Trunk perimeter was measured at three phenological stages in each season: budbreak, endocarp hardening (coinciding with the end of shoot growth), and maturity (mid-March). With the same frequency of TCSA measurements and in the same trees, canopy volume and porosity were estimated. The canopy volume was calculated by measuring the total tree height measured from the soil, the insertion height of the first branch, and the radii of the canopy in the four directions (according to its shade projection on the ground) by applying the following equation:

$$Canopy\ vol.\ (m^3) = \frac{1}{3} * \pi * \frac{(mean \quad width \quad (m))^2}{4} * (height\ (m) - height\ of\ first\ branch(m))$$

Canopy porosity (gap percentage) was estimated using photographs of the shadow projection at midday sun on a white blanket of a known area (1 m^2) extended 1 m from the trunk of the central tree of each replicate. The photographs were then processed to determine the percent of unshaded area (i.e., gap percentage) with CobCal V2.1.

2.4.3. Yield, yield components, and crop water productivity

Once the nuts reached maturity (March 23 in 2019 and March 19 in 2020), one central tree per replicate was manually harvested and immediately weighed. A sample of 100 nuts was taken and weighed with a precision balance (Precisa 320 XT, Dietikon, Switzerland). The average nut fresh weight was then estimated. The number of nuts per tree was determined from the total yield weight and the average nut fresh weight. The sample of 100 nuts was oven-dried with forced air current at 30 °C to a seed water concentration of 4%. A thermobalance with an accuracy of 0.001 g (Precisa XM60, Dietikon, Switzerland) was used to check seed moisture during drying. The dry yield per tree was estimated from the nut dry weight (moisture = 4%) and the estimated number of nuts per tree.

Next, the 100 nuts were manually cracked, and the kernels weighed to obtain the percentage of nut fill. Oil concentration was estimated by solvent extraction with an automated soxhlet extractor (Ankom XT10, New York, USA). The official methodology AOAC 920.39 (Thiex et al., 2003) was used, which consisted of grinding 30 kernels per treatment, and 2 g samples were taken in duplicate from the paste formed. The subsamples were dried until constant weight in an oven with a forced air flow at 70 °C. Solvent extraction was carried out with petroleum ether in a cyclic extraction program of 60 min. Once the extraction was finished, the sample was weighted, and the kernel oil concentration was estimated. Crop water productivity (CWP) was estimated for each replicate and season as the ratio of dry yield per hectare of unshelled nuts (kg ha^{-1}) and the total amount of water applied (i.e., irrigation water plus effective rainfall (mm)). Relative dry yield was calculated as the proportion of maximum dry yield in each season.

2.5. Statistical analysis

Data analysis was performed in the R v.4.1.2 (R Core Team, 2021) environment for statistical computing with nlme (Pinheiro et al., 2021) and emmeans (Length, 2021) packages. A linear mixed model was used, assuming treatment was a fixed effect and block was a random effect. Graphics and regression analyses were performed with GraphPad Prisms v.8.3.0 (GraphPad Software, San Diego, California, USA; www.graphpad.com).

3. Results

3.1. Weather conditions and irrigation water use

Absolute maximum temperatures were similar in both seasons, at 35.2 °C on December 24, 2018, in season 1, and 34.2 °C on January 25, 2019, in season 2. Absolute minimum temperatures varied between growing seasons. During the 2018–2019 season, the minimum temperature recorded was 1.1 °C on October 2 and − 1.1 °C on May 7, at the end of the 2019–2020 season (Fig. 1a). The ET0, ETc, rainfall, and total irrigation water applied to each treatment in both seasons are shown in Table 3. In 2018–2019, the total rainfall accumulated was 524 mm, with events mostly above 20 mm uniformly distributed in the summer months. The 2019–2020 season was drier than 2018–2019, with an accumulated rainfall of 374 mm, with events concentrated in January and February (Table 3 and Fig. 1b). In this sense, ET0 was nearly similar between seasons, with 774 mm accumulated in the 2018–2019 season and 802 mm in 2019–2020 (Fig. 1b), It is also important to note that ETc in both seasons was 656 mm and 709 mm, respectively (Table 3). Effective rainfall contributed to an equivalent of 20% and 11% of ETc in 2018–2019 and 2019–2020, respectively. Irrigation plus effective rainfall (total applied water) was slightly higher than the planned treatments at 50%, 75%, 100% and 125% of Etc, replenishing volumes equivalent to 65%, 80%, 100%, and 123% of ETc in 2018–2019, and 62%, 79%, 100%, and 125% of ETc in 2019–2020.

3.2. Stem water potential and stomatal conductance

Stem water potential had similar seasonal behavior among treatments in both seasons (Fig. 2a-b). T100 maintained SWP values of around − 0.80 MPa over the growing season. The T75 treatment showed similar seasonal patterns and values to T100. In T50, SWP values were significantly lower than T100, especially at mid-season when T50

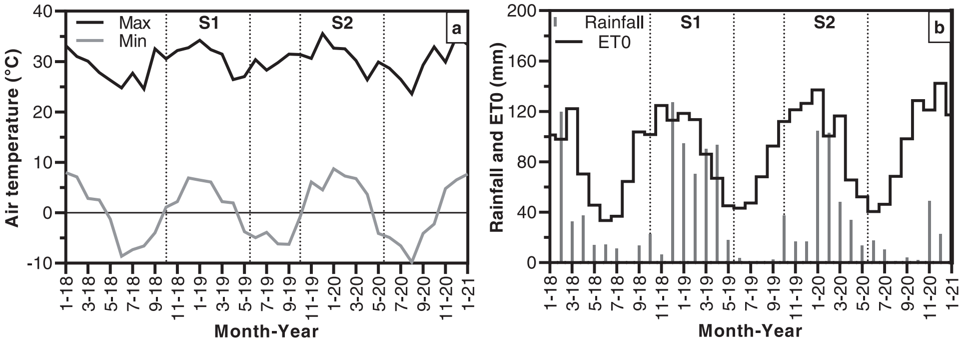

Fig. 1. Maximum and minimum monthly air temperatures (a) and monthly rainfall and ET0 (b) during the seasons 2018–2019 (S1) and 2019–2020 (S2). Dashed lines indicate the start and end of each season.

Table 3
Seasonal accumulated values of reference evapotranspiration (ET0), crop evapotranspiration (ETc), rainfall, effective rainfall, number of irrigation events, irrigation amount applied to each treatment, and total water applied (irrigation + effective rainfall) for each experimental season 2018–2019 and 2019–2020.

Season	ET0 (mm)	ETc (mm)	Rainfall (mm)	Effective rainfall (mm)	Seasonal irrigation events (# season^{-1})	Treatment	Irrigation (mm)	Total water applied (mm)
2018–2019	774	656	524	134	19	T50	340	474
						T75	452	586
						T100	596	730
						T125	761	895
2019–2020	802	709	374	80	21	T50	363	443
						T75	483	563
						T100	636	716
						T125	813	893

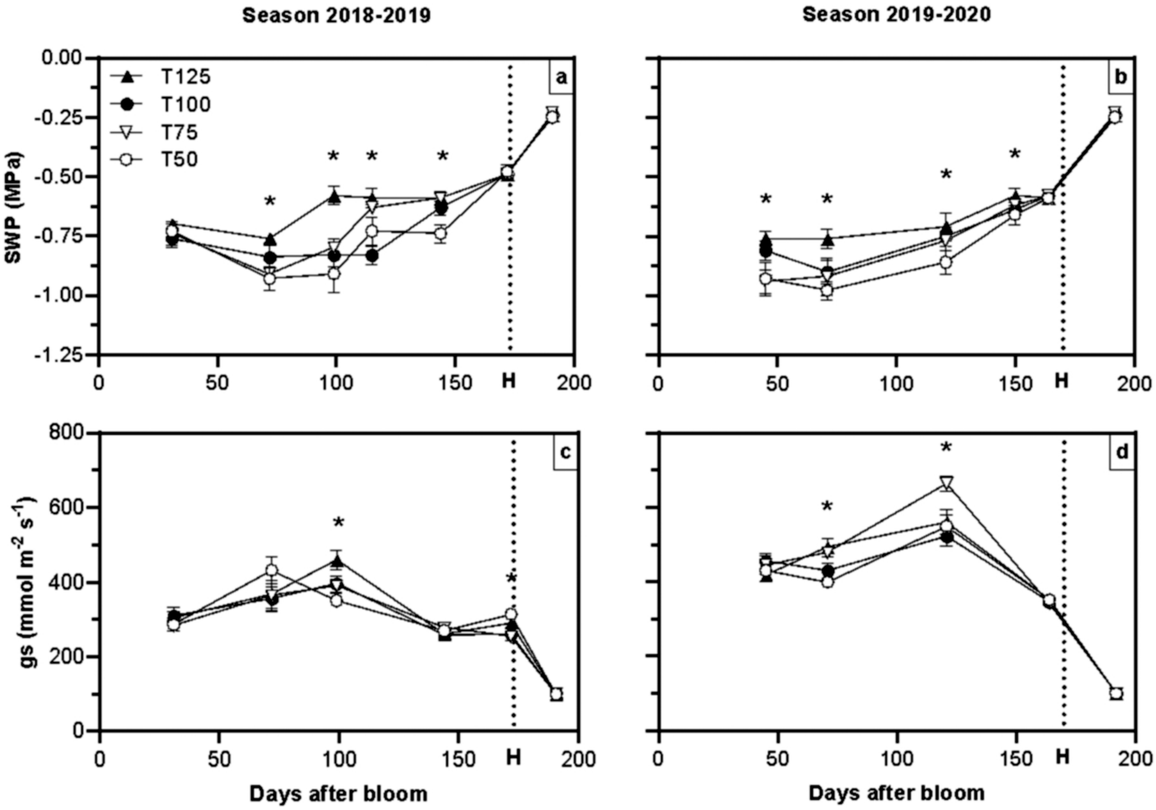

Fig. 2. Dynamics of stem water potential (SWP) (a-b) and stomatal conductance (gs) (c-d) during the seasons 2018–2019 (a-c) and 2019–2020 (c-d). The asterisk indicates significant differences among treatments at $P < 0.05$. Error bars represent the mean standard error. The letter H and dashed line indicate the harvest date.

reached a SWP of − 0.90 MPa. On the other hand, T125 presented a consistently higher SWP than T100, from − 0.7 to − 0.5 MPa. At harvest and post-harvest, all treatments had a similar SWP of − 0.50 MPa and − 0.25 MPa, respectively. Stomatal conductance in the first season ranged between 350 and 450 mmol m^{-2} s^{-1} for all treatments (Fig. 2c). In the second season, gs values ranged from 400 to 600 mmol m^{-2} s^{-1} (Fig. 2d), higher than in the first seasons when higher cumulative rainfall occurred (Table 3). Statistical differences in gs among treatments were observed around 100 DAB in both seasons and at harvest only in the second season. On these measurement days, the gs of T125 and T100 were higher than those of T75 and T50. Stomatal conductance towards post-harvest was drastically reduced at 100 mmol m^{-2} s^{-1} in both seasons.

3.3. Trunk cross-sectional area, canopy volume, and canopy porosity

Canopy volume growth was not significantly affected by treatments in 2018–2019 but showed differences in the early 2019–2020 season. Canopy volumes in most cases were similar in T100 and T125; T75 was intermediate, and T50 was the lowest (Fig. 3a). Trunk cross-sectional area (Fig. 3c) was more responsive to the irrigation treatments at the beginning of both seasons, when TCSA from T50 was significantly lower than from the rest of the treatments. Later, although these differences were not statistically significant, a different behavior could be appreciated when comparing T50 with the T75–100–125 group. TCSA and canopy volume had a positive relationship (R^2 = 0.52; Fig. 3d). At harvest, canopy porosity, determined as a proportion of transmitted irradiance at midday, did not differ among treatments during both seasons (Fig. 3b).

3.4. Yield, yield components and crop water productivity

Yield and its components were not affected by irrigation treatments (Table 4). Dry yield in-shell nuts (moisture = 4%) did not differ among treatments in both seasons, but when comparing T50 and T100, there was a reduction of 20% in the first season and 17% in the second season. The fresh and dry weight of 100 nuts did not vary among treatments. Similarly, nut fill did not differ among treatments, but a marked trend was evident with the T50 treatment losing 3% nut fill when compared to the T75–100–125 group. Nut numbers per tree were the highest in T125 (1088 nuts per $tree^{-1}$ in 2018–2019 and 1270 nuts per $tree^{-1}$ in 2019–2020) and the lowest in T50 (805 nuts $tree^{-1}$ in 2018–2019 and 1048 nuts $tree^{-1}$ in 2019–2020). Although oil concentration was not significantly different among treatments, nuts from the T50 treatment accumulated 5% less oil than T100 in 2018–2019, while oil concentration increased by 2% in T125 compared to T100. In 2019–2020, T125 had 3% more oil concentration compared to the average of the other treatments.

CWP significantly varied among treatments, where T50 showed higher CWP with increases of 1 and 2 kg dry yield mm^{-1} ha^{-1} compared to T100 in 2018–2019 and 2019–2020, respectively. Treatment T125 showed lower CWP, with an average CWP value of 1 kg dry yield mm^{-1} ha^{-1} lower than T100 in both seasons. In this context, it is interesting to note that the T75 CWP did not differ from the T100 CWP, allowing irrigation water savings of 24% in both seasons. Relative dry yield was strongly associated with total water applied (Fig. 4), in a single segmental linear regression for both seasons (R^2 = 0.90), where the 0-slope (breakpoint) was obtained at 663.2 mm. The pre-breakpoint slope was 0.9% relative yield per mm of applied water, and the intercept was 38% relative yield. On the other hand, the relative yield post-breakpoint was 98%.

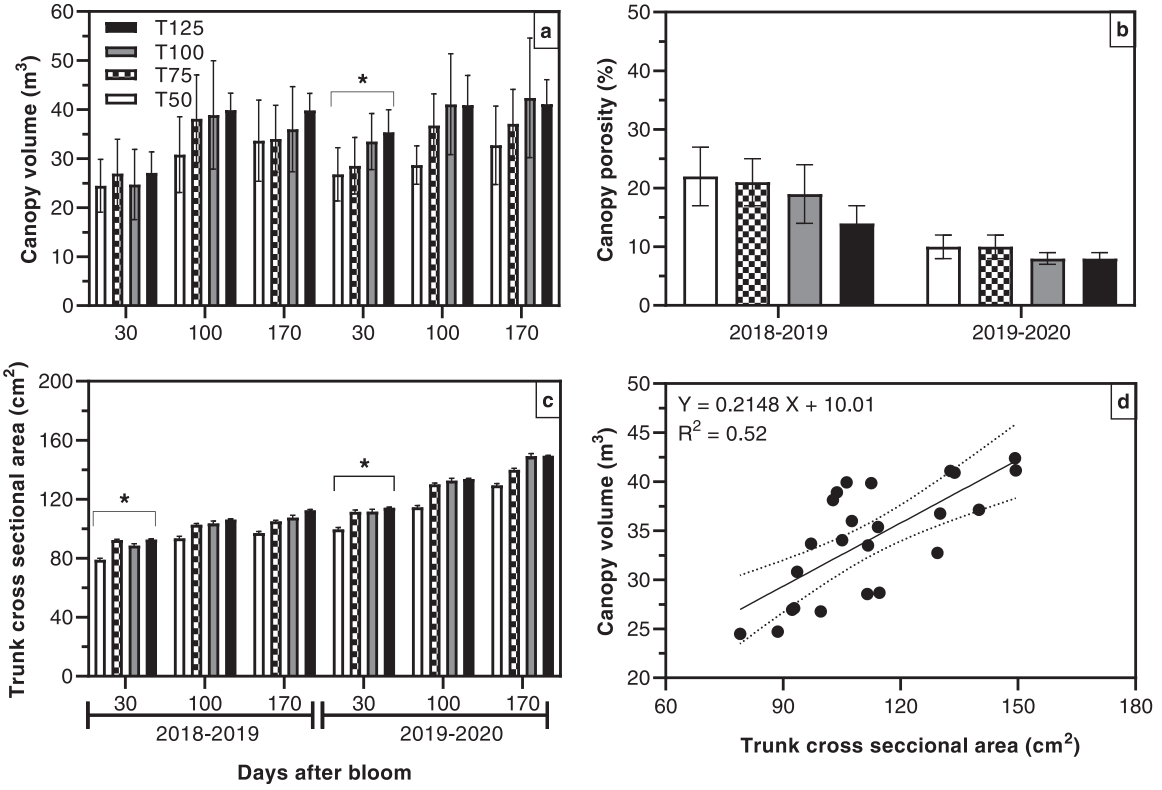

Fig. 3. Average canopy volume (a) and trunk cross-sectional area per irrigation treatment (c) at early, middle, and late season during the seasons 2018–2019 and 2019–2020. Mean canopy porosity per treatment at harvest (b). The asterisk indicates significant differences at $P < 0.05$ among treatments. Error bars represent mean standard error. Average canopy volume and porosity at harvest linear regression is presented in panel d.

Table 4
Effect of irrigation treatment on yield and yield components per treatment in each study season.

Season	Treatment	Fresh yield (t ha^{-1})	Dry yield (t ha^{-1})	100 nuts fresh weight (kg)	100 nuts dry weight (kg)	Nuts per tree (#)	Nut fill (%)	Oil concentration (% on dry basis)	CWP (kg dry yield mm^{-1} ha^{-1})
2018–2019	T50	4.18	2.50	1.85	1.10	805	41	56	5.29
	T75	5.27	2.97	1.91	1.09	956	43	59	5.07
	T100	5.45	3.14	1.91	1.10	1002	44	59	4.30
	T125	5.63	3.28	1.86	1.07	1088	43	61	3.66
	p-value	0.5096	0.5751	0.7031	0.9599	0.5312	0.4400	0.1549	0.2717
2019–2020	T50	5.71	3.13	1.98	1.09	1048	41	62	7.28 **a**
	T75	5.87	3.50	1.76	1.05	1173	43	63	6.23 **ab**
	T100	6.28	3.75	1.87	1.09	1208	43	62	5.25 **ab**
	T125	6.57	3.83	1.83	1.06	1270	43	65	4.28 **b**
	p-value	0.6973	0.5919	0.5888	0.6730	0.6678	0.5730	0.4700	**0.0088**

CWP, Crop water productivity
P-values > 0.05 are not significantly different between treatments within each season by LSD test.
Different letters indicate statistical differences between treatments.

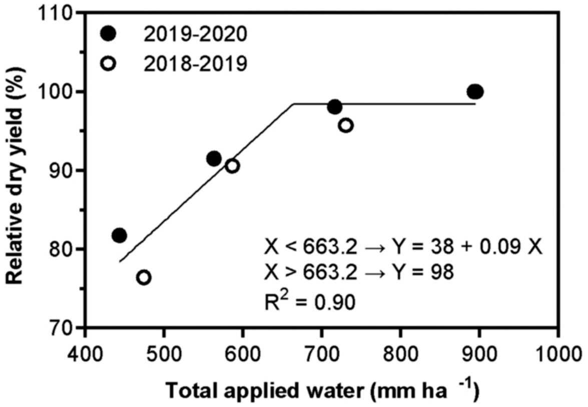

Fig. 4. Single bilinear regression of relative yield per treatment on total water applied (irrigation + effective rainfall) at harvest during the seasons 2018–2019 and 2019–2020.

4. Discussion

4.1. Stem water potential and stomatal conductance

In walnut trees irrigated between 75% and 125% of the Control treatment showed midday SWP values above − 0.8 MPa throughout the growing season, in line with the threshold of absent water deficit proposed by Fulton et al. (2014). However, SWP in the T50 treatment was close to − 1 MPa from 25 DAB (i.e., fruit set) to 100 DAB (i.e., kernel-filling) with no significant yield loss (Table 4). This finding suggests that the severity, phenological stage, and duration of the water deficit period with water potentials below − 0.8 MPa are determining factors for whether there is yield loss or not. In addition, our results, obtained from a semiarid environment, could also indicate that SWP thresholds vary according to the environmental conditions of each site, in agreement with what Corell et al. (2016) reported for olives in different locations in Spain.

Stem water potential was more sensitive to irrigation treatments than gs, showing significant differences between treatments throughout the entire season. Average gs was similar among treatments within each season as it varied between 277 and 291 mmol m^{-2} s^{-1} in the 2018–2019 season and between 365 and 405 mmol m^{-2} s^{-1} in the 2019–2020 season. Rosati et al. (2006) found an exponential relationship between gs and SWP in walnut trees irrigated at 50% ETc. When their SWP was lower than − 0.8 MPa (up to −1.2 MPa), the gs ranged between 20 and 200 mmol m^{-2} s^{-1}. However, for trees irrigated at 100% ETc and with SWP higher than − 0.8 MPa (up to 0 MPa), the response was less linear, with gs between 200 and 800 mmol m^{-2} s^{-1}. Therefore, the absence of significant differences in our gs measurements may be due to the fact that we did not reach critical levels of stomatal closure and, therefore, the amount of assimilated CO_2 was not severely affected.

4.2. Vegetative growth indicators comparisons among irrigation regimes

Vegetative growth, expressed as canopy volume, was not significantly affected by treatments even though significant differences in SWP appeared between 50 and 75 DAB at the time of active full vegetative and fruit growth. TCSA behaved similarly to canopy volume, so it may serve as an indicator of canopy growth during the season. In line with Cohen et al. (1997), a significant reduction in water supply to the crop at T50 may reduce TCSA growth. The difference in canopy volumes near the end of the second season resulted in a difference in nut load between T50 and T100 of 200 nuts, but with no significant differences between treatments. The combination of a compact canopy with high porosity (i.e., minor canopy leaf area) allows a significant reduction in ETc by reducing the transpiration surface (Pereira et al., 2006). Although these results could lead to a significant reduction in the proportion of intercepted radiation, they seem to be a good way to form and manage high-density walnut orchards, minimizing pruning tasks while generating a reduction in crop maintenance costs and the amount of water applied (Costa, 2007). To understand the behavior of vegetative growth, it is necessary to consider soil water retention capacity, its textural class (Table 1), and atmospheric water inputs (Table 3). At our experimental site, ETc was 656 and 709 mm yr^{-1} in a Monzonic-like regime, equivalent to 70% of the average ETc in California (1050 mm in a Mediterranean-like rainfall regime, Goldhamer et al., 1998). Therefore, the Kc used in our study may lead to an overestimation of irrigation demands.

4.3. Yield components and crop water productivity responses to water regimes

In general, yield and yield component responses to study water deficit regimes differ from those reviewed by Fulton and Buchner (2015) from deficit irrigation experiences in California, where yield was severely affected by 20–50% irrigation reductions. In this sense, we did not find significant differences in yield or yield components (Table 4). The most stable yield component was the weight of 100 fresh nuts and fruit fill (kernel-whole nut weight ratio). Ramos et al. (1978) reported that if the water deficit occurs in the first half of the season, the size and quantity of nuts could be affected, while if the deficit occurs in the second half, kernel quality and oil concentration will be the most affected. In our experiment, soil filling at the beginning of the season may have had an effect, which is why kernel size remained stable, since as the season progressed, the soil water reserve was depleted in irrigation deficit treatments. Oil concentration did not show significant differences, but a difference of 5% and 3% when comparing the results of treatments T50 and T75 seems to indicate greater sensitivity to the deficit in the second half of the cycle when most oil accumulation in seeds occurs (Ramos et al., 1978).

Buchner et al. (2008) in walnut trees grafted on two different rootstocks evaluated different irrigation strategies for three consecutive seasons. The strategy consisted first of maintaining a high SWP through the vegetative growth phase (thus trying to ensure vegetative growth and nut size), and once vegetative growth had stopped, three irrigation levels were applied: fully irrigated (SWP from −0.3 to −0.6 MPa), medium water deficit (SWP from −0.7 to −0.9 MPa) and moderate water deficit (−0.9 to −1.1 MPa). Their results indicated that the nut load was reduced in the medium deficit treatment by 19–28% with respect to T100, while for the moderate deficit irrigation treatment the load was reduced from 30% to 38%. Considering our case, the mean SWP of treatment T50 was − 0.68 and − 0.71 MPa for seasons 1 and 2, respectively. In comparison to our treatment, T50 would correspond to the moderate water deficit treatment.

5. Conclusions

The application of deficit irrigation regimes at 50% and 75% of ETc improved crop water productivity (relationship between relative yield and total applied water) and partially controlled vegetative growth without significant negative implications on the production and yield components. This was observed in two consecutive seasons on young walnut trees in the semi-arid central-western Argentina, where water is the most limiting factor and the cost of each unit of water applied weighs on the crop's economic efficiency. Moreover, in relation to the water productivity function irrigation at 90% of T100 would have allowed us to reach the maximum productivity in both seasons. This relationship is interesting for areas where water is not limited or has a low cost. Continuing observation at the current experimental site and further work elsewhere are needed to confirm these conclusions, especially concerning the similar productive performance of T50 and T100. In this context, it would also be interesting to study the effect of a more restrictive deficit irrigation regime than T50.

CRediT authorship contribution statement

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Franco Emmanuel Calvo, Sonia Teresa Silvente and Eduardo Rafael Trentacoste. The first draft of the manuscript was written by Franco Emmanuel Calvo, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

Acknowledgements

This work is part of a thesis submitted by FEC in partial fulfillment of the requirements for a PhD degree (Facultad de Ciencias Agrarias, Universidad Nacional de Cuyo, Mendoza, Argentina). We are grateful to Nadia García and Lourdes Brizuela y Doria for their help in data collection. Special thanks also to Coralino S.A. providing the experimental site and Silvia Barbuzza for her help with proofreading. This work was supported by grants from the Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET) (pre-doctoral fellowship 4199/17).

References

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration - Guidelines for computing crop water requirements - FAO Irrigation and Drainage Paper No. 56, 1–15. http://www.fao.org/3/x0490e/x0490e00.htm.

Buchner, R.P., Fulton, A.E., Gilles, C.K., et al., 2008. Effects of Regulated Deficit Irrigation on Walnut Grafted on 'Northern California Black' or 'Paradox' Rootstock. Acta Hortic. 795, 141–146. https://doi.org/10.17660/ActaHortic.2008.792.14.

Cohen, M., Valancogne, C., Dayau, S., Ameglio, T., Cruiziat, P., Archer, P., 1997. Yield and physiological responses of walnut trees in semi-arid conditions: applications to irrigation scheduling. Acta Hortic. 449, 273–280.

Corell, M., Pérez-López, D., Martín-Palomo, M.J., et al., 2016. Comparison of the water potential baseline in different locations. Usefulness for irrigation scheduling of olive orchards. Agric. Water Manag. 177, 308–316. https://doi.org/10.1016/j.agwat.2016.08.017.

Costa, J.M., Ortuño, M.F., Chaves, M.M., 2007. Deficit Irrigation as a Strategy to Save Water: Physiology and Potential Application to Horticulture. J. Integr. Plant Biol. 49 (10), 1421–1434. https://doi.org/10.1111/j.1672-9072.2007.00556.x.

Fereres, E., Martinich, D., Aldrich, T., Castel, J.R.E., HolZapfel, E., Schulbach, H., 1982. Drip irrigation saves money in young almond orchards. Calif. Agric. 36 (9), 12–13.

Fulton, A., Buchner, R., 2015. Drought Strategies for California Walnut Production. ANR Publ. 8533. https://doi.org/10.3733/ucanr.8533.

Fulton, A., Grant, J., Buchner, R., Connell, J., 2014. Using the Pressure Chamber for Irrigation Management in Walnut, Almond, and Prune. ANR Publ. 8503. https://doi.org/10.3733/ucanr.8503.

Goldhamer, D.A., Beede, R., Sibbett, S., et al., 1988. Third year effects of deficit irrigation on walnut tree performance. Walnut Res. Rep. 1988, 42–52.

INDEC (Instituto Nacional de Estadística y Censos), 2020. Censo Nacional Agropecuario 2018. Resultados preliminares. Ministerio de Economía de la Nación. Buenos Aires,, Argentina. ⟨https://l2018.indec.gob.ar/⟩.

Lemus, G., 2010. Innovative methods of walnut production in South America. Acta Hortic. 861, 191–198. https://doi.org/10.17660/ActaHortic.2010.861.25.

Length, R., 2021. emmeans: Estimated Marginal Means. R package version 1.7.0.

McCutchan, H., Shackel, K.A., 1992. Stem-water potential as a sensitive indicator of water stress in prune trees (Prunus domestica L. cv. French). J. Am. Soc. Hortic. Sci. 117 (4), 607–611. https://doi.org/10.21273/JASHS.117.4.607.

Parkash, V., Singh, S., 2020. A Review on Potential Plant-Based Water Stress Indicators for Vegetable Crops. Sustainability 12 (10), 3945. https://doi.org/10.3390/su12103945.

Pereira, A.R., Green, S., Nova, N.A.V., 2006. Penman–Monteith reference evapotranspiration adapted to estimate irrigated tree transpiration. Agric. Water Manag. 83 (1–2), 153–161. https://doi.org/10.1016/j.agwat.2005.11.004.

Pereira, L.S., Allen, R.G., Smith, M., Dirk, R., 2015. Crop evapotranspiration estimation with FAO56: Past and future. Agric. Water Manag. 147, 4–20. https://doi.org/10.1016/j.agwat.2014.07.031.

Pinheiro, J., Bates, D., DebRoy, S., Sarkar, D., Core Team, R., 2021. nlme: Linear and Nonlinear Mixed Effects Models. R. Package Version 3, 1–153.

Puertas, C.M., 2009. Efecto del riego deficitario controlado sobre el rendimiento y calidad de aceite en Olivo (Olea europaea L.) cv. Arbequina. Thesis MSc. Universidad Nacional de Cuyo.

Ramos, D., Brown, L., Uriu, K., Marangoni, B., 1978. Water stress affects size and quality of walnuts. Calif. Agric. 32 (10), 5–8.

Rivera, J.A., Otta, S., Lauro, C., Zazulie, N., 2021. A Decade of Hydrological Drought in Central-Western Argentina. Front. Water 3 (2021), 28. https://doi.org/10.3389/frwa.2021.640544.

Rosati, A., Metcalf, S., Buchner, R., Fulton, A., Lampinen, B., 2006. Tree water status and gas exchange in walnut under drought, high temperature and vapour pressure deficit. J. Hortic. Sci. Biotechnol. 81, 415–420. https://doi.org/10.1080/14620316.2006.11512082.

Rubí Bianchi, A., Cravero, S.A.C., 2010. Atlas climático digital de la República Argentina, 1st ed...,. Instituto Nacional de Tecnología Agropecuaria,, Buenos Aires.

Sibbett, G.S., Coates, W., Edstrom, J., 1997. Orchard planning, design and planting. In: Ramos, D.E. (Ed.), Walnut Production Manual, 6. University of California, Division of Agriculture and Natural Resources, pp. 39–53.

Steduto, P., Hsiao, T.C., Fereres, E., Raes, D., 2012. Crop yield response to water. FAO Irrigation and Drainage. FAO,, Rome.

Thiex, N.J., Anderson, S., Gildemeister, B., et al., 2003. Crude fat, diethyl ether extraction, in feed, cereal grain, and forage (Randall/Soxtec/submersion method): collaborative study. J. AOAC Int. 86, 888–898. https://doi.org/10.1093/jaoac/86.5.888.