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ORIGINAL PAPER

Optimization of irrigation on walnut through the IRRIFRAME water balance model

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Abstract

In recent years, reduced summer precipitation frequencies related to climate change have raised the probability of water scarcity, even in the Po Valley of Italy, thus requiring an optimization of the irrigation management for walnut cultivation which has become very present in the area. The aim of the present study was to evaluate, during four consecutive seasons (2018–2021), the physiological (stem water potential Ψ_w, leaf photosynthesis A and stomatal conductance g_s), yield (nut weight, shelled yield, kernel colour) and water use efficiency (WUE) responses of walnut trees to different irrigation levels (100% ET_c, 75% ET_c, and 50% ET_c) in order to obtain an improved water balance model, fit for walnut production under Emilia Romagna conditions. Water supply in 100% ET_c (CTRL) was managed according to the IRRIFRAME water balance model. CTRL trees generally showed higher stem Ψ_w at midday, than those irrigated at 75% (DI75) and 50% ET_c (DI50). Less sensitivity was found for g_s and A, than for Ψ_w, to the different water regimes: in fact, differences among treatments occurred only in the first two years, when yield was reduced by 50% ET_c irrigation, compared to 100% and 75% ET_c. No differences were registered for shelled yield and kernel colour during the experimental period. On the contrary, irrigation treatments affected WUE in all the seasons, with CTRL being the less efficient treatment, followed by DI75 and DI50.

Introduction

Traditionally, walnut used to be one of the major Italian nut tree species, with approximately 728,871 ha in the first half of the XX Century (i.e., 1938), making Italy one of the major European walnut producers (53,648 t, average production 1934–1938) (Zito 1941). At that time, walnut cultivation was mainly characterized by an agroforestry cultivation system, rainfed and with a limited management (Zito 1941). Few specialized orchards (1,500 ha) were characterized by a low-density planting scheme (i.e., 45 trees ha^{-1}, spaced at 15 m X 15 m) (Zito 1941). Recently, modern walnut orchards have been established with a tree density of 250–300 trees ha^{-1} and provided with permanent irrigation systems. Among the Italian regions, Emilia-Romagna has the highest number of walnut orchards (1,236 ha out of 6,256 ha at the national level), producing 3,203 t out of the total Italian production of 22,227 t, in 2022 (Istat 2022). The reduced availability of water resources (e.g., especially rainfall frequency during summer months), and the increase of irrigation water prices in Emilia-Romagna, stimulate/require a deeper knowledge of walnut water demands, to achieve optimal yields with the lowest use of water. Walnut is known for its high-water needs, since drought stress negatively affects yield and nut quality (e.g., size, kernel colour, kernel shrivel) (Cohen et al. 1997).

Walnut water requirements are usually based on crop evapotranspiration (ET_c), typically obtained with weather data and different computational procedures, more often using the FAO56 method (Allen et al. 1998). Most of the studies evaluated walnut water requirements based on ET_c, with K_c values (0.12–1.14, depending on the phenological stages) estimated for Californian and Argentinian conditions (Calvo et al. 2023), reaching an average water consumption,

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in those locations, of about 1,000 mm ha^{-1} (Goldhamer et al., 1998).

Despite the expansion of walnut cultivation in Emilia-Romagna region, studies in the area that focused on crop water demand are limited, with irrigation management often based on general FAO56 ET_c values, or only on farmers experience. Limited knowledge of walnut water needs is one of the causes of inadequate water use and poor irrigation management (Abuzar et al. 2013). As a result of little knowledge of crop water demand, over-irrigation often occurs in areas with high water availability (still like in the case of Emilia Romagna).

Soil-plant water balance models have been barely developed on walnut (Dokmen et al., 2023). These models typically integrate various water inputs (e.g., rainfall, irrigation) and outputs (e.g., evapotranspiration, deep percolation) to maintain an adequate soil moisture for crop growth. Such essential supply of information enables sustainable management practices, predicting future water availability and ensuring efficient water use (Hirich et al., 2018). The information needed to better calibrate and fit a site-specific irrigation model, should be obtained from the crop's performances (e.g., plant water status, leaf stomatal conductance), subjected to different water regimes (Rosati et al. 2006; Fulton et al., 2015).

Different studies evaluated the effect of moderate (20% of ET_c) and severe (up to 50% of ET_c) reduction of irrigation amounts, with contrasting results, possibly due to different environmental conditions (Cohen et al. 1997; Buchner et al. 2008, Fulton et al. 2014; Calvo et al. 2022). Stem water potential (Ψ_w) is widely used to monitor the plant water status and consequently to adapt irrigation scheduling (Fulton et al. 2014). Stem Ψ_w below −0.8 MPa is considered the threshold for production losses and mild vegetative growth control (Fulton et al. 2014). Buchner et al. (2008) found that yield was severely affected by an irrigation reduction of 20–50% ET_c. On the other hand, no significant differences in yield and nut quality were found with a reduction of 50% ET_c and where a stem Ψ_w of -1 MPa was reached (Calvo et al. 2022). At the same time, over-irrigation (e.g., 130% ET_c) did not affect plant productivity and nut quality, while promoting excessive vegetative growth and reducing water use efficiency (WUE) (Cohen et al. 1997).

Given the specificity of Emilia Romagna region, the use of parameters and indexes from California or Argentina climates may give unprecise information. In the present study, walnut irrigation requirements were evaluated with the aid of a Decision Support System (DSS), IRRIFRAME (Rossi et al. 2004; Giannerini and Genovesi 2011; Giannerini et al. 2013). IRRIFRAME includes an irrigation model, developed by the Canale Emiliano Romagnolo (CER) consortium (www.irriframe.it) and has been validated in Emilia Romagna, with a 30-year experience of field trials on numerous species, from fruit trees to horticultural crops (Morandi et al. 2014; Munaretto and Battilani 2014; Torres-Ruiz et al., 2016; Pereira et al. 2020). This regional web-based platform provides irrigation scheduling, based on Hargreaves-Samani equation, and takes into account orchard-specific parameters (soil, training system, density, cultivar, rootstock, irrigation system, etc.) and meteorological data, collected by nearby weather stations.

The aim of the present study was to evaluate the physiological, yield, nut quality and water use efficiency (WUE) responses of walnut trees to different irrigation levels (100% ET_c, 75% ET_c, and 50% ET_c) in order to obtain an improved water balance model, fit for walnut production under Emilia Romagna conditions.

Materials and methods

Study area and orchard description

The study was conducted from 2018 to 2021, in a commercial walnut (*Junglans regia*) orchard planted in 2009, in S. Martino in Strada (Forlì province, Emilia Romagna region, Italy; 44° 11' N; 12° 02' E; 34 m a.s.l). Trees were spaced at 7 m x 5 m (286 trees ha^{-1}) and irrigated with a micro-jet system. The Chandler variety was grafted on seedling rootstocks of *J. regia*. The climate of the area is classifide, according to Köppen and Geiger, as Cfa (Humid subtropical climate) with a mean annual temperature of 14.0 °C and annual rainfall of 761 mm, mainly occurring during autumn-spring months (Climate-Data 2023). Meteorological data (e.g., air temperatures, rainfall) were provided by a weather station installed in the farm. Trees were subjected to pruning, pest, disease and fertilization according to the ICM 2023.

The orchard soil had a loam texture, both at 0.0–0.25 m and 0.25–0.50 m depths (Table 1) and a water table level at 3 m depth. The organic matter presented lower values in

Table 1 Soil main characteristics measured at different soil depths at the beginning of the experiment

Depth (m)	Clay (%)	Sand (%)	Silt (%)	Texture	Organic matter (%)	pH
0.00-0.25	18	36	46	Loam	1.10	8.17
0.25–0.50	20	30	50	Loam	0.57	8.11

the first layer than in the second layer; pH showed a limited decrease from 0 to 0.25 to 0.25–0.50 m (Table 1).

Experimental design

The experiment was made up of 4 blocks, with each block containing a plot of each irrigation level, according to a complete randomised block design. The following 3 irrigation levels were compared (16 trees per treatment): 50% ET$_c$ (DI50), 75% ET$_c$ (DI75) and 100% ET$_c$ (CTRL). In each plot, only the two central trees (in the row direction) were selected for data collection, keeping the remaining 2 as border trees.

Irrigation treatments were applied from May to September, in 2020 and 2021; in 2018 and 2019, irrigation started in July and June, respectively. To differentiate the irrigation amount among the treatments, a micro-sprinkler system was used, spaced every 5 m on the row, with different flow rates: CTRL = 75 L h^{-1}; DI75 = 51 L h^{-1}; DI50 = 39 L h^{-1}, with the same dispensing time for the 3 treatments.

The irrigation management followed the IRRIFRAME Decision Support System (DSS) developed by the Canale Emiliano Romagnolo (CER) consortium (www.irriframe.it) (Giannerini and Genovesi 2015; Mannini et al. 2013; Pereira et al. 2020). To determine ET$_c$, the IRRIFRAME water balance method takes into account the continuous interaction between soil, plant, and atmosphere, utilizing evaporimetric data to calculate crop water requirements (Munaretto and Battilani 2014). Based on the plot's location, the system autonomously acquires data on soil and meteorological conditions; the latter is acquired from the regional weather forecast provider. End users can eventually adjust soil characteristics, local rainfall and other meteorological data, as well as soil moisture data, as a % (v: v), or as soil matric potential (Ψ_m) (https://www.irriframe.it/irriframe/Content/IF_Pub_3.htm). The management of the water balance and irrigation advice to the user, require the following specifications: (i) site weather data for calculating reference evapotranspiration (ET$_0$), using the Hargreaves-Samani formula, which highly fits the Penman-Monteith equation ($R^2 = 0.959$), although it slightly underestimates ET$_0$, however balanced out by the DSS calibration and validation process; (ii) depth of the water table (provided by the regional weather service); (iii) soil characteristics (in the 0.0–0.5 m layer), obtained through pedo-functions for deriving hydrological constants, such as maximum water holding capacity (WHC), field capacity (FC) and wilting point (WP) (Table 2): the pedo-function was calibrated over the years on a wide range of Emilia-Romagna region soils, in particular: FC = 34.462076–0.317904 * (% sand) + 0.117667 * (% clay); WP = 16.448542–0.158817 * (% sand) + 0.063374 * (%clay); Total Available Water (TAW) = 92.0 (mm); Readly Available Water (RAW) = 78.30 (mm); p = WP + TAW*(1-0.85); (iv) plant specific growth models based on cumulative degree days (°D), that were estimated using the following formula: $\sum$ Temperature (°D) = (T_x-t_0) x n, where “x” is the daily average temperature and “t_o” the base temperature (it was considered 5 °C for walnut), and “n” are the days in each considered phenological stage; (v) the utilized irrigation system, water quantity and distribution frequency. All the parameters defining the water balance model, associated with each walnut phenological stage, are listed in Table 2.

Table 2 Water balance parameters used for the walnut orchard irrigation management

[1]Upper Threshold (%)	[2]Intervention Threshold (%)	Phenological phase	Degree Days (°D)	[3]K$_c$
45	15	Vegetative Rest	0.00	0.45
45	15	Bud Sprout	90.0	0.50
65	40	Male Flowering	163	0.60
65	40	Female Flowering	127	0.70
65	40	Nut Hardening (>50%)	900	1.00
65	40	Nut Dehiscence	1360	1.00
60	35	Harvest Initiation	400	0.65

[1]Upper threshold:% of soil moisture reached at the end of the irrigation event

[2]Intervention irrigation threshold:% of soil moisture triggering the irrigation event (measured on the % of soil available water)

[3]K$_c$: based on the conditions provided by the FAO 56 manual and updated based on Fulton et al. (2017), and thus utilizing walnut kc$_{ini}$, kc$_{mid}$, and kc$_{end}$ as bases, but progressively discretized throughout the season these values according to the different phenological phases involved in the Irriframe model. The transition among each phenophase is automatically handled by the system, based on historical weather data from the past five years

Plant measurements

Plant water status

Ψ_w was measured in sunny days of July (31st, 26th, 21st and 12th in 2018, 2019, 2020 and 2021, respectively) and August (21st, 27th, 17th and 17th in 2018, 2019, 2020 and 2021, respectively) on 8 trees per treatment. These measurements were carried out using a Scholander pressure chamber (Model 3000 F01, plant water status console, Soil moisture Equipment Corp., Goleta, Santa Barbara, CA, USA) on apical leaflets of a mature leaf, located in the inner part of the canopy, as close as possible to the trunk, following the protocol of Turner and Long (1980). The selected leaves were covered with an aluminium foil and enclosed in a plastic bag for at least 90 min before measuring, to reach moisture equilibrium between plant and soil. Then, water potential was measured, immediately after excision, according to the methodology reported by Naor et al. (1995).

Leaf photosynthesis (A) and stomatal conductance (g_s) were measured in the same days and time of stem water potential on the same 8 trees per treatment, using an open-circuit infrared gas exchange analyser fitted with a LED light source (Li-COR 6400, LI-COR, Lincoln, NE, USA). Measurements were performed on one well-exposed fully developed apical leaflet per tree. During each measurement, light intensity was maintained constant, setting the LED light source to the natural irradiance (which was always above 1,700 µmol m^{-2} s^{-1}) intercepted by the leaves immediately before the measurement, while air CO_2 concentration was set at 400 ppm.

In spring of 2021 and 2022, the trunk circumference (cm) was measured 40 cm above the grafting union.

Yield, nut quality and water use efficiency

Harvest was performed each year in two periods, due to the progressive nut ripening, between the end of September and the beginning of October (27/9–12/10). In the first pick, naturally fallen nuts (approximately 10%), due to physiological drop, were manually collected from the ground. The second pick was done mechanically after shaking the trees. During each harvest time, the total nut fresh weight (in-shell nut without the hull) and the percentage of hulled, not hulled and damaged nuts, were determined. The number of nuts per tree, nut weight and the average nut fresh weight were recorded. To calculate the nut dry weight (in-shell nut), a representative sub-sample of 100 nuts per treatment was placed inside an oven and subjected to a forced air current at 38 °C to reach kernel water content of 7–8%. A thermobalance was used to check kernel moisture during drying. The dry yield per tree was calculated from the nut dry weight and the estimated number of nuts per tree. Furthermore, on the same subsample of 100 nuts, the following parameters were also assessed: nut size distribution classes (<28, 28–30, 30–32, 32–34, 34–36, 36–38 e>38 mm), shelled yield (kernel dry weight/total nut dry weight), kernel colour (extra light, EL; light, L; light-amber, LA; amber, A; following USDA classification, https:/www.ams.usda.gov/grades-standards/walnuts-shell-grades-and-standards) and kernel defects (rotten kernel, shrivelled kernel). WUE was estimated for each treatment and in each season, as the ratio between the dry yield of unshelled nuts and the total amount of water applied (i.e., irrigation water plus rainfall).

Statistical analysis

Ψ_w, leaf gas exchange parameters, yield, nut quality parameters, trunk circumference and WUE data were compared among treatments using a one-way ANOVA, performed with R software (www.rproject.org) code. When statistical significance was established ($p<0.05$), means were separated with the Tukey HSD test.

Results

Weather, evapotranspiration and irrigation restitutions

The four consecutive years showed similar climatic conditions in terms of air temperatures and ET_0 (Fig. 1). Instead, the total annual precipitation was different among the years with 775, 803, 469 and 451 mm registered in 2018, 2019, 2020 and 2021, respectively. The highest precipitation was recorded in spring and in fall of 2018 and 2019 (Fig. 1). Concerning the irrigation season (May-September), in 2018 and 2019, rainfalls were 315 and 450 mm, respectively; 2020 and 2021 were drier, with 206 and 271 mm of cumulated rainfall, respectively (Fig. 1). Irrigation restitutions, based on the 100% of ET_c (CTRL) were 296 mm, in 2018 and 2019, and 400 mm and 462 mm, in 2020 and 2021, respectively. Rainfall contributed to approximately 45%, 67%, 31% and 40% of ET_c in 2018, 2019, 2020 and 2021, respectively.

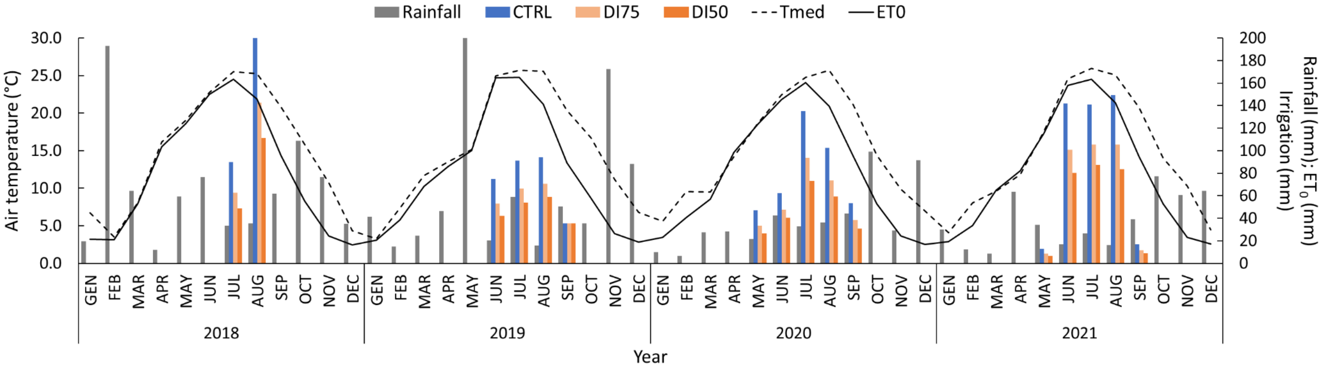

Fig. 1 Monthly rainfalls (grey columns), reference evapotranspiration (continuous-black line), mean air temperature (dashed-black line) and irrigation restitution in 100% of ET_c (CTRL - blue columns), DI75 (light-orange columns), DI50 (orange histograms) during 2018, 2019, 2020 and 2021

Plant water status measurements

Ψ_w showed significant higher values for CTRL compared to DI75 and DI50 in July (in 2019 and 2021) and in August (in 2018 and 2019) (Fig. 2). During these months, CTRL showed Ψ_w ranging from −0.34 to -0.86 MPa. DI50 maintained lower stem Ψ_w values than DI75 only in August 2019 and July 2021, when it reached −1.10 and −0.69 MPa, respectively. Concerning the other measurement dates, no differences were found among treatments. The four-year average Ψ_w, for each treatment were: −0.74, -0.86 and −0.87 MPa, respectively for CTRL, DI75 and DI50. Furthermore, Ψ_w tended to gradually increase from 2018 to 2021, regardless of the treatments (Fig. 2).

The application of irrigation amounts to maintain 100% ET_c (CTRL) increased leaf C assimilation (A) compared to the DI50, only in August 2018 (Fig. 3a). In other periods, no effect of irrigation was found (Fig. 3a). The four-year average of A, for each treatment was: 13.9, 12.8 and 11.9 µmol CO_2 m^2 s^{-1}, for CTRL, DI75 and DI50, respectively.

The well-watered CTRL and DI75 induced a statistically higher g_s compared to DI50, in August 2018 (Fig. 3b). In 2019 (August), CTRL showed a higher g_s compared to DI75 and DI50 that reached the same g_s value (i.e., 0.11 mol CO_2 m^2 s^{-1}). No g_s differences were found among all the treatments in July 2018, 2019 and in July and August 2020 and 2021 (Fig. 3b). The four-year average g_s were 0.15, 0.13 and 0.11 mol CO_2 m^2 s^{-1}, for CTRL, DI75 and DI50, respectively.

The circumference of tree trunk was not affected by the irrigation treatment, showing an annual increase ranging between 2.5 and 4.55 cm (Table 3).

Yield, nut quality parameters and walnut water use efficiency

Dry yield (in-shell nut) was affected by irrigation treatments only in 2018 and 2019. In 2018, DI50 production was significantly lower compared to DI75 and CTRL (Table 4). In 2019, DI50 still showed the lowest productivity, followed by CTRL and DI75 which instead showed the highest yield (Table 4). Nut dry weight was unaffected by irrigation treatments in all the considered years, except for 2021, when DI50 had a lower weight compared to CTRL; DI75 showed intermediate values not different from the other treatments (Table 4).

The number of nuts per tree was influenced by the irrigation treatment only in 2019, when DI75 exhibited the highest number of nuts compared to the other two treatments, that, instead, showed similar values (Table 4). The percentage of damaged nuts, hulled nuts, shelled yield and mold kernel, were unaffected by irrigation treatments in all four years of experimentation. In 2018, kernel humidity was significantly higher in CTRL compared to DI75 and DI50, while shrivelled kernel percentage significantly increased by DI50 compared to DI75 and CTRL (Table 4). The kernel colour was unaffected by irrigation treatments during the four years of experimentation (Table 5). Kernels, in 2018, 2019 and 2021 were mainly found, regardless of the treatments, in the extra light classification, except in 2020, where the light class exhibited the highest percentages (Table 5).

Similarly, in 2018, 2019 and 2020, no differences in nut size classes were recorded among treatments (Table 6). The highest number of nuts showed a diameter of 32–34 mm in 2018, 2020 and 2021, while it was 30–32 mm in 2019. Only in 2021, DI50 showed the highest percentage of nut of 30–32 mm of diameter; while the lowest of nut of 34–36 mm and 36–38 mm (Table 6). On the contrary, the CTRL treatment showed the highest nut percentage of

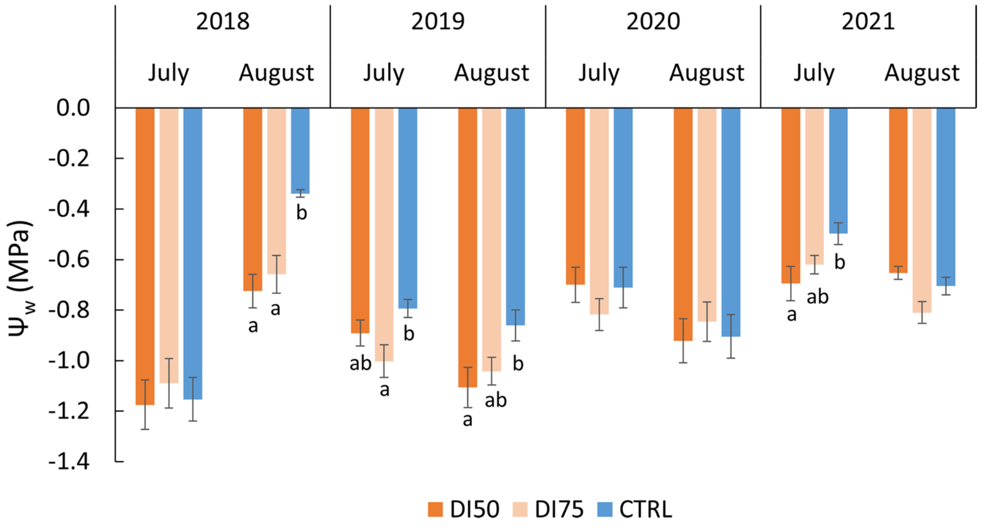

Fig. 2 Effect of irrigation treatments on midday stem water potential (Ψ_w) measured in July and August in 2018, 2019, 2020 and 2021. DI50 (orange columns), DI75 (light-orange columns) and Control (CTRL - blue columns). Within the same month, means column with the same letter are not statistically different for $p<0.05$. * and **: significant effect at $p\leq0.05$ and $p\leq0.01$, respectively. Bars indicate standard error

Fig. 3 Effect of irrigation treatments on midday leaf gas exchanges (**a**) A, leaf photosynthesis; **b**) g_s, stomatal conductance) measured in July and August during the seasons 2018, 2019, 2020 and 2021. DI50 (orange columns), DI75 (light-orange columns) and 100% of ET_c (CTRL - blue columns). Within the same month, columns with the same letter are not statistically different for $p<0.05$). * and **: significant effect at $p\leq0.05$ and $p\leq0.01$, respectively. Bars indicate standard error

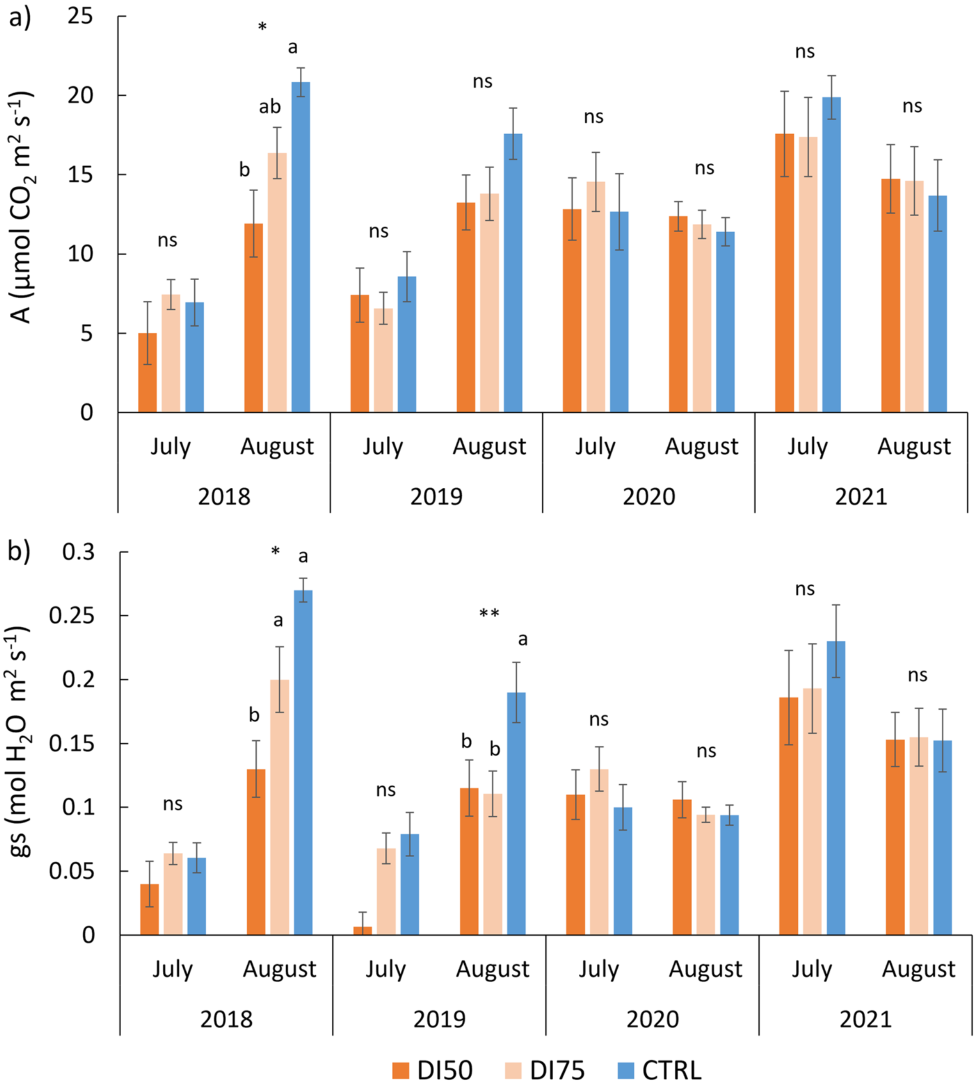

Table 3 Effect of irrigation rate on trunk circumference in 2020 and 2021 and circumference increase

Parameter	Trunk circumference (cm)		Trunk increase (cm)
Season	2020	2021	2020–2021
Treatment			
DI50	57.7	60.2	2.50
DI75	52.5	57.1	4.55
CTRL	56.8	60.3	3.45
Significance	*ns*	*ns*	*ns*

Ns effect of treatment not significant

34–36 and 36–38 mm and the lowest ones, together with DI75, of 30–32 mm diameter (Table 6).

Water use efficiency was significantly influenced by irrigation treatments, with DI50 and CTRL showing respectively the highest and lowest WUE values for all the considered years (Fig. 4). The four-year average value of WUE was 1.42 g L^{-1} for DI50 and 1.15 g L^{-1} for CTRL, respectively. DI75 had WUE ranging between DI50 and CTRL in 2018 and 2019, with similar values to DI50 in 2020 and 2021. In 2019, WUE was the lowest for all the treatments (Fig. 4).

Discussion

During the study, the walnut trees showed a limited sensitivity to drought stress, since the main physiological parameters were slightly, or not, affected, by a reduction of 50% irrigation rate. Ψ_w, considered the main parameter to evaluate walnut plant water stress (Fulton et al. 2014), was decreased by water reduction only in half of the performed measurements. Furthermore, these differences were more evident in the first two years (2018 and 2019) than in the last two (2020 and 2021), when Ψ_w values increased in all the treatments. This result suggests a plant adaptation, over years, to soil water reduction, enhanced by walnut root system ability to growth and explore the deeper soil layers

Table 4 Effect of irrigation treatments on yield and nut quality parameters during the experimental period

Season	Treatment	Dry yield ($t\ ha^{-1}$)	Nut dry weight ($g\ nut^{-1}$)	Number of nuts ($nut\ tree^{-1}$)	Damaged nuts (%)	Hulled nuts (%)	Kernel humidity (%)	Shelled yield (%)	Shrivelled kernel (%)	Moldy kernel (%)
2018	DI50	6.71 b	9.82	2136	4.38	2.25	8.00 b	49.8	6.00 a	3.50
	DI75	7.97 a	10.3	2402	3.11	1.46	8.00 b	49.5	3.00 b	2.75
	CTRL	8.26 a	10.5	2474	2.83	0.61	10.6 a	48.9	3.00 b	4.50
	Significance	**	*n.s.*	*n.s*	*n.s.*	*n.s.*	*	*n.s.*	*	*n.s.*
2019	DI50	5.22 b	10.2	1897 b	4.99	7.66	3.61	47.2	13.5	1.50
	DI75	6.27 a	9.93	2322 a	5.08	7.30	3.57	47.4	14.0	2.50
	CTRL	5.58 ab	10.2	1996 b	4.94	7.26	3.95	47.1	10.5	2.00
	Significance	*	*n.s.*	*	*n.s.*	*n.s.*	*n.s.*	*ns*	*n.s.*	*n.s.*
2020	DI50	6.97	9.43	2626	3.87	5.87	4.70	53.1	6.50	8.50
	DI75	7.42	9.18	2834	7.60	5.89	4.27	52.9	7.00	3.50
	CTRL	7.12	10.0	2559	6.09	6.86	4.40	52.0	6.50	4.00
	Significance	*n.s.*	*n.s.*	*n.s.*	*n.s.*	*n.s.*	*n.s.*	*n.s.*	*n.s.*	*n.s.*
2021	DI50	8.53	10.5 b	2784	1.28	3.32	4.70	53.6	4.00	5.00
	DI75	9.23	11.1 ab	2916	0.96	3.80	5.00	53.0	5.00	3.50
	CTRL	8.86	11.5 a	2696	1.29	3.59	5.34	52.3	2.50	8.00
	Significance	*n.s.*	*	*n.s.*	*n.s.*	*n.s.*	*n.s.*	*n.s.*	*n.s.*	*n.s.*

Within the same column and year, means followed by the same letter are not statistically different ($p \leq 0.05$). *ns*, * and ** effect of treatment not significant or significant at $p \leq 0.05$ or $p \leq 0.01$, respectively

Table 5 Effect of irrigation treatments on kernel colour in 2018, 2019, 2020 and 2021

Season	Treatment	Extra light (%)	Light	Light amber	Amber
2018	DI50	90.5	5.75	1.75	1.75
	DI75	92.5	4.00	1.25	2.25
	CTRL	86.5	11.0	0.75	1.75
	Significance	*n.s.*	*n.s*	*n.s*	*n.s.*
2019	DI50	92.0	5.50	2.80	0.45
	DI75	91.5	6.00	2.70	0.80
	CTRL	89.5	7.00	4.00	0.35
	Significance	*n.s.*	*n.s*	*n.s*	*n.s.*
2020	DI50	16.0	75.0	8.50	2.50
	DI75	19.0	71.0	9.50	2.00
	CTRL	19.5	71.5	8.00	3.50
	Significance	*n.s.*	*n.s*	*n.s*	*n.s.*
2021	DI50	63.5	32.0	3.00	1.50
	DI75	60.5	36.0	3.00	1.00
	CTRL	70.0	25.0	3.00	1.50
	Significance	*n.s.*	*n.s*	*n.s*	*n.s.*

n.s effect of treatment not significant

(Cohen et al. 1997). This is especially true for adult walnut trees, as those considered in this trial (12 years old) that are typically characterized by a large, well-developed and deep root system (deeper than 1 m; Fig. S1). These results seem to be confirmed (especially in 2020) by the IRRIFRAME estimated DI75 and DI50 soil humidity data that, in 2020, were almost always in between the IRRIFRAME irrigation intervention threshold (24%vol) and the soil WP (16.6%vol) (Fig. S2). Similar results were achived in 2021 but mainly in August and September (Fig. S2). On the contrarly the CTRL treatment was almost never below the IRRIFRAME irrigation intervention threshold in both the years (2020–2021). Cohen et al. (1997) found plant water stress only in young walnut plantations, subjected to different irrigation regimes. Regardless of the applied water stress, walnut trees progressively adapted to the deficited irrigation supply. In our study, when Ψ_w differences occurred, plants irrigated with 100% of ET_c (CTRL) generally showed higher Ψ_w than DI75 and DI50 and maintained values close to the water stress threshold −0.8 MPa (optimal condition, indicated by Fulton et al. (2014).

Stomatal conductance was less sensitive to the reduction of irrigation rate than stem Ψ_w. Differences among treatments were recorded only in August 2018 and 2019, when the evaporative demand was high and water reserves in deeper soil layers were likely more depleted. Walnut seemed to limit water losses in response to high vapour pressure gradient and appeared to behave as a drought avoider (Lucier and Hincklet, 1982). Walnut is indeed sensitive to xylem cavitation, which can occur despite the presence of moderate tension in the xylem (Cochard et al. 2007). CTRL and DI75 showed higher g_s than DI50 in 2018, while CTRL in 2019 showed higher values compared to DI75 and DI50. G_s results, in 2020 and 2021, agree with those reported by Calvo et al. (2022) who compared 4 different water regimes in walnut, without finding differences in g_s. As hypothesized, also photosynthesis rate was barely affected by irrigation treatments, with A ranging between 5.01 and 20.8 $\mu mol\ m^{-2}\ s^{-1}$. The high variability registered in plant water status and in leaf gas exchange parameters could be likely explained

Table 6 Effect of irrigation treatments on nut size (mm) class distribution in 2018, 2019, 2020 and 2021

Season	Treatment	<28 (%)	28–30	30–32	32–34	34–36	36–38	>38
2018	DI50	1.00	6.00	22.7	37.7	27.0	5.25	0.25
	DI75	0.70	4.00	20.2	32.5	26.5	14.5	1.50
	CTRL	1.50	3.50	17.2	34.7	31.5	9.75	1.75
	Significance	*n.s.*	*n.s.*	*n.s.*	*n.s.*	*n.s.*	*n.s.*	*n.s.*
2019	DI50	8.85	26.9	39.6	22.9	2.48	0.50	0.00
	DI75	8.87	25.9	40.8	22.2	2.74	0.32	0.00
	CTRL	11.9	25.8	37.1	21.8	4.77	0.50	0.00
	Significance	*n.s.*	*n.s.*	*n.s.*	*n.s.*	*n.s.*	*n.s.*	*n.s.*
2020	DI50	3.00	8.50	32.0	34.0	19.0	3.00	0.00
	DI75	2.00	8.50	27.5	36.5	22.0	4.00	0.00
	CTRL	1.00	6.00	29.5	37.0	22.5	4.00	0.00
	Significance	*n.s.*	*n.s.*	*n.s.*	*n.s.*	*n.s.*	*n.s.*	*n.s.*
2021	DI50	0.00	6.00	29.0 a	44.0	20.0 b	1.50 b	0.00
	DI75	1.00	4.00	16.5 b	46.0	28.5 ab	3.50 ab	0.50
	CTRL	1.00	4.50	14.5 b	41.0	32.0 a	7.50 a	0.00
	Significance	*n.s.*	*n.s.*	***	*n.s.*	*	*	*n.s.*

Within the same column and year, means followed by the same letter are not statistically different ($p \leq 0.05$). *ns*, * and ***: effect of treatment not significant or significant at $p \leq 0.05$ or $p \leq 0.001$, respectively

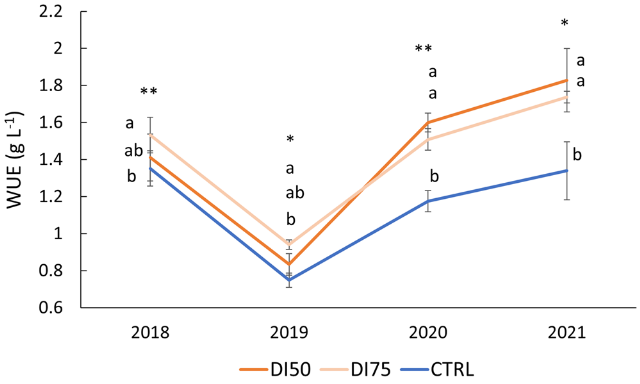

Fig. 4 Effect of irrigation treatments on water use efficiency (WUE) in 2018, 2019, 2020 and 2021. DI50 (orange line), DI75 (light-orange line) and 100% ET_c (CTRL - blue line). Within the same year, means followed by the same letter are not statistically different ($p \leq 0.05$). * and **: significant effect at $p \leq 0.05$ or $p \leq 0.01$, respectively. Bars indicate standard error

by the high inter-plant variability, probably related to the effect of the seedling rootstocks (*J. regia*). Studies report how seedling rootstocks could differently affect the overall plant water use through their impact on root architecture, depth, structure, water uptake capacity and stomatal control, as found for other fruit tree species (Fullana-Pericàs et al., 2020; Opazo et al. 2020; Maleki et al. 2023). In addition, the different environmental conditions registered during the experiment could also have conditioned the variability of the above-mentioned parameters.

Given the limited response of plant physiological performances to deficit irrigation, even yield and the main nut quality parameters were slightly affected by irrigation treatments. Only in the first two years (2018 and 2019), DI50 showed a reduced productivity compared to CTRL and DI75 (19% reduction in 2018). Furthermore, in 2018, DI50 showed an increased percentage of shrivelled kernels that typically occur under plant water stress conditions (Fulton et al. 2014). Concurrently in CTRL, the 20% increase in kernel humidity could indicate a likely effect of overirrigation. Nut fresh weight, other than being slightly reduced only in 2021 in the DI50 treatment, did not differ during all the experiment. This likely suggests the absence of severe water stress conditions in the second half of the season (July, August) when kernel filling typically occurs (Fulton et al., 2015). Furthermore, the lack of differences in plant nut load in 2018, 2020 and 2021, likely confirms that plants subjected to water reduction (DI50 and DI75) were not experiencing severe water stress conditions.

The complete absence of differences in kernel colour classification (e.g., light-amber, amber) among the treatments for all four consecutive years, supports the fact that walnut plants, subjected to a 75 and 50% ET_c, did not experience strong water stress periods. High percentages of light-amber and amber kernels typically occur when plants are exposed to water stress conditions (Fulton et al., 2015). Nut size class distribution was also similar among treatments, in three out of four years. This result stresses the hypothesis that, in our experimental conditions, water stress was limited, even in the first part of the season (before early June), when nuts are in cell division stage, to reach their maximum shell size (i.e., at hardening stage) (Fulton et al., 2015). At this stage of the season (e.g., end of spring), to satisfy their low water requirements, walnut trees could probably still benefit from water stored in the root zone, cumulated from autumn/spring rainfall. Typically, there are 400 mm of rain in Emilia Romagna region, between November and May. Our results, especially in 2020 and 2021 seasons, were similar to what reported by Cohen et al. (1997), stating no differences in yield and nut quality parameters, when applying different water regimes.

On the contrary, irrigation treatments highly affected the WUE in all the considered years, with well-watered CTRL being the less efficient treatment; DI75 and DI50, were more efficient with about 1.8 g of dry nut produced for 1 L of water consumed in 2021 (30% of increase of WUE of DI50 compared to CTRL). This means that both treatments, under a deficit irrigation rate, had a better utilization of soil water reserves. Similar results were achieved by Goldhamer et al. (1998) who found a WUE increase of 18.5% in the 33% ET_c irrigation treatment, compared to the CTRL (100% ET_c). Results of this 4-year study, achieved through the IRRIFRAME water balance model, showed large quantities of water savings, compared to typical Emilia-Romagna walnut orchard irrigation management (still often based on farmers experience). The four years average estimated ET_c with IRRIFRAME, based on site-adjusted K_c (ranging from 0.45 to 1.00) and on soil pedo-function data, was 655 mm year^{-1} (100% ET_c). Similar values were found by Calvo et al. (2022) in Argentina and are equivalent to 70% of the average ET_c, obtained in California (1050 mm year^{-1}) by Goldhamer et al. (1998). Nevertheless, based on the four-years assessment of CTRL, DI75 and DI50 physiological performances, yield, nut quality characteristics, and considering the pedo-climatic conditions of the area (loam soil in a humid climate), the IRRIFRAME model could be further improved. The applied K_c could be reduced in some specific phenological phases (e.g., beginning of the vegetative cycle) and the pedo-function equation could be integrated with deeper soil (below 0.50 m) moisture data.

Conclusion

The adoption of deficit irrigation rates (50% and 75% of ET_c), for four consecutive seasons on an adult walnut orchard, did not affect, to a high degree, walnut physiological performances, nut quality parameters and yield. A moderate reduction of plant physiological performances and yield was found in the 50% ET_c irrigation treatment, however only in the first two years. Nevertheless, applying 50% and 75% of ET_c, improved tree water use efficiency for all four consecutive years. These results suggest that, in Emilia Romagna pedoclimatic conditions, walnut roots can draw water from deeper soil layers. Consequently, water regimes could be easily reduced to 75% (with no yield penalization) and even to 50% of ET_c without experiencing severe plant water stress conditions. As a result, the walnut IRRIFRAME model, allowed large quantities of water savings, compared to typical Emilia-Romagna walnut orchard irrigation management. Furthermore, it did not penalize tree productivity and nut quality parameters. Based on the obtained results, the IRRIFRAME model could still be improved. Definitely, the assessment of plant physiological parameters during the whole vegetative season (e.g., May-September), along with monitoring of deep soil layers moisture and a revision of the applied K_c, could provide more precise information for a better irrigation scheduling of walnut, helping to avoid overestimation of irrigation demands.

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Declarations

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