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ORIGINAL PAPER

Effects of deficit irrigation on the yield and irrigation water use efficiency of drip-irrigated sweet pepper (*Capsicum annuum* L.) under Mediterranean conditions

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Abstract

Water scarcity is seriously affecting agricultural production, especially in arid and semi-arid areas. Therefore, there is increasing interest in improving water productivity in agriculture. This research aims to study the effects of deficit irrigation on the productive response of sweet pepper plants. Nine deficit irrigation strategies were assayed during two seasons (2017 and 2018) in a randomised complete block design with three replicates. These irrigation strategies consisted of applying 100%, 75% and 50% of the irrigation water requirement (IWR) during the entire growing period (continued deficit irrigation) or applying 75% or 50% of the IWR during one of the following stages (regulated deficit irrigation): vegetative growth, fruit setting, and harvesting. Pepper plants cultivated under deficit irrigation reduced fruit biomass and indicators of plant water status. Applying water deficits during the vegetative growth and fruit-setting stages had minimal effects on the marketable yield but with minimal water savings. Irrigating pepper plants with 75% or 50% of the IWR during the entire crop cycle or with 50% of the IWR during harvesting resulted in a high incidence of fruits affected by blossom end rot, which in turn, led to a drastic reduction of the marketable yield in relation to fully irrigated plants (−36%, −55% and −44%, respectively). These strategies also recorded the highest soluble solid and phenolic contents. Reducing the water applied to 75% of the IWR at harvesting led to a yield reduction (−19%) but with important water savings (21%) and acceptable levels of soluble fruit solids and phenolic compounds.

Abbreviations

AWC	Available water content
BER	Blossom end rot
CI	Colour index
C^*	Chroma
CDI	Continued deficit irrigation
ET	Evapotranspiration
ETa	Actual crop evapotranspiration
ETm	Maximum crop evapotranspiration
ETo	Reference evapotranspiration
ETc	Crop evapotranspiration
DM	Dry matter
Ef	Irrigation efficiency
Epan	Evaporation from a class A pan
FC	Field capacity
FW	Fresh weight
GS	Growing season
$H°$	Hue angle
HI	Harvest index
IS	Irrigation strategy
IWA	Irrigation water applied
IWR	Irrigation water requirement
IWUE	Irrigation water use efficiency
K_c	Crop coefficient
K_p	Pan coefficient
K_y	Yield response factor
MY	Marketable yield
MI	Maturity index

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MSI	Membrane stability index
Pe	Effective precipitation
PWP	Permanent wilting point
RDI	Regulated deficit irrigation
RWC	Relative water content
SSC	Soluble solids content
VSWC	Volumetric soil water content
WUE	Water use efficiency
Ya	Actual marketable yield
Ym	Maximum marketable yield

Introduction

The sweet pepper (*Capsicum annuum* L.) is one of the most important vegetable crops worldwide, and it has important economic value. The total land area of pepper cultivation in 2017 was approximately 2 million ha, leading to the production of approximately 36 million tonnes, being China the largest worldwide pepper producer, followed by Mexico and Turkey; in Europe, Spain, Italy and Romania are the main producers, and Spain is the second largest exporter of peppers after Mexico (Faostat 2018).

Water scarcity is one of the major limiting factors for vegetable crop production. The Mediterranean climate is characterised by mild winter temperatures and long, hot and dry summers, with precipitation subject to high inter-annual and seasonal variability; therefore, irrigation is essential for crop production (Galindo et al., 2018). Irrigation water use efficiency (IWUE, defined as the weight of marketable crop produced per unit volume of irrigation water applied) and water use efficiency (WUE, defined as the weight of marketable crop produced per unit volume of water applied) are common indicators to assess the efficiency of irrigation water usage in agriculture (Tolk and Howell 2003). IWUE improvement is closely related to the reduction of water consumption and loss (ET, runoff and losses in depth) while maintaining crop yield at a certain level (Leskovar et al. 2014.) Several investigators (Costa et al. 2007; Chai et al. 2016), have reported that deficit irrigation (DI) can improve water productivity. DI is an irrigation practice whereby crops are irrigated with water amounts less than their requirements for optimal plant growth. DI includes continuous deficit irrigation (CDI) and regulated deficit irrigation (RDI) (Fereres and Soriano 2007). The CDI approach is based on imposing the water deficit uniformly over the entire crop cycle, thereby avoiding severe water stress at any particular growth stage that might affect marketable yield; the RDI approach is a stage-based deficit irrigation, consisting of imposing water deficits at specific phenological stages, when crops are less sensitive to water stress (Fereres and Soriano 2007; Geerts and Raes 2009).

As these water reductions may lead to considerable yield reductions (Fereres and Soriano 2007), effective application of RDI requires identification of the most critical growth stages for each specific crop species and cultivar. Therefore, crop sensitivity to water deficit must be evaluated at different stages to determine the optimal timing and extent of water reduction required to achieve efficient water use while obtaining adequate yield (Chai et al. 2016). Doorenbos and Kassam (1979) introduced a linear crop–water production function to describe the reduction in yield when crop is under stress due to a shortage of soil water, being the yield response factor (K_y), the factor that describes the reduction in relative yield according to the reduction in the crop evapotranspiration (ETc). Monitoring soil moisture can ensure adequate soil water status, limiting drainage and leading to improved water productivity while minimising the risk of yield reduction (Blanco et al. 2018).

A short period of mild water deficit may affect plant water status (Pérez-Pastor et al. 2014), which had been traditionally estimated by the water content and water potential as indicators of leaf water status. It is currently also estimated by the relative water content (RWC), which is a measurement of the leaf water status relative to its maximal water holding capacity; it estimates the stress level under drought or heat stress (González and González-Vilar 2001). RWC is closely related to cell turgor, which is the process directly driving cell expansion (Jones 2004), and it is used as a meaningful index for dehydration tolerance (Kalariya et al. 2015). Water stress modifies cell membrane structure and composition, which causes leakage of ions; the rate of damage to cell membranes by water stress may be assessed through the cell membrane stability index (MSI), which detects the degree of cell membrane injury induced by water stress (Bajji et al. 2002). The pepper plant is considered sensitive to water stress, which can result in large yield reductions (Steduto et al. 2012).

Fresh pepper fruit is an important source of ascorbic acid (vitamin C) and phenolic compounds, which are well known for their antioxidant activity (Howard et al. 2000; Frary et al. 2008). Currently, there is an increase in consumer interest in pepper fruit quality, due to its beneficial effects for human health, functional properties and nutritional value, in addition to the sensorial traits of taste and aroma (Howard et al. 2000). Several authors have proposed that not only water productivity but also fruit quality parameters could be improved by certain levels of deficit irrigation in solanaceous plants (Yang et al. 2017).

To maximise both water productivity (Fernández et al. 2005; Mardani et al. 2017) and pepper fruit quality (Yang et al. 2017), an optimal irrigation management is essential. These parameters depend to a large extent on the plant variety and the environment in which they are grown, so irrigation management should be adapted to each variety and environmental conditions. The objective of this study is to evaluate the vegetative and productive responses of pepper plants, including plant water status, yield, K_y, IWUE and fruit quality, to CDI and RDI under Mediterranean conditions.

Materials and methods

Experimental site description

The field studies were carried out at the Cajamar Experimental Centre in Paiporta, Valencia, Spain (39.4175 N, 0.4184 W) over two consecutive growing seasons (GS; 2017 and 2018). To avoid soil replanting disorders resulting from serial pepper cropping, the experiment in each growing season was carried out in different and adjacent subplots within the experimental plot. The soil at the site is deep with a medium texture (silt loam) and is classified as Petrocalcic Calcixerepts, according to the USDA Soil Taxonomy (Soil Survey Staff 2014). The soil was very slightly alkaline (pH = 7.55) and highly fertile [on average: organic matter = 1.9%; high available phosphorous (44 mg kg^{-1}; Olsen) and potassium (515 mg kg^{-1}; ammonium acetate extract) concentrations]. Soil was uniform in the root zone depth (30 cm), and volumetric soil water contents (VSWC) at the field capacity and permanent wilting point were (on average) 28.73% and 16.0%, respectively, for 2017, and 28.84% and 16% for 2018. Available soil water content (AWC) for 0–30 cm soil depth was 38.4 mm for 2017 and 38.5 mm for 2018. The local climate, according to Papadakis's agroclimatic classification (Verheye 2009), is subtropical Mediterranean (Su, Me) with hot and dry summers. The annual average rainfall is approximately 450 mm, irregularly distributed throughout the year with the majority occurring in autumn and the beginning of spring. Figure 1 shows the most significant climatological data of the experimental GS.

Plant material and agronomic details

The sweet Italian pepper 'Estrada F1' (Nunhems®) was used in the experiments. This cultivar was chosen because of its adequate adaptation to the soil and climate conditions in the area, its high productivity under open field cultivation and its great acceptance by consumers (verified in public demonstrations periodically conducted in the Experimental Centre). The fruit, which is adequate for fresh green pepper production, has a triangular longitudinal section 15–30 cm in length with a dark green colour. The plants present an indeterminate growth pattern with intermediate vigour and show intermediate resistance to *Tomato Spotted Wilt Virus*.

Sowing took place on 27 January 2017 and 12 February 2018, in 104-cell polystyrene trays, in a peat moss-based substrate (70% blonde and 30% dark) recommended for vegetable seedbeds (Pindstrup Mosebrug S.A.E., Sotopalacios, Spain). The seeds were germinated in a Venlo-type greenhouse. Thereafter, seedlings were transplanted on 28 March 2017 and 13 April 2018 (when plants reached the four-leaf stage) in ridges in an open field, with one plant row per ridge, spaced 0.30 m apart. The distance from ridge centre to ridge centre was 1.5 m, and they were 7.25-m long and 0.15-m high. Each experimental plot included three ridges, considering the two extremes as blank. Ridges were covered by black polyethylene sheeting which is 0.025-mm thick and 1.0-m wide. Plants were horizontally supported by three nylon guide cords parallel to both sides of the plant line. Plants were not pruned. The incorporation of nutrients (200–100–300 kg ha^{-1} N–P_2O_5–K_2O) was performed by fertigation, following the criteria indicated by Condés (2017). Harvesting in 2017 was undertaken from 13 June until 16 October 2017 and consisted of 12 passes, while in 2018 was undertaken from 22 June until 22 October, and required 11 passes; therefore, the duration of the total crop cycle, including the initial stage, was 202 days in 2017 and 193 days in 2018.

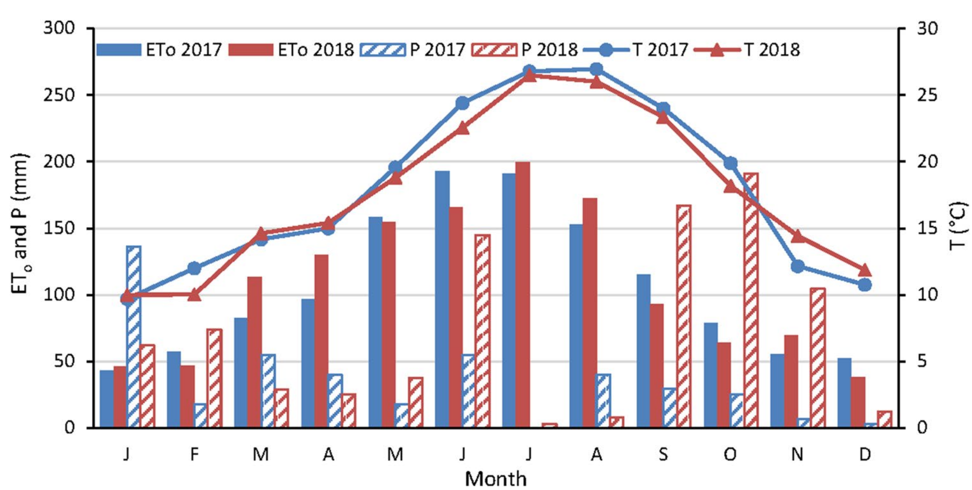

Fig. 1 Monthly reference evapotranspiration (ETo), precipitation (*P*) and average temperature (*T*) in 2017 and 2018

Deficit irrigation strategies and growth stages

The pepper growth period was divided into four stages; (1) initial, from transplanting to plant establishment; (2) vegetative growth, from establishment until early fruit setting; (3) early fruit setting and bearing (hereafter referred as fruit setting), from setting until initial harvest; and (4) harvesting, which extends throughout the harvest period. All the plants were irrigated without restrictions during the initial stage to ensure good plant establishment. Afterwards, nine irrigation strategies (IS) were applied in both GS. These IS differed in the amount of water applied in each irrigation event, as presented in Table 1. The experiment was laid out in a randomised complete block design with three replicates.

Irrigation scheduling and management

For each irrigation event, the corresponding IWR was determined as:

$$\mathrm{IWR} = \frac{\mathrm{ETc} - \mathrm{Pe}}{\mathrm{Ef}},$$

where ETc (mm) is the crop evapotranspiration, Pe is the effective precipitation (mm), determined from rainfall data using the U.S. Bureau of Reclamation method (Stamm 1967), and Ef is the irrigation efficiency. This Ef was 0.95, considering the distribution uniformity (1; in situ determined) and the leaching requirements (0.95; Cajamar, unpublished data). The frequency of irrigation ranged between daily, when the water requirements were maximum (harvesting), and weekly, when the water requirements were minimum (vegetative growth). Irrigation dose was determined retrospectively to replace the water requirements of the previous period.

Following the criteria described by Allen et al. (1998) ETc was determined from the reference evapotranspiration (ETo) and the single crop coefficient (K_c), with values of 0.3, 0.95 and 0.8, corresponding to initial, mid-season and late season stages, respectively, which were proposed for local conditions by the IVIA (2011) adapting for the duration of each stage to the growing cycle.

$$\mathrm{ETc} = \mathrm{ETo} \times K_c.$$

ETo was determined according to Allen et al. (1998) as follows:

$$\mathrm{ETo} = E_{pan} \times K_p,$$

where E_{pan} (mm day^{-1}) is the evaporation from a class A pan installed adjacent to the experimental plot, and K_p (0.815) is the pan coefficient determined according to Allen et al. (1998).

Plants were irrigated by a drip irrigation system with a single lateral line per bed using a turbulent flow dripline (16 mm; AZUDRIP Compact; Sistema Azud S.A., Murcia, Spain) with emitters (2.2 L h^{-1}) spaced 0.30 m apart. The irrigation was controlled by a NODE-100 single station controller (Hunter, California, USA). In each IS, the IWA was recorded by a water flow meter (MJ-SDC TYP E, Ningbo Water Meter Co., Ltd., Ningbo, China).

Volumetric soil water content

VSWC (m^3 m^{-3}) was continuously monitored by ECH_2O EC-5 capacitance sensors connected to an Em50 data logger, using the ECH_2O Utility software (Decagon Devices, Inc., Pullman, WA, USA). Factory calibration provides ± 3% accuracy for mineral soils and therefore used directly. One sensor per replicate was placed below the dripline, at a 20-cm depth, equidistant between two adjacent emitters. In previous experiments (data not shown) performed at the same experimental plot, it was stated that the maximum root density of sweet Italian pepper plants occurred at a depth of 0.20 m. The VSWC was measured and stored every 15 min, and its variation was used to determine the in situ field capacity (FC). For each IS, the irrigation event began when the VSWC in T1 dropped to 80% of the FC, applying to each IS the corresponding IWA. This criterion was already satisfactorily used in preliminary studies (unpublished data), and on the other hand, Yang et al. (2018) indicated that this irrigation threshold resulted in the highest yield and fruit quality in pepper, when compared with other. The fact that irrigation was managed with the VSWC expressed as percentage of FC reduced the importance of sensor calibration. To compare the VSWC between IS and GS, their values are presented as AWC before each irrigation event, determined as reported Fernández et al. (2005):

Table 1 Irrigation strategies, expressed as percentage of the irrigation water requirements applied in each growth stage: initial (1), vegetative growth (2), early fruit setting and bearing (3), and harvesting (4)

Irrigation strategy	1	2	3	4
T1	100%	100%	100%	100%
T2	100%	75%	75%	75%
T3	100%	50%	50%	50%
T4	100%	75%	100%	100%
T5	100%	100%	75%	100%
T6	100%	100%	100%	75%
T7	100%	50%	100%	100%
T8	100%	100%	50%	100%
T9	100%	100%	100%	50%

$$\text{AWC} = \left(1 - \frac{\text{SWC}_{\text{FC}} - \text{SWC}_{\text{a}}}{\text{SWC}_{\text{FC}} - \text{SWC}_{\text{PWP}}}\right) * 100$$

considering that SWC is the soil water content for 0–30-cm soil depth, expressed in mm, and the subscripts a, FC and PWP correspond to the actual (before irrigation), field capacity and permanent wilting point soil water content, respectively.

Data collection and measurements

Relative water content (RWC) and membrane stability index (MSI)

Both the leaf relative water content (RWC; %) and membrane stability index (MSI; %) were evaluated at the end of each growth stage. The relative water content was determined from fresh leaf discs of 2 cm in diameter, as reported by Barrs (1968), using the equation:

$$\text{RWC}\ (\%) = \frac{(\text{FW} - \text{DW})}{(\text{TW} - \text{DW})} * 100,$$

where FW is the fresh weight (g) of leaf disc, TW is the leaf disc weight (g) at full turgidity, and DW is the corresponding dry weight (g).

The membrane stability index was determined from samples of fully expanded leaf tissue (0.2 g), as described by Rady (2011), using the equation:

$$\text{MSI}\ (\%) = \left(1 - \frac{C_1}{C_2}\right) * 100,$$

where C_1 is the electrical conductivity of the solution (samples submerged in distilled water) after 30 min in a water bath at 40 °C, and C_2 is the electrical conductivity of the solution after 10 min at 100 °C.

Plant growth and harvest index

Growth parameters were analysed at the end of the crop cycle. Plant height and stem diameter were determined from three plants from each plot in the field. Plant height was measured with a measuring tape, while the stem diameter was measured by a digital calliper TOP CRAFT (Ovibell GmbH & Co., Mülheim an der Ruhr, Germany). The aboveground part of the plants was partitioned into two parts and analysed separately: vegetative, including shoots with all their leaves (hereafter referred to as shoots), and fruits (including all the fruits of all the passes performed during harvesting). Each part was weighed with an analytical balance (Mettler Toledo AG204; Greifensee, Switzerland) and dried at 65 °C in a forced-air oven (Selecta 297, Barcelona, Spain) until reaching a constant weight, allowing the measurement of dry weights and fruit dry matter (DM) content. The harvest index (HI) was determined as the ratio of total yield to total aboveground biomass on a dry mass basis (Fernández et al. 2005).

Yield, irrigation water use efficiency and yield response factor (K_y)

Twenty plants from each plot were harvested for determining yield. Following the criteria described by European Regulations (Official Journal of the European Union 2011), yield was partitioned into three categories: «Extra» Class and Class I (together hereafter referred to as marketable yield; MY) and Class II and fruits that due to their defects do not reach these categories (jointly hereafter referred to as non-marketable yield). The non-marketable yield was classified according to the nature of the blemish, including fruits affected with blossom end rot (BER), sunburn and fruits that were small or with defects in shape.

IWUE and WUE were calculated as reported by Abdelkhalik et al. (2019); IWUE as the ratio of MY (fresh mass; kg m^{-2}) to IWA (m^3 m^{-2}) and WUE as the ratio of MY (kg m^{-2}) to Pe plus IWA (m^3 m^{-2}). The yield response to water deficits was determined by the following equation (Doorenbos and Kassam 1979):

$$\left(1 - \frac{Y_a}{Y_m}\right) = K_y\left(1 - \frac{\text{ET}_a}{\text{ET}_m}\right),$$

where Y_a and Y_m are the actual and maximum MY (kg m^{-2}), respectively; ET_a and ET_m are the actual and maximum ET (mm), respectively; and K_y is the yield response factor. ET_a and ET_m were calculated with the water balance equation:

$$\text{ET} = I + P \pm \Delta\text{SW} - \text{Dp} - \text{Rf},$$

where I is the IWA, P the Pe, ΔSW the change in soil water content over the crop cycle, Dp the deep percolation, and Rf the run off. The leaching requirement was considered as Dp. Rf was considered negligible given that IWA was controlled and only Pe was considered. ΔSW was also negligible since the average VSWC remained fairly constant.

Fruit quality parameters

Nine representative fruits at similar states of maturation were selected from those harvested from each plot on 31 July 2017 (fifth pass) and on 25 July 2018 (fourth pass) to determine principal fruit quality parameters that included physical, taste and nutrient quality classifications.

Fruit length and width were measured with a measuring tape. The colour indexes [Hue angle ($H°$), Chroma (C^*) and colour index (CI)] were calculated, as presented in Abdelkhalik et al. (2019), from CIELAB (CIE 1976

$L^*a^*b^*$) colour space coordinates, which were calculated from the mean value of four readings, each of which was obtained from each of the cardinal points of the fruit equatorial zone. Fruit colour coordinates (L^*, a^* and b^*) were measured using a chroma meter (Minolta CR-300; Konica Minolta Sensing, Inc., Tokyo, Japan). Colour indexes were calculated as presented in Abdelkhalik et al. (2019), as following.

Hue angle:

$$H° = \text{Arctang}\left(\frac{b}{a}\right) + 180.$$

Chroma:

$$C^* = \sqrt{\left(a^2 + b^2\right)}.$$

Colour index:

$$\text{CI} = \frac{a * 1000}{L * b}.$$

Fruit firmness was measured by a digital penetrometer with an 8-mm-diameter tip (Penefel DFT 14, Agro Technologies, Forges les Eaux, France). The flesh thickness was measured with a digital calliper model TOP CRAFT (Ovibell GmbH & Co., Mülheim an der Ruhr, Germany).

The nine fruits used to determine the above-mentioned parameters were liquefied with a domestic blender. The filtered juice was used to determine the soluble solids content (SSC, °Brix) using a digital refractometer (PAL-1, Atago, Tokyo, Japan). Acidity was determined as citric acid (g citric acid 100 g^{-1} FW), as measured by titration with 0.1-M NaOH. Maturity index was calculated as the ratio of SSC (° Brix) and acidity (g citric acid 100 g^{-1} FW).

Ascorbic acid (vitamin C) was determined by the volumetric method of 2,6-dichloroindophenol (AOAC 2000). Total phenolic content was determined by the spectrophotometric method of Folin–Ciocalteu with a standard curve of gallic acid at 670 nm in UV–vis spectrophotometer (Unicam-Helios α, USA; Domene and Segura 2014).

Profitability

Gross revenue (the money generated by the sale of the fruits) and economic value of water (the money generated by the sale of the fruits obtained by m^3 of irrigated water applied) were determined by multiplying the average pepper fruit price corresponding to the last 3 years [0.80 euros (€) kg^{-1}; MAPA 2018] by MY and IWUE, respectively.

Statistical analysis

The results for the different parameters were evaluated by analysis of variance (ANOVA) using Statgraphics Centurion XVII (Statistical Graphics Corporation 2014). Percentage data were arcsin transformed before analysis. Least significant difference (LSD) at a 0.05-probability level was used as the mean separation test.

Results

Most of the studied parameters, as shown in Tables 3, 4, 5, 6, were affected by GS and IS, ($P \leq 0.05$ or $P \leq 0.01$), but in no case by their interaction (except WUE; $P \leq 0.05$). Thus, these factors are discussed separately. In general, only factors that are significantly different ($P \leq 0.05$) are shown in the tables.

Growth stages and irrigation water applied

The duration of each growth stage is presented in Table 2. The ETo values for 2017 and 2018 were 956 and 905 mm, respectively. The Pe registered during 2018 (249 mm)

Table 2 Duration (days) and irrigation water applied (mm) per irrigation strategy in each growth stage, from establishment and during the 2017 (28 March–16 October) and 2018 (13 April–22 October) growing seasons

	Growth stages	Days	Irrigation water applied (mm)								
			T1	T2	T3	T4	T5	T6	T7	T8	T9
2017											
	Vegetative growth	34	42	31	21	31	42	42	21	42	42
	Fruit development	29	89	67	44	89	67	89	89	44	89
	Harvesting period	125	593	445	297	594	594	446	594	594	297
	Total	188	724	543	362	715	703	576	704	681	428
2018											
	Vegetative growth	28	44	31	22	32	44	44	22	44	44
	Fruit development	28	30	22	15	30	22	30	30	15	30
	Harvesting period	123	407	305	203	407	407	305	407	407	203
	Total	179	481	359	240	468	473	379	458	465	277

was 2.3 times that in 2017 (109 mm). Therefore, the IWA was lower in 2018 than in 2017, ranging from 274 (T3) to 515 mm (T1) in 2018 and from 389 (T3) to 751 mm (T1) in 2017. These values include 27 and 34 mm in 2017 and 2018, respectively, which corresponds to the initial irrigation that was equally applied for all IS to insure adequate plant establishment.

Volumetric soil water content

Figure 2 shows the AWC for the different IS as well as the daily rainfall during both GS. The average AWC (before irrigation events) ranged from 38.9% (T3) to 57.7% (T1) in 2017, and from 32.8% (T3) to 48.1% (T1) in 2018. It can be observed that the largest decrease in AWC corresponded to

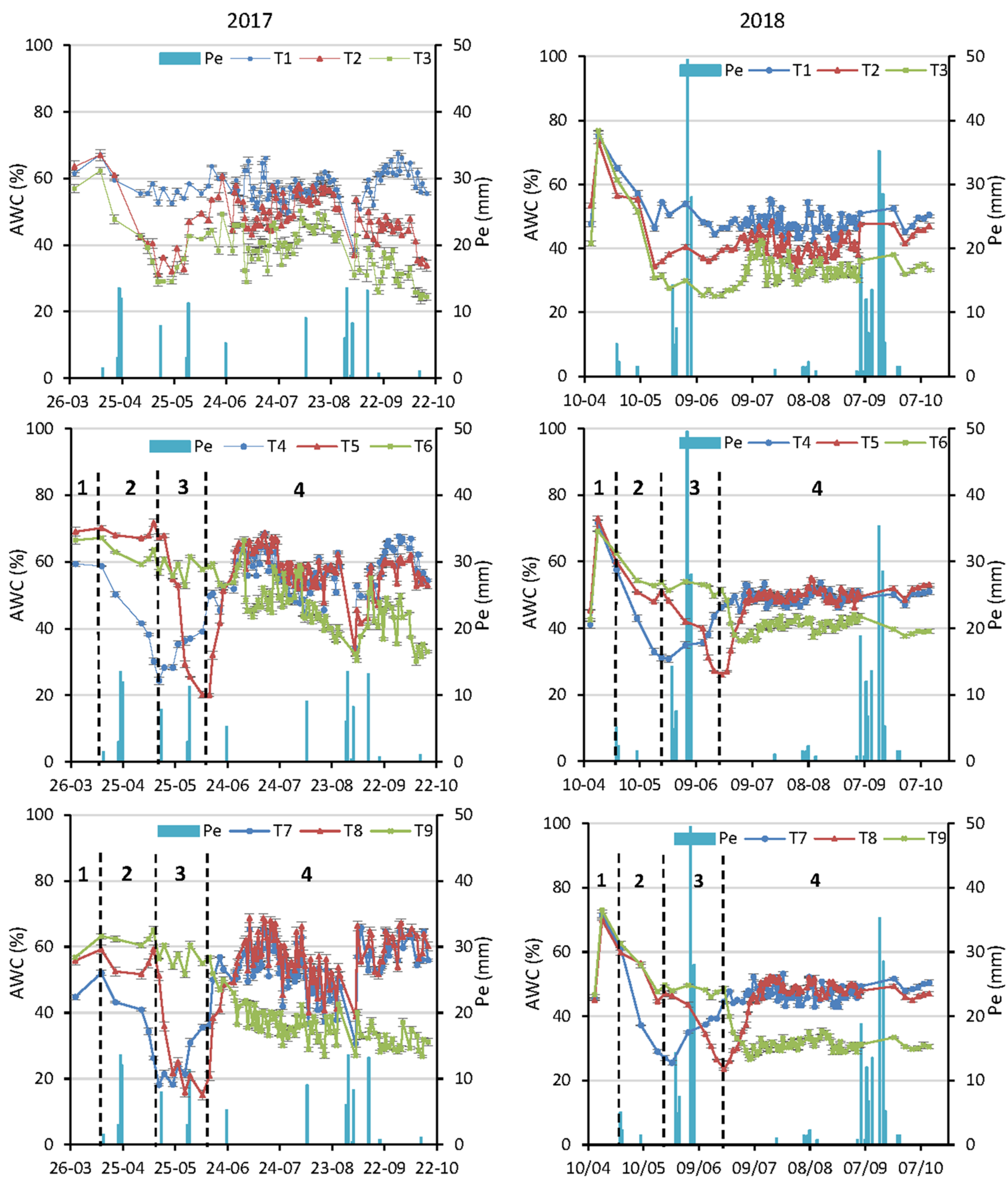

Fig. 2 Available water content before each irrigation event (AWC) for each irrigation strategy during each growing season; vertical bars in each point represent the corresponding standard error. Daily effective precipitation (Pe). Crop growth stages: (1) initial; (2) vegetative growth; (3) early fruit setting and bearing; (4) harvesting

the stage when the water restriction was applied for each IS, with greater differences for the severe restriction.

Relative water content and membrane stability index

The RWC and the MSI at the end of harvest were higher ($P \leq 0.01$) in 2018 than in 2017 (Table 3); while at the end of the vegetative growth stage, there were no differences between years. At the end of the vegetative growth stage, neither RWC nor MSI were affected ($P \leq 0.05$) by the IS. At the end of harvesting, the highest values of RWC and MSI corresponded to T1, and the lowest to T3 and T9 ($P \leq 0.05$). At the end of the fruit setting stage, the lowest RWC and MSI values ($P \leq 0.05$) were obtained when the severe water restriction was applied in this stage (T3 and T8).

Plant growth and harvest index

Some pepper plant growth traits were significantly affected ($P \leq 0.01$; $P \leq 0.05$) by GS and IS (Table 4). Plants grown in 2018 were shorter than in 2017, but they had a larger diameter stem. Plant height and stem diameter were not affected ($P \leq 0.05$) by the IS.

Shoot dry weight was affected ($P \leq 0.01$; Table 4) by GS, with higher values in 2018, while it was not affected by IS. Fruit dry weight (Table 4) was not affected by GS. The highest fruit dry weights were obtained in T1, while the lowest corresponded to T3 and T9. HI was affected ($P \leq 0.01$) by GS, with higher ratio in 2017, and it was also affected by the IS ($P \leq 0.01$), ranging from 0.51 (T3) to 0.58 (T7).

Yield, irrigation water use efficiency and yield response factor

Yield was not affected by GS ($P \leq 0.05$). Nevertheless, higher MY and «Extra class» yield, and lower percentages of the different non-marketable fruit batches (except for BER) were obtained in 2018 than in 2017 (Table 5; $P \leq 0.01$). MY corresponding to T2 and T3 was reduced by 36% and 55%, respectively, compared to T1, with slightly greater reductions (40% and 60%, respectively) when «Extra» class yield was analysed. T6 and T9 reduced significantly ($P \leq 0.05$) both MY and «Extra» class yield in relation to fully irrigated plants, while the other RDI

Table 3 Effect of the growing season and irrigation strategy on the leaf relative water content (RWC) and membrane stability index (MSI) at the end of each growth stage: vegetative growth (2), fruit setting (3) and harvesting (4)

	RWC (%)			MSI (%)		
	2	3	4	2	3	4
Growing season (GS)						
2017	81.42	79.05	75.49 b	76.91	74.31 b	74.04 b
2018	80.76	79.81	82.99 a	77.21	75.43 a	76.14 a
LSD	1.16	1.39	0.84	1.14	0.91	0.84
Irrigation strategies (IS)						
T1	82.05	81.47 a	81.50 a	78.10	76.82 a	77.37 a
T2	80.48	77.65 bcd	77.33 b	76.67	73.57 cd	73.35 cd
T3	79.53	75.55 d	73.57 c	75.72	71.70 d	70.97 e
T4	80.52	80.03 ab	81.10 a	76.18	75.23 abc	77.08 a
T5	81.57	79.62 abc	81.37 a	77.90	75.28 abc	76.32 ab
T6	82.28	81.43 a	80.87 a	78.28	76.15 a	75.12 bc
T7	79.55	80.48 ab	81.20 a	75.68	75.28 abc	76.82 ab
T8	81.82	77.05 cd	80.98 a	77.85	73.95 bc	76.90 ab
T9	82.03	81.58 a	75.22 c	77.18	75.82 ab	71.90 de
LSD	2.46	2.94	1.78	2.42	1.94	1.78
ANOVA (*df*)	% Sum of the squares					
GS (1)	2.5 ns	1.6 ns	58.5 **	0.5 ns	6.4 *	12.8 **
IS (8)	23.9 ns	47.2 **	34.5 **	23.6 ns	43.9 **	61.1 **
GS*IS (8)	6.6 ns	4.2 ns	0.6 ns	5.4 ns	12.6 ns	8.0 ns
Residuals (36)	67.0	47.0	6.4	70.4	37.2	18.1
Standard deviation	2.1	2.5	1.5	2.1	1.7	1.5

Mean values followed by different lower-case letters in each column indicate significant differences at $P \leq 0.05$ using the LSD test

df degrees of freedom, *ns* no significant difference

** (*) Indicates significant differences at $P \leq 0.01$ ($P \leq 0.05$)

Table 4 Effect of the growing season and irrigation strategy on plant height (H), stem diameter (D), shoot dry weight (SDW), fruit dry weight (FDW) and harvest index (HI)

	H (cm)	*D* (mm)	SDW (kg m^{-2})	FDW (kg m^{-2}(	HI (−)
Growing season (GS)					
2017	132.40 a	23.78 b	0.91 b	1.18	0.56 a
2018	129.94 b	27.20 a	1.01 a	1.17	0.54 b
LSD	1.41	0.55	0.05	0.06	0.01
Irrigation strategy (IS)					
T1	133.67	25.96	1.06	1.33 a	0.56 ab
T2	131.71	25.25	0.91	1.13 cd	0.55 ab
T3	129.63	25.64	0.86	0.92 e	0.51 d
T4	130.58	25.13	0.99	1.28 ab	0.57 ab
T5	130.71	25.15	1.01	1.23 abc	0.55 ab
T6	131.17	25.50	1.00	1.21 abc	0.54 bc
T7	132.00	25.75	0.94	1.28 ab	0.58 a
T8	130.04	26.07	0.94	1.20 bc	0.56 ab
T9	131.00	24.94	0.94	1.02 de	0.52 cd
LSD	2.99	1.17	0.12	0.12	0.03
ANOVA (*df*)	% Sum of the squares				
GS (1)	5.3**	41.5**	17.6**	0.0 ns	15.9**
IS (8)	4.5 ns	2.0 ns	22.5 ns	67.8**	39.7**
GS*IS (8)	1.7 ns	1.9 ns	12.1 ns	2.5 ns	4.1 ns
Residuals (144/36[a])	88.6	54.7	47.9	29.6	40.3
SD	5.3	2.0	0.1	0.1	0.02

Mean values followed by different lower-case letters in each column indicate significant differences at $P \leq 0.05$ using the LSD test

df degrees of freedom, *SD* standard deviation, *ns* no significant difference

**Significant differences at $P \leq 0.0$

[a]Degrees of freedom for SDW, FDW and HI

strategies did not affect these parameters. The larger percentage of non-marketable fruits obtained in 2017 ($P \leq 0.05$; Table 5) than in 2018, was mainly due to a greater abundance of small fruits and to a lesser extent a higher incidence of sunburnt and deformed fruits. The largest percentage of non-marketable fruits in T3 ($P \leq 0.01$) was due to a higher presence of BER ($P \leq 0.01$) in this treatment.

The highest WUE and IWUE ($P \leq 0.01$) values were obtained in 2018, as a consequence of both the higher MY and the lower IWR in 2018 than in 2017. Regarding the IS, the CDI and T9 led to lower WUE values ($P \leq 0.05$) than the other strategies. Although a similar trend could be observed for IWUE, it was not statistically significant ($P \leq 0.05$).

MY (kg m^{-2}) increased linearly ($P \leq 0.01$), with increasing water applied (mm; Pe + IWA) for CDI and for strategies applying the water reduction at harvesting (Fig. 3). The relationships between MY and water applied for water stress applied at vegetative growth and fruit setting stages were not significant ($P \leq 0.05$).

Considering both GS together, the K_y for the CDI was 1.53, while it was 0.80 and 1.32 for the vegetative growth and harvest stages, respectively. All linear regression equations were significant ($P \leq 0.01$), with correlation coefficients (*r*) from 0.83 to 0.99.

Fruit quality traits

Fruit diameter and colour indices (Hº, C* and CI) were unaffected ($P \leq 0.05$) by GS, IS or their interaction. The average fruit diameter was 39.3 mm, and the average Hº, C* and CI values were 127.41, 21.40 and −20.51, respectively. Fruit length was affected ($P \leq 0.01$; Table 6) by IS, with shorter fruits obtained with the irrigation water reduction; the shortest fruits were obtained under T3, followed by T2 and T9. Fruits obtained in 2018 presented a thicker flesh than those obtained in 2017 ($P \leq 0.01$; Table 6). As to IS, the fruits with the thickest ($P \leq 0.05$) flesh were those obtained with full irrigation, while the fruits with the thinnest flesh were those corresponding to T3 and T9.

The average fruit weight for marketable fruits produced in 2018 was higher ($P \leq 0.01$) than that produced in 2017, and in relation to IS, the results were according to those of fruit length. Fruit firmness was only affected by GS ($P \leq 0.01$); the fruits obtained in 2018 presented a higher firmness (12.29 N) than those obtained in 2017 (10.65 N).

Table 5 Effect of the growing season and irrigation strategy on the total yield (yield), marketable yield (MY; kg m^{-2}), «Extra class», non-marketable yield (NMY, % of yield) and its partitioning into fruits presenting with defects of shape (DS), small size, sunburn and blossom end rot (BER), water use efficiency (WUE) and irrigation water use efficiency (IWUE)

	Yield (kg m^{-2})	MY(kg m^{-2})		NMY (%)					WUE (kg m^{-3})	IWUE (kg m^{-3})
		MY	Extra class	NMY (%)	Small (%)	Sunburn (%)	BER (%)	DS (%)		
Growing season (GS)										
2017	11.89	6.94 b	4.28 b	42.80 a	8.18 a	2.47 a	20.67	11.43 a	9.59 b	11.39 b
2018	11.98	7.74 a	5.13 a	36.40 b	4.86 b	1.02 b	20.05	10.12 b	11.77 a	19.29 a
LSD	0.56	0.52	0.39	2.29	0.62	0.38	2.42	0.97	0.74	1.26
Irrigation strategies (IS)										
T1	13.52 a	9.02 a	5.92 a	33.38 d	7.06	1.57	14.36 d	10.35	11.62 a	15.73
T2	10.97 cd	5.78 c	3.56 c	47.45 b	6.64	1.54	27.83 b	11.14	9.32 b	13.77
T3	8.81 e	4.02 d	2.40 d	54.69 a	5.88	1.71	36.23 a	10.72	8.34 b	14.35
T4	13.03 a	8.95 a	5.83 a	31.42 d	6.88	1.86	11.40 d	11.01	11.71 a	15.95
T5	12.91 a	8.84 a	5.69 a	31.60 d	6.94	1.57	11.58 d	11.41	11.59 a	15.80
T6	12.04 bc	7.31 b	4.71 b	39.20 c	6.12	1.83	20.52 c	10.55	11.16 a	16.03
T7	13.43 a	8.80 a	5.62 a	34.56 cd	6.73	2.09	15.80 cd	9.78	11.67 a	15.98
T8	12.95 ab	8.48 a	5.44 ab	35.04 cd	6.39	2.19	15.31 d	11.00	11.34 a	15.54
T9	9.89 de	5.06 c	3.29 c	49.04 b	6.16	1.38	30.23 b	10.99	9.54 b	15.08
LSD	1.19	0.97	0.83	4.85	1.31	0.81	5.14	2.06	1.56	2.68
ANOVA (df)	% sum of the squares									
GS (1)	0.0 ns	3.8 **	8.5 **	11.4 **	69.6**	52.5 **	0.1 **	11.9 **	29.6 **	76.8 **
IS (8)	76.3 **	79.7 **	73.1 **	73.6 **	3.9 ns	6.4 ns	79.9 **	5.9 ns	36.8 **	4.1 ns
GS*IS (8)	3.0 ns	2.5 ns	2.7 ns	2.2 ns	5.2 ns	8.8 ns	5.7 ns	24.8 ns	3.9 ns	1.6 ns
Residuals (36)	20.7	14.0	15.7	12.7	21.3	32.2	14.3	57.4	29.7	17.4
SD	1.0	0.9	0.7	4.14	1.11	0.70	4.39	1.76	1.3	2.3

Mean values followed by different lower-case letters in each column indicate significant differences at $P \leq 0.05$ using the LSD test

df degrees of freedom, *SD* standard deviation, *ns* no significant difference

**Indicates significant differences at $P \leq 0.01$

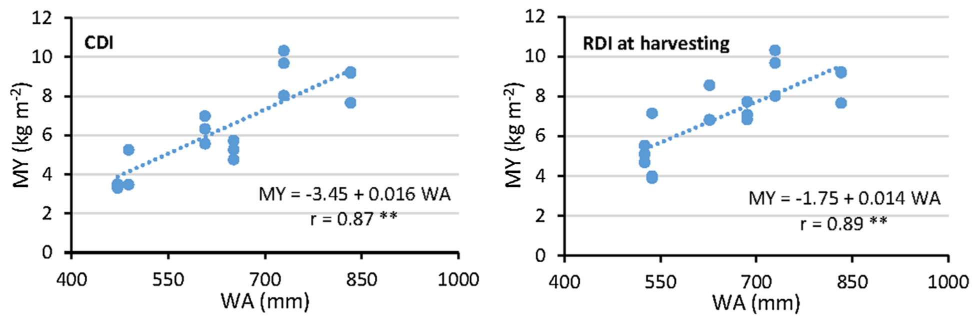

Fig. 3 Linear relationship between the marketable yield (MY) and the water applied (WA; irrigation water applied + effective precipitation) for the continued deficit irrigation (CDI) and the regulated deficit irrigation (RDI) at harvesting

Table 6 Effect of the growing season and irrigation strategy on fruit traits: length, flesh thickness (FT), average fruit weight (AFW), dry matter content (DM), soluble solids content (SSC), and total phenolic (TPs) contents

	Length (cm)	FT (mm)	AFW (g fruit^{-1})	DM (%)	SSC (° Bix)	TPs (mg 100 g^{-1})
Growing season (GS)						
2017	19.73	2.91 b	77.55 b	9.88	5.44 b	161.11 a
2018	19.87	3.09 a	86.61 a	9.86	6.67 a	116.91 b
LSD	0.37	0.16	5.27	0.20	0.38	12.94
Irrigation strategies (IS)						
T1	20.50 a	3.47 a	94.77 a	9.80 bc	5.58 c	113.07 d
T2	19.49 b	2.89 bc	77.12 cd	10.17 ab	6.34 ab	145.48 abc
T3	18.06 c	2.74 c	62.25 e	10.39 a	7.14 a	163.90 a
T4	20.47 a	3.20 ab	91.82 ab	9.80 bc	5.38 c	125.97 bcd
T5	20.26 a	3.16 ab	84.43 abc	9.51 cd	5.54 c	119.61 cd
T6	20.05 ab	3.02 bc	80.90 bcd	10.04 ab	6.55 ab	148.49 ab
T7	20.28 a	3.08 bc	94.20 a	9.54 cd	5.91 bc	136.62 abcd
T8	19.81 ab	3.03 bc	82.63 bc	9.24 d	5.60 c	137.31 abcd
T9	19.31 b	2.84 c	70.62 de	10.36 a	6.83 a	160.62 a
LSD	0.77	0.34	11.18	0.43	0.81	27.45
ANOVA (df)	% Sum of squares					
GS (1)	0.3 ns	2.6 *	10.4 **	0.2 ns	35.4 **	41.3 **
IS (8)	28.6 **	14.1 **	53.8 **	60.9 **	33.1 **	23.0 **
GS*IS (8)	6.1 ns	7.0 ns	5.2 ns	1.6 ns	2.1 ns	4.8 ns
Residuals (144)	65.0	76.3	30.7	37.3	29.4	31.0
SD	1.2	0.5	9.5	0.4	0.7	23.4

Mean values followed by different lower-case letters in each column indicate significant differences at $P \leq 0.05$ using the LSD test

df degrees of freedom, *SD* standard deviation, *ns* no significant difference

** (*): Indicates significant differences at $P \leq 0.01$ ($P \leq 0.05$

Fruit DM content was only affected by IS ($P \leq 0.01$; Table 6), with the highest values obtained for the plants subjected to water stress during harvesting (T3, T9, T2 and T6). Acidity only was affected by the GS ($P \leq 0.01$), with higher values obtained in 2018 (0.11%) than in 2017 (0.08%). SSC was affected ($P \leq 0.01$) by both GS and IS. In relation to GS, the highest SSC values corresponded to 2018, and in relation to IS, the fruits with the highest SSC were those obtained with T3 and T9, followed by T2 and T6. MI was not significantly affected ($P \leq 0.05$) by any of the analysed factors, being 64.9 its average value.

Ascorbic acid content (on average 123.3 mg 100 g^{-1}) was not affected by the GS or by IS ($P \leq 0.05$). However, total phenolic content was affected by both factors ($P \leq 0.01$). As for GS, the highest value was obtained in 2017, while in relation to IS, T3 and T9 led to the highest values ($P \leq 0.05$), while T1 led to the lowest value. Moderate water deficit (at any stage) or severe water deficit during the first stages led to intermediate results.

Profitability

Under the present study conditions, full irrigation (T1) led to the highest MY and therefore to the highest gross revenue (on average 90.2 tonnes ha^{-1} and 71,258 € ha^{-1}, respectively), with an economic value per unit of water consumed of 12.43 € m^{-3}. T4 and T5 led to a reduction of 0.7% and 2.0%, respectively, of the gross revenue in relation to T1; while, these reductions increased to 2.4% and 6.4%, respectively, with the severe water restriction (T7 and T8). T6 led to a 21% water savings and a reduction of 19% of the gross revenue in relation to T1. With CDI strategies, water savings of 25% (T2) and 50% (T3) were obtained, but the gross revenues were reduced 36% and 55%, respectively, in relation to T1. Considering the plant response to the different climatic conditions in the two GS, the gross revenues along the crop cycle are presented separately for each GS in Fig. 4. In both GS, T2, T3 and T9 showed lower gross revenue than the other IS since the first harvest pass, increasing the differences between IS throughout this stage.

Discussion

The harvest stage is substantially longer than other plant growth stages, and this stage presented the highest IWR as consequence of the growth of most of the fruits. Therefore, water restriction applied in this stage had greater influence than that applied in the other stages, both in relation to IWA and in the yield and quality of the fruits.

Demand for irrigation water was higher in 2017 than in 2018, when rainfall was abnormally high at the end of spring and in autumn. The volume of IWA in T1 in 2017 was similar to that applied by Sezen et al. (2019; 743 mm), while that applied in 2018 coincided with that applied by González-Dugo et al. (2007; 480 mm).

Given that each irrigation event started when the VSWC for T1 dropped to the 80% of the FC, and considering that this FC value was higher in 2017 than in 2018, the corresponding AWC before each irrigation event for T1, and consequently for the other strategies, was higher in 2017 than in 2018. For RDI, a decrease in the AWC was observed during the stages when the water restriction was applied, particularly with the more severe water restriction. It can be observed that the yield is reduced according to the average AWC reduction, It is known that leaf conductance responds earlier to soil water content than to leaf turgor (Costa et al. 2007), and this response depends on the plant species (Fahad et al. 2017). Stomatal closure is mediated by hormonal signals (mainly abscisic acid) that travel from dehydrating roots to shoots, increasing the physiologically active abscisic acid concentrations in the leaf apoplast adjacent to guard cells, inducing stomata closure (Costa et al. 2007).

At the vegetative growth stage, both RWC and MSI were unaffected ($P \leq 0.05$) by GS or by IS, probably because in this stage, the water status difference was small since it immediately followed the establishment stage, in which the amount of water applied was greater than the IWR to ensure adequate plant establishment. With the growth of the plant, the differences in leaf water status corresponding to the different IS increased, resulting in significant differences at harvesting. Both at the end of harvesting and at the fruit-setting stage for MSI, higher RWC and MSI values were measured in 2018 than in 2017. This could be related to the differences in VSWC and climatic conditions (temperature, ETo and rainfall; Fig. 1), particularly the rainfall that occurred during the fruit-setting and harvest stages in the 2018 season (181 mm in each stage). In relation to IS, at the end of harvesting, the highest RWC and MSI values corresponded to T1, and the lowest to T3. The RWC value for T3 is similar to that reported for water-stressed pepper plants by López-Serrano et al. (2019), Okunlola et al. (2017) and

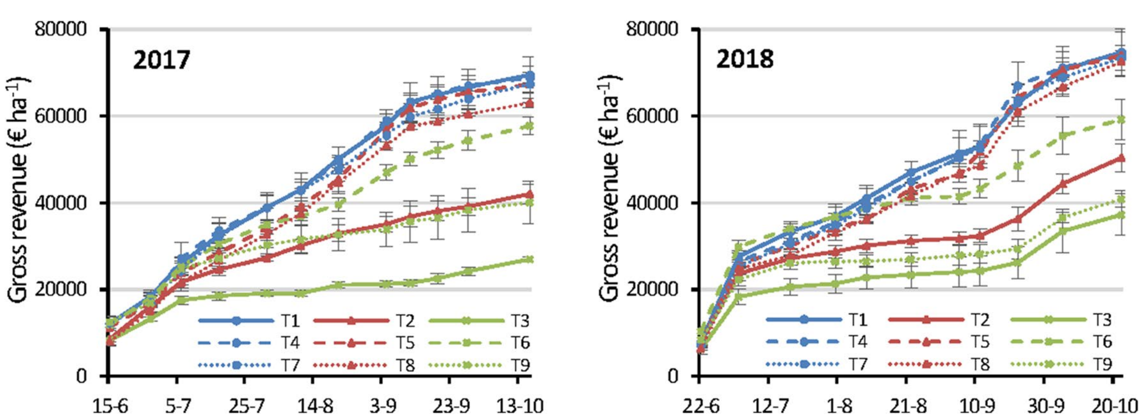

Fig. 4 Gross revenue accumulation throughout harvesting during each growing season. Average values; vertical bars represent the standard error

Camoglu et al. (2018). In each analysis performed, the lowest RWC values corresponded to the severe shortage in the corresponding stage. Difference between the values of the full irrigation strategy (T1) and severe shortages could explain the differences in vegetative growth and yield, given that an initial reduction in leaf RWC induces stomatal closure (González and González-Vilar 2001). Stomatal closure leads to a reduction of the internal CO_2 availability in leaves, which consequently decreases the rate of photosynthesis and therefore decreases cell division and enlargement, and consequently overall plant growth, reducing the yield (Osakabe et al. 2014). In accordance with González and González-Vilar (2001), as a general rule, an initial reduction in leaf RWC (100–90%) induces stomatal closure, reducing cellular growth; lower values of RWC (90–80%) induce changes in tissue composition and modifications in the relative rates of photosynthesis and respiration; a greater decreased RWC (below 80%) commonly implies changes in metabolism, leading to photosynthesis ceasing, respiration increasing and abscisic acid accumulation. Regarding MSI, Dwivedi et al. (2018) stated that tolerant wheat genotypes could maintain higher mean MSI (85%) compared to susceptible ones (75%), and these values are consistent with those obtained in T1 and T3 in the present study.

Given that the sweet Italian pepper is an indeterminate crop, its growth could be affected by water shortage at any time. Overall, CDI strategies reduced fruit dry weight, which decreased with increasing water stress. These results are similar to those obtained by Mardani et al. (2017). In contrast, water shortage at the vegetative growth and fruit-setting stages affected to a lesser extent the fruit dry weight, which is in agreement with that reported by Guang-Cheng et al. (2010). T9 reduced the fruit dry weight to the same extent as T3. When water restriction was applied only during the vegetative growth stage, it had a reversible effect from which the plant could recover to become of similar height, stem diameter and shoot and fruit dry weight as fully irrigated plants.

The HI values obtained in the present study are similar to those obtained by Fernández et al. (2005) for sweet pepper grown in greenhouses in Spain. In soils with high water storage capacity, CDI allows plants to develop slowly and to adapt to water deficits (Fereres and Soriano 2007). Under CDI with moderate water stress, water deficits lead to reduced biomass production due to the reduction in canopy size. In that case, dry matter partitioning is usually not affected and the HI is maintained, as occurred in T2, but, as the water stress increases in severity, it can affect HI in many crops (Fereres and Soriano 2007), as occurred in T3. HI for T9 was similar to that obtained in T3 since the same water restriction (50% of the IWR) was applied during harvesting, whose duration corresponded to approximately 68% of the season duration.

The yield (total and marketable) obtained by the fully irrigated plants can be considered satisfactory compared to those usually obtained by the growers in the area (4.5 kg MY m^{-2}; MAPA 2018) and to those obtained in greenhouses with "enarenado" soil by Fernández et al. (2005; 9.20 kg m^{-2}) and Ćosić et al. (2015; 8.40 kg m^{-2}) in field experiments.

The CDI strategies led to a large reduction of yield and MY (particularly in «Extra» Class), which decreased as IWA decreased. Pepper fruits of the «Extra» class, which represent the high-quality yield corresponding to the highest price, supposed 65.6%, 61.6% and 59.7% of the corresponding MY for T1, T2 and T3, respectively. Although these values show a negative trend with water deficit, their differences were not significant ($P \leq 0.05$). These results agree with those obtained by Sezen et al. (2019). Ćosić et al. (2015) observed higher first-class fruit yield with full irrigation that decreased with increasing water stress. Applying a water shortage at the vegetative growth (T4 and T7) and fruit development (T5 and T8) stages did not reduce yield and MY parameters in relation to the fully irrigated plants. However, when water shortage was applied during the harvesting, particularly when restriction was severe (T9), yield and MY traits were reduced drastically in relation to T1. These results might be attributed to the fact that water shortage at early stages of pepper growth allows plants to develop slowly and to adapt to the water deficits (Fereres and Soriano 2007), as previously indicated. Yang et al. (2017) reported that DI during the vegetative and flowering and fruit-setting stages did not affect the hot pepper yield.

Larger percentages of BER and, consequently, non-marketable yield were obtained with the most severe IS during the entire cycle (T3) and at harvesting (T9). These results agree with those of Fernández et al. (2005), who stated that water stress increases the incidence of fruits with BER. BER is produced because of the poor translocation of calcium to fruit, and this physiologic plant disorder can be accentuated by high temperatures, low relative humidity and water deficit (Condés 2017), among other factors.

The lower values of WUE obtained with CDI and T9 indicates that the water savings did not compensate the yield reductions. Water reduction at vegetative growth and fruit-setting stages (T4, T5, T7 and T8) led to similar MY values to T1 with not important water savings, thus obtaining similar WUE. The result agrees with the results reported for greenhouse experiments by Fernández et al. (2005) and in field experiments by Ćosić et al. (2015). IWUE was not affected by the IS, due to the low variability between their values (Table 5), without a clear trend, and the large variability represented by the GS.

Linear relationships between MY and IWA for pepper were also reported, among other authors, by Gadissa and Chemeda (2009), Yang et al. (2018) and Sezen et al. (2019). The positive linear relationship between MY and IWA, suggest that IWA did not exceed the maximum crop water demands, as reported by Tolk and Howell (2003) who indicated that curvilinear relationships may be related with excess water.

K_y in the present study (1.53 for CDI) is consistent with that determined by Gadissa and Chemeda (2009) under CDI (1.57). Values of K_y greater than 1 indicate that the crop is sensitive to water deficit, and values lower than 1 indicate that it is tolerant (Doorenbos and Kassam 1979; Steduto et al. 2012). When considering the different stress stages separately, it can be concluded that the pepper plant is less sensitive to water deficits at the vegetative growth stage than in the later stages, in accordance with the results obtained for yield in this and other studies (Yang et al. 2017).

Colour indexes of the fruit skins were not affected by either GS or IS, and they corresponded to the dark green colour characteristic of this cultivar. The CDI led to a reduction in the values of length, flesh thickness and average weight of the fruits, which is in agreement with those reported by Sezen et al. (2006) who observed a reduction in pepper fruit size under CDI. The RDI led to a reduction in the average fruit weight only when the water stress was applied during harvesting, but not when it was applied during the vegetative growth stage since plants can recover from the stress, as mentioned above. Fruit firmness was affected by GS, with the highest values obtained in 2018. Although IS did not significantly affect the fruit firmness ($P \leq 0.05$), a similar trend to that of the fruit DM content was observed, such that water deficits applied at harvesting led to fruits with higher DM content and with greater firmness.

In relation to fruit DM content, reducing the IWA, both in CDI and RDI at harvesting, increased the fruit DM. Fruits with the highest SSC were those obtained with T3 and T9. These results are in accordance with those obtained by Guang-Cheng et al. (2010) for CDI and by Yang et al. (2017) for RDI; both reported an increase in SSC with DI compared to full irrigation. The higher values of SSC obtained in DI were mainly due to the reduction of fruit water content, not to the accumulation of sugars.

Fruit MI is an important quality criterion for consumer acceptance, usually considered a better indicator of acceptability than either SSC or acidity alone. The average MI value was 64.9, which is much higher than those reported in literature (Rubio et al. 2010). Although MI was not affected significantly by any of the analysed factors, fruits from T1 had a clearly lower value (50.6) than those from other irrigation strategies, with the highest values obtained in plants exposed to water shortage at harvesting, for both CDI (77.4) and RDI (71.1). T3 and T9 led to fruits with the highest total phenolic compound content, followed by T6, as presented for fruit DM content and SSC. The increase in total phenolic content under drought conditions was also observed by Okunlola et al. (2017) in plant tissues, and López-Serrano et al. (2019) in leaves and roots of pepper plants.

Currently, it is necessary to improve irrigation water productivity in agriculture, particularly in arid and semiarid regions, through increasing the output per unit of water (Howell 2006). At times, it is even more important to maximise crop water productivity rather than crop yield per unit area (Ruiz-Sanchez et al. 2010), and an adequate DI application requires an evaluation of the economic impact of the yield reduction produced by water stress (Geerts and Raes 2009). Important water savings of 25% and 50% were obtained with CDI strategies, but they led to large reductions of the gross revenues (36% and 56%, respectively), seriously compromising the economic viability of the crop. The water economic values for these IS were 11.07 € m^{-3} (T2) and 11.5 € m^{-3} (T3), lower than the other IS (12.6 € m^{-3} for T1). Applying RDI during the vegetative growth (T4 and T7) and fruit-setting (T5 and T8) stages demonstrated a low reduction in the gross revenue, lower than 2% for T4 and T5 (lower than 6% for T7 and T8), but the water savings achieved were also small, particularly for the moderate reduction, which was below 2.5% (5% for severe restrictions). The average water economic value for these strategies ranged between 12.4 € m^{-3} (T8) and 12.8 € m^{-3} (T7), similar to that obtained for fully irrigated plants (T1).

Given the long duration of the harvesting stage, reducing the water applied to 50% in this stage (T9) led to important water savings (41.5%) but also to a considerable gross revenue loss (44%), which makes this IS not recommended for peppers under the studied conditions. When moderate water restrictions were applied during the harvesting (T6), 21% of the IWA was saved, while the gross revenue dropped 19% in relation to T1. These water economic values are much higher than those obtained, by the research team, in the area for watermelon (6.14 € m^{-3}; Abdelkhalik et al. 2019) and chufa (*Cyperus esculentus* L. var. *sativus* Boeck.; also known as tigernut; 4.08 € m^{-3}) under field conditions. When the climatic conditions were similar to those in 2017, a consideration would be to end the crop cycle at the beginning of September since it would suppose a gross revenue of 47,070 € ha^{-1} (corresponding to 82% of the MY obtained at the end of the cycle for this IS), a water saving of 23% in relation to the entire crop cycle, and a water economic value of 10.64 € m^{-3}. Furthermore, this earlier ending of the crop cycle would leave the land available for other crops.

A possible solution to cope with the reduction of yield in some vegetables (as tomato, watermelon and cucumber) because of water stress is the use of grafting technology. Recently, in a study conducted in the same area, López-Serrano et al. (2019) found that water stress severity in pepper plants was alleviated by a rootstock previously selected by them. Therefore, it would be interesting to study the response of pepper ‘Estrada F1’ plants (and other pepper cultivars) when grafted onto drought-tolerant rootstocks in response to deficit irrigation strategies.

Conclusions

The present study analysed the effect of deficit irrigation on the plant water status, growth, and productive response of sweet pepper ‘Estrada F1’ under Mediterranean field conditions. Deficit irrigation reduced pepper yield. If water is readily available, full irrigation should be applied because it leads to the higher gross revenue. If water restriction is applied during the first stages, plant growth can recover and fruit yield is not reduced, although the water savings are not substantial, leading to slight increments in WUE, not differing from full irrigation. Continued deficit irrigation, applying 75% or 50% of the water requirement, or reducing the water applied to 50% of the water requirement at harvesting, leads to a large reduction of the marketable yield and gross revenue, worsening WUE and are not recommended strategies. Applying 75% of the water requirement during harvesting results in a considerable reduction in yield; however, substantial water savings are obtained in relation to full irrigation. This strategy also led to an improvement of the marketable fruit quality in terms of the soluble solids and polyphenol contents. Under severe water limiting conditions, it may be feasible to apply 75% of the water requirement during harvesting, ending the crop cycle at the beginning of September, when most of the marketable yield is already harvested, leading to the 82% of the gross revenue corresponding to this IS, saving 23% of the irrigation water and leaving the land available for other crops.

Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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