The Journal of Agricultural Science

cambridge.org/ags

Climate Change and Agriculture Research Paper

Cite this article: Bozkurt Çolak Y, Yazar A, Yıldız M, Tekin S, Gönen E, Alghawry A (2023). Assessment of crop water stress index and net benefit for surface- and subsurface-drip irrigated bell pepper to various deficit irrigation strategies. *The Journal of Agricultural Science* **161**, 254–271. https://doi.org/10.1017/S0021859623000205

Received: 6 April 2022
Revised: 15 November 2022
Accepted: 12 February 2023
First published online: 23 March 2023

Keywords:
Deficit irrigation; drought mitigation; economic analysis; water saving

Author for correspondence:
Y. Bozkurt Çolak,
E-mail: yesimcolak@ymail.com

Assessment of crop water stress index and net benefit for surface- and subsurface-drip irrigated bell pepper to various deficit irrigation strategies

Y. Bozkurt Çolak[1], A. Yazar[2], M. Yıldız[1], S. Tekin[3], E. Gönen[1] and A. Alghawry[2]

[1]Soil and Water Resources Research Unit, Alata Horticultural Research Institute, Tarsus-Mersin, Turkey; [2]Department of Irrigation and Agricultural Structures Science, Faculty of Agriculture, Cukurova University, Adana, Turkey and [3]Department of Biosystems Engineering, Faculty of Agriculture, Kahramanmaraş Sütçüimam University, Kahramanmaraş, Turkey

Abstract

This study addresses the assessment of crop water stress index (CWSI) of bell pepper (*Capsicum annuum* L.) and net income generated under regulated deficit irrigation (RDI), conventional deficit irrigation and partial root-zone drying (PRD) and full irrigation (I_{100}) using surface- and subsurface-drip systems (DI and SDI) during 2016 and 2017 in the Mediterranean region. The experimental design was split-plots with four replications. RDI was supplied with 50% of I_{100} during vegetative stage until flowering, then received 100% of crop water requirement. PRD_{50} received 50% of I_{100}, but from alternative laterals each watering. The results revealed that CWSI was correlated significantly ($P < 0.01$) and negatively with yield, yield per plant, total soluble solid, ETa, fruit weight and plant height indicating that yield of bell pepper declined with increasing CWSI values ($P < 0.01$). Bell pepper should be irrigated at mean CWSI value of 0.20 without any yield reduction. CWSI in the RDI and I_{75} treatments were slightly greater than 0.20. Irrigation treatments had significant effect on yield and quality traits. The highest total soluble solutes were found in PRD_{50} and I_{50}. The DI I_{100} treatment generated the highest net income followed by the SDI I_{100} and RDI. In conclusion, RDI and I_{75} appear to be good alternatives to I_{100} for sustainable bell pepper production in the Mediterranean region.

Introduction

Water shortages are very frequent in many countries, and, together with the rising demand for industry, growth of human population, climate change and specifically the trend towards irrigated agriculture, have led to widespread problems of water scarcity, especially in Mediterranean countries (Romero-Trigueros *et al.*, 2020). Increasing scarcity of freshwater and growing competition, particularly in arid and semi-arid regions, is a sharp constraint on agricultural production. The development of water-efficient agricultural practices such as low pressure irrigation systems like surface- and subsurface-drip systems along with scientific irrigation scheduling techniques is thus required for sustainable food production. Irrigation water management in an era of water scarcity will have to be carried out most efficiently, aiming at saving water and at maximizing its productivity (Fereres *et al.*, 2011). Deficit irrigation (DI) is a strategy that allows a crop to sustain some degrees of water deficits in order to reduce costs and potentially increase income (English and Nuss, 1982; Zhang, 2003; Fereres and Soriano, 2007; Chai *et al.*, 2016). Regulated deficit irrigation (RDI), conventional deficit and partial root-zone drying (PRD) are among these strategies developed for management of irrigation under water scarcity conditions. PRD is a DI technique in which opposite parts of the plant root system is alternately wetted and dried (Marsal *et al.*, 2008). RDI has been developed recently as an important water-saving strategy in irrigated agriculture. Under RDI, crops are allowed to sustain some degree of water deficit in less sensitive growth stages and yield reduction, and it is considered an optimizing strategy (Chartzoulakis and Maria, 2015; Chai *et al.*, 2016).

Crop water status is an important water stress indicator used in irrigation management (Cohen *et al.*, 2017; Han *et al.*, 2018). Therefore, reliable estimation of plant water stress is of paramount importance for the efficient irrigation scheduling. Although soil-based methods for assessing crop water status are more widely used, there is a growing interest in plant-based methods (Jones and Vaughan, 2010), because they serve as a direct proxy of actual plant water status. Hence, there is a need to determine the threshold values of plant water stress at which irrigation can be initiated. Among the possible measures of plant water status include direct measurements of some aspect of canopy temperatures (Aladenola and Madramootoo, 2014; Bozkurt Çolak *et al*., 2015; Sezen *et al*., 2019). Infrared thermometers (IRTs) measure canopy temperature (Tc) which has received considerable attention in detecting and diagnosing crop water stress (DeJonge *et al*., 2015; Gonzalez-Dugo *et al*., 2020). Thus, infrared thermometry can help in precise management of irrigation water since it enables continuous monitoring of crop water status with ability to integrate both soil water status and climatic conditions. Crop water stress index (CWSI) is based on a solid theoretical base (Idso *et al*., 1981) and it normalizes Tc firstly, by the actual difference between canopy and air temperature (Tc–Ta) and secondly, by the Tc–Ta of fully transpiring and non-transpiring crops commonly referred to as the lower and upper limits, respectively (Jackson *et al*., 1981). Different models to calculate CWSI have been developed based on differences in how the upper and lower limits are derived (Maes and Steppe, 2012). The empirical CWSI (Idso *et al*., 1981) model establishes a relationship between Tc–Ta and vapour pressure deficit (VPD) from which the lower limit, known as the 'non-water-stressed baseline', is derived. The CWSI is one of the most frequently used indices to quantify crop water stress based on Tc. There is a growing interest of using Tc-based methods, including CWSI, for irrigation management (Katimbo *et al*., 2022). The application of the CWSI in irrigation scheduling has been evaluated for different crops including vegetables (Yazar *et al*., 1999; Erdem *et al*., 2010; Aladenola and Madramootoo, 2014; Bozkurt Çolak *et al*., 2015; Sezen *et al*., 2019).

Using low-pressure systems such as surface drip and subsurface drip has the potential to save water and increase yield, quality as well as water productivity when utilized with the proper irrigation scheduling. Irrigation systems can directly influence crop performance and result in qualitative and quantitative improvements in vegetable yield (Dukes *et al*., 2010; Bozkurt Çolak *et al*., 2018; Evett *et al*., 2019). The subsurface drip (SDI) has been proven to be an efficient irrigation method with potential advantages of high water use efficiency, efficient fertilizer application and lower labour costs than in a conventional drip irrigation system (Lamm and Camp, 2007; Lamm and Rogers, 2017). In SDI system, the irrigation system is placed under ground and when coupled with an effective irrigation management programme provides the opportunity to supply crops with proper amount of water and nutrient requirements directly into root-zone and reduces surface soil evaporation due to irrigation (Irmak *et al*., 2016).

Pepper (*Capsicum annum* L.) is an important commercial crop, cultivated for vegetable, spice and value-added processed products (Kumar and Rai, 2005). Its production and consumption is increasing worldwide. Water management in bell pepper is crucial as bell pepper is one of the most water stress-sensitive crops due to its shallow rooting system and the sensitivity of the bell pepper foliage characteristics. Sustainable water management is therefore required to optimize bell pepper yield and water use efficiency while maintaining maximum yield and quality. The pepper plant is considered sensitive to water stress, which can result in large yield reductions (Steduto *et al*., 2012). Thus, bell pepper has been classified as susceptible to water stress, with flowering growth stage being the most sensitive period (Yahaya *et al*., 2012). Such sensitivity has been noticed in several researches that studied the fresh and dry matter yield reduction affected by water stress (Sezen *et al*., 2006; Costa *et al*., 2007; González-Dugo *et al*., 2007; Ferrara *et al*., 2011; Zotarelli *et al*., 2011; Sezen *et al*., 2019; Abdelkhalik *et al*., 2020).

The Mediterranean climate is characterized by mild and rainy winters, and dry and hot summers, with highly variable rainfall distribution, and therefore, irrigation is essential for crop production (Galindo *et al*., 2018). In the Mediterranean region, the vegetative and reproductive growth stages of horticultural and field crops are generally affected by recurrent water stress episodes. Therefore, it is very important to understand to what extent water stress negatively affects physiological processes, plant growth and yield and quality in field-grown bell pepper (Delfine *et al*., 2002).

To achieve optimal bell pepper production and best irrigation regime, there is a need for a comprehensive assessment of the yield, and physiological response of the plant to a particular soil type, production system and irrigation regime (Bozkurt Colak, 2021). Therefore, the present study was conducted to assess crop water status by means of the CWSI for irrigation scheduling and net profit generation on differentially irrigated bell pepper. Thus, the main objectives of this study are to investigate the yield, quality and CWSI of field-grown bell pepper response to various DI regimes such as RDI, PRD and conventional DIs along with full irrigation applied with surface- and subsurface-drip systems in a Mediterranean environment.

Materials and methods

Description of experimental site and soil

This study was conducted at the Soil and Water Resources Unit of Alata Horticultural Research Institute (36°53' N and 34°57' E, at an altitude of 30.0 m), in Tarsus in the Mediterranean region of Turkey during 2016 and 2017 growing seasons. The Mediterranean climate is characterized by mild and rainy winters, and dry and hot summers, with highly variable rainfall distribution. In the experimental site, the mean annual rainfall is 616 mm, mean evaporation from Class A pan is 1487 mm, average annual temperature is 17.8°C and mean relative humidity is 71.0% (MGM, 2019). Approximately 65% of the rainfall is received in the period November through May. The experimental soil is classified as silty-clay-loam texture with relatively high water holding capacity (58.2 mm in the 40 cm soil depth). Some physical and chemical properties of the experimental soil are presented in Table 1.

Experimental design and treatments

The experimental plots were arranged according to a split-plot design with two irrigation systems (surface drip, DI; and subsurface drip, SDI) as the main plots and irrigation regimes (I) as the subplots with four replicates. In this study, two irrigation methods (DI, SDI) and five irrigation strategies designated as full irrigation (I_{100}); conventional DI, I_{50}; conventional DI, I_{75}; partial root-zone drying (PRD_{50}); and RDI were considered as treatments. Irrigations were initiated when 25% of available water in the effective root-zone depth of 40 cm was depleted and replenished to field capacity in I_{100} plots. The RDI treatment plots received 50% of I_{100} until flowering growth stage, then it received 100% of water requirement until harvest the same as I_{100}. In the conventional DI treatment plots of I_{75} and I_{50}, 75 and 50% of I_{100} were applied, respectively, throughout the growing season. The PRD_{50} plots received 50% of I_{100}, but from the alternative drip lateral lines in each irrigation application. The experimental subplots had dimensions of 10 m long and 3.5 m wide (5 plant rows).

https://doi.org/10.1017/S0021859623000205 Published online by Cambridge University Press

Table 1. Some physical and chemical properties of the soils at the experimental site

Soil depth cm	Sand %	Silt %	Clay %	Texture class	FC %	WP %	BD g/cm^3	EC dS/m	pH	$CaCO_3$ (%)	P_2O_5 kg/ha	K_2O kg/ha	OM (%)
0–20	20.2	41.9	37.9	Clay	29.92	19.14	1.30	0.914	7.91	21.78	19.0	1343.2	1.80
20–40	15.9	42.0	42.1	Silty-clay	29.77	18.95	1.40	0.976	7.97	28.30	9.0	684.9	1.06
40–60	11.7	44.1	44.3	Silty-clay	29.64	19.09	1.42	1.028	8.08	24.80	5.0	430.1	0.77
60–90	11.1	42.2	46.7	Silty-clay	29.40	19.71	1.45	0.995	8.11	31.64	5.0	385.1	0.63

FC, field capacity; WP, permanent wilting point; BD, bulk density; EC, electrical conductivity; CaCO3, calcium carbonate; P_2O_5, phosphorus pentoxide; K_2O, potassium oxide; OM, organic matter.

Layout of the experimental treatments and details of an experimental sub-plot is shown in Figs 1(a) and (b).

Irrigation systems

In this study, surface- and subsurface-drip irrigation systems were used. In the surface-drip irrigation plots (DI), drip laterals with a diameter of 16 mm with in-line emitters spaced 0.33 m apart and flow rate of 2.0 litres/h at an operating pressure of 100 kPa were used. A locally produced surface-drip irrigation system (Betaplast Comp., Adana, Turkey) was used in the study. One drip lateral line was placed in the bell pepper plant rows of 0.70 m in the experimental plots except the PRD_{50} treatment. In PRD_{50} plots, two drip laterals were laid on both sides of the crop row at 15 cm away from the centre of plant row. In PRD_{50}, plots received 50% of I_{100}, but from the alternative drip lateral lines in each irrigation application.

In the SDI plots, drip lateral lines with in-line emitters with flow rate of 2.0 litres/h and spaced at 0.33 m (Geoflow Corte Madera, CA, USA) were placed below 20 cm of the soil surface in the raised plant beds by means of a chisel plows at 70 cm intervals. Both DI and SDI systems were laid out in the experimental plots several days before the transplantation of bell pepper seedlings.

The source of irrigation water for the experiments was from the irrigation canal passing through the experimental site, with an average electrical conductivity (EC) of 0.74 dS/m. A centrifugal pump was used at the pump station to pressurize the irrigation systems.

Plant material and agronomic details

Sowing took place on 29 March 2016 and 21 March 2017, in polystyrene trays, in a peat moss-based substrate recommended for vegetable seedbeds. The seeds were germinated in a greenhouse. Thereafter, 21 days old seedlings of Zafer bell pepper (*Capsicum annuum* L.) were transplanted into the experimental plots with row spacing of 70 cm and in-row plant spacing of 20 cm on 19 April 2016 and 11 April 2017 in the experimental years. This cultivar was chosen because of its adequate adaptation to the soil and climate conditions in the area, and its high productivity under open field cultivation. A composite fertilizer of 50 kg/ha N, 50 kg of P_2O_5 and 50 kg K_2O (15%–15%–15% N, P_2O_5, K_2O) was applied to the strips parallel to the plant rows and incorporated into the soil prior to the bell pepper seedlings transplanted in the trial plots. The remaining amount of N fertilizer was applied to the plots by fertigation by dissolving 1.25 kg of urea (46% N) in water at fertilizer tank, each irrigation starting 3 weeks after transplanting. Thus, all treatment plots received 164 kg/ha of N by means of fertigation and the total amount of N applied to all plots was 214 kg/ha. Other agricultural practices including weeding, pruning and chemical spraying were carried out as needed.

Measurements and data collections

Daily weather conditions during the study period were monitored using an automatic recording weather station installed on site. Weather parameters such as rainfall, maximum and minimum air temperatures, relative humidity, wind speed and solar radiation were measured on a daily basis and summarized for each growing season along with the long-term mean weather data from 1950 to 2019 in Fig. 2.

Soil water content (SWC) monitoring in the experimental plots was carried out starting from the transplanting to harvest

https://doi.org/10.1017/S0021859623000205 Published online by Cambridge University Press

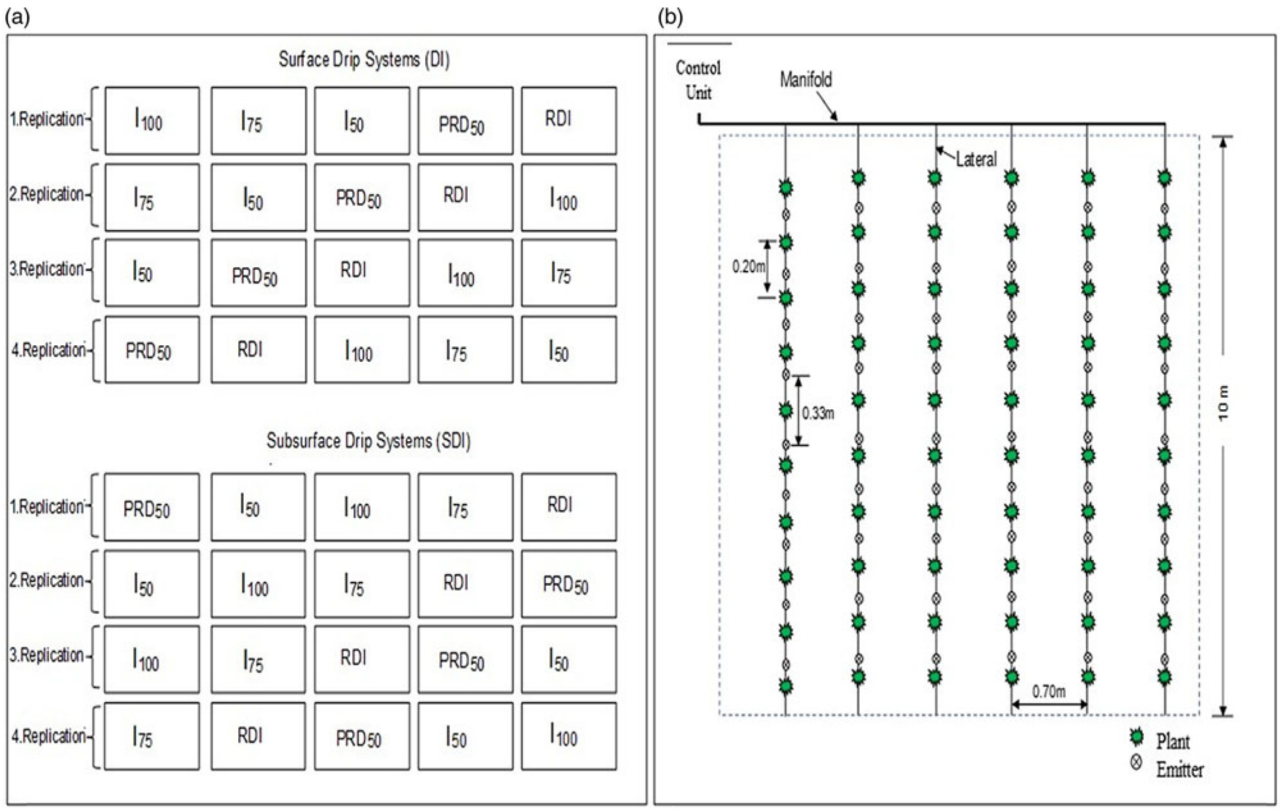

Fig. 1. Experimental design (a) and layout of the individual treatments (b).

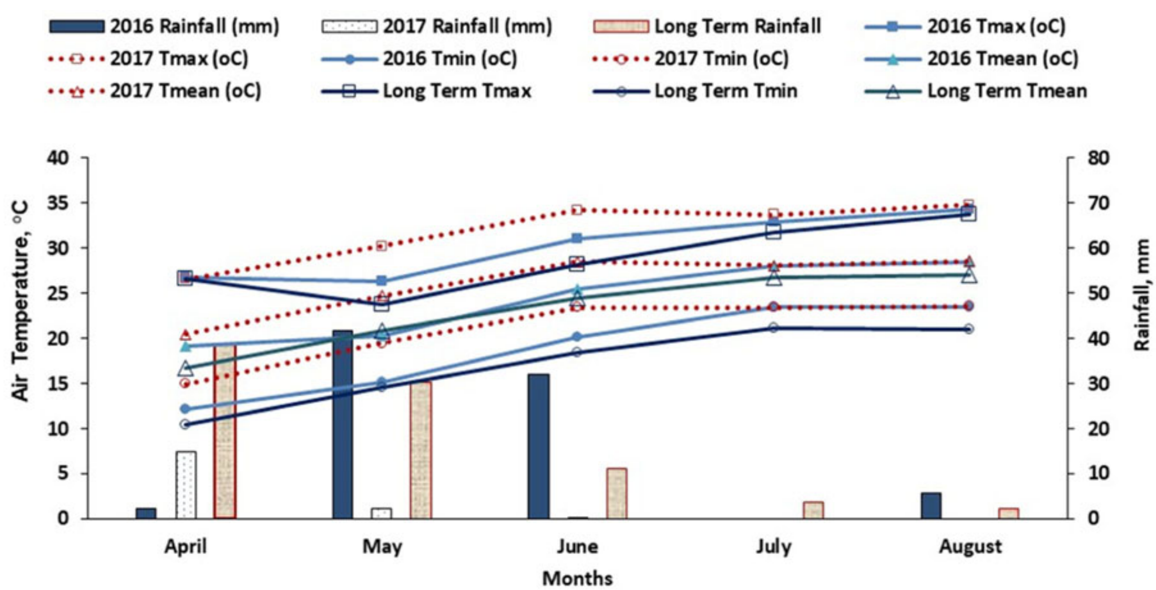

Fig. 2. Mean monthly weather data in the experimental years along with long-term means (monthly rainfalls; growing seasons' maximum, minimum and mean air temperatures; long-term rainfall; long-term mean maximum, minimum and mean air temperatures).

both with gravimetric method in 0–60 cm with 20 cm increments (0–20, 20–40 and 40–60 cm) and by time domain reflectometry method (TDR) in the upper soil layer of 0–20 cm. SWC sensors (SM-150, Delta T Devices, UK) connected to data loggers were placed between the two plants in the crop row at 20 cm depth at one replication for each irrigation treatment. Factory calibration of the sensors provides ±3% accuracy for mineral soils and therefore they were used directly.

Equal irrigation was uniformly applied to all treatments for the first 4 weeks after transplanting, based on 100% replacement of

https://doi.org/10.1017/S0021859623000205 Published online by Cambridge University Press

ETa, and, afterwards, variable amounts of water were applied according to the treatments considered. The amount of water applied to the full irrigation I_{100} sub-plots under DI and SDI systems was calculated with Eqn (1):

$$Iv = \Delta S \times A \times PC \tag{1}$$

where Iv is the volume of irrigation water (L); ΔS is the soil water deficit in 40 cm root zone depth, which corresponded to approximately 25% of available water in the I_{100} plots (mm); A is the sub-plot area (m^2); and PC is the plant cover percentage (%), which is estimated as the ratio of crop covered area to row space (70 cm). The amount of water applied to other treatments was calculated with reference to I_{100}. All treatment plots were irrigated simultaneously.

Water balance equation was utilized for the estimation of the seasonal actual crop evapotranspiration (ETa) of bell pepper in the experimental treatments.

$$ETa = R + I - Dp - Roff \pm \Delta SW \tag{2}$$

where ETa is crop evapotranspiration (mm); R is rainfall (mm); I is the quantity of irrigation water applied (mm); ΔSW is the change in the soil water storage in 40 cm soil depth at planting and at harvest (mm); Dp is deep percolation losses below the root-zone depth (mm); and Roff is runoff from the experimental plots (mm). Rainfall events greater than the soil water deficit in 40 cm soil depth were considered as deep percolation loss below the root-zone depth.

Plant observations were started just after the bell pepper seedling transplanting in the experimental plots and continued until the crops reached to physiological maturity. Bell pepper yields were determined by hand harvesting all the plants within the 6 m sections of the three adjacent centre rows in each plot depending on the physiological maturity of plants. The harvest area in each plot was 12.6 m^2 (three rows, each 6 m long). Bell pepper was harvested five times in each experimental year. A total of five harvests were taken as the yield from an experimental treatment.

The starting and ending dates of the phenological development periods of the bell pepper plant were determined by observing the general condition of plants in the plots. The length of the total growing season was determined as 114 and 122 days for I_{100} treatments in the experimental years, respectively. The length of the growth period in 2017 was 10 days longer than that in 2016. The length of the growing season here represents the total time elapsed from transplanting of the seedlings in the field to the final harvest.

Yield components and quality parameters such as number of bell pepper fruit per unit area, mean fruit weight, fruit volume, fruit length and width, total soluble solids (TSS) and plant height were determined in each harvest period in the experimental years. Fruit numbers per plant and the weight of each fruit for the selected 10 plants per treatment plot were recorded at each harvest. TSS content in juice was determined by an Atago N1 refractometer (Atago Co. Ltd., Japan) and expressed as Brix at 20°C.

Tc were measured with a hand-held IRT (Everest Interscience model 100L DL, USA). Tc measurements were taken from four different corners of the plots at around 1.5 m distance from the bell pepper plant canopies. IRT measurements were made between solar noon time (12:00 and 14:00 h local standard time) under clear sky conditions. Dry- and wet-bulb temperatures were measured with an aspirated psychrometer in the open area near the experimental plots. The mean VPD was computed as the average of the calculated instantaneous wet and dry bulb temperatures and the standard psychrometer equation (List, 1971) with a mean barometric pressure of 101.25 kPa. Thus, CWSI, lower and upper limits were calculated by following the empirical approach outlined by Idso *et al.* (1981).

$$CWSI = [(Tc\text{-}Ta)\text{- } LL)/(UL\text{-}LL)] \tag{3}$$

where LL is the lower baseline and UL is the non-transpiring upper baseline; Tc = canopy temperature (°C); Ta = air temperature (°C). LL was determined using data collected only from the unstressed treatments (I_{100}). To verify the upper baseline, Tc of the fully stressed plants in the non-irrigated plots were determined several times during the growing season of bell pepper.

Economic evaluation

An economic analysis was conducted for estimating the net benefit generated by experimental treatments considered in the study. The net benefit or net return was estimated as the difference between total production costs and gross incomes per unit area (Sezen *et al.*, 2015). Information on the production costs and sale prices of bell pepper in 2016 and 2017 was obtained from the Agricultural Provincial Directorate (APD) in Mersin (APD, 2016, 2017). Production costs include land rental, fertilizers, seed, soil cultivation, plant protection and labour costs for irrigation, harvesting and transportation costs. The total production cost of bell pepper was estimated by the sum of crop production costs, the yearly cost of the irrigation system, irrigation labour and water costs.

Statistical analysis

Analysis of variance was performed using SAS (SAS Institute, Inc., Cary, NC, USA) to determine significant differences between all measured parameters, and EXCEL software was used to plot the graphs. Comparisons of treatment means ($P \leq 0.05$) at each level of irrigation were done using Least Square Difference (LSD) method.

Results

Applied irrigation water amount (I) and crop evapotranspiration (ETa)

Weather conditions were quite different in the two consecutive growing seasons of our study. When the weather conditions in the experimental years were evaluated, it was observed that the 2016 growing season was typical of the conditions that prevail in the Mediterranean region. However, the mean air temperatures in 2017 season (May through July) were several degrees greater than those in 2016 as well as long-term means. Monthly rainfalls varied between the two growing seasons. In general, the 2016 growing season was relatively wet with a total rainfall of 81.8 mm when compared with the 2017 growing season with a total rainfall of only 17.2 mm. Rainfall received in May–June period in 2016 was also greater than the long-term means (45.7 mm).

Detailed information on irrigation amounts, relative irrigation, seasonal crop water use or actual crop evapotranspiration (ETa), relative ETa, water productivity and irrigation water productivity for the different irrigation strategies under two drip irrigation methods for the experimental years was presented in a previous publication by Bozkurt Colak (2021). Therefore, brief information about these parameters will be provided below. The treatment irrigation was initiated on 20 June 2016 and 9 May 2017 and the final irrigation was applied on 8 August in both years. Both in DI and SDI plots, 2 and 3 equal and 22 treatment irrigation applications with 3–5 days intervals were made in 2016 and 2017 growing seasons, respectively. In 2016, in DI plots, the seasonal total irrigation amount varied from 335 to 545 mm; the corresponding values for the SDI plots were 307 to 489 mm. In 2017, the total amounts of irrigation water in DI treatment plots varied from 359 to 647 mm; and the corresponding values for the SDI treatment plots were 335 to 618 mm. Due to warmer weather conditions prevailed in 2017 growing season, the total amount of irrigation water applied to treatments in 2017 was 16 and 21% greater in I_{100} treatment plots under DI and SDI, respectively, than those in 2016. RDI plots received 5.0 and 19.3% less water than I_{100} plots under DI and SDI, respectively, in 2016; the corresponding vales were 11.9 and 9.9% in 2017.

Actual crop ETa values ranged from 484 mm in PRD_{50} to 693 mm in I_{100} in DI and varied between 456 mm in PRD_{50} and 635 mm in I_{100} in SDI plots in 2016 growing season. In 2017, ETa values varied from 529 mm in PRD_{50} to 797 mm in I_{100} in DI plots; and varied between 501 and 760 mm in SDI plots. In 2016, ETa values in I_{75} and RDI treatments in DI system were 587 and 669 mm, respectively. The corresponding values for the SDI were 548 and 618 mm, respectively. RDI treatments used 3.5 and 10% less water than I_{100} in DI and SDI, respectively, in 2016; and corresponding values for 2017 were 11.9 and 5.7%. The results revealed that the highest and the lowest ranges of water consumption were found in the I_{100} and PRD_{50} treatments in both experimental years. Bell pepper plants in PRD_{50} consumed slightly less water as compared to I_{50} in both experimental years although these two treatments received the same amount of water.

Variation of soil water content

Fluctuations in the SWC with time in the 0–20 cm upper soil layer for the different treatments under DI and SDI in 2016 and 2017 growing season are depicted in Figs 3(a) and (b). As shown in Figs 3(a) and (b), variations in SWC have shown similar trends during the experimental periods for DI and SDI systems for the same irrigation treatment. SWC in the 0.20 m soil depth decreased gradually towards the physiological maturity period in all treatments in the experimental years. The highest SWC were found in I_{100} plots both under DI and SDI systems and SWC remained above 25% of available water throughout the growing seasons except towards the end of growing seasons during which it fell below 25% level. In RDI plots, SWC decreased gradually during vegetative growth stage until flowering since this treatment received 50% of water that applied to I_{100} under DI and SDI systems. However, RDI received the same amount of water as I_{100} following flowering growth stage. Therefore, SWC in RDI plots remained just below the I_{100} treatment throughout the growing seasons. In I_{50} and PRD_{50}, SWC remained below 50% available water during most of the growing seasons. SWC values in I_{50} and PRD_{50} plots were found to be around the wilting point starting from the late June under DI and SDI systems in 2016 and 2017 growing seasons. It was observed that SWC in the I_{75} treatment also was maintained relatively high as compared to DI_{50} and PRD_{50} treatments, in which SWC variations were the greatest among the treatments, and water stress gradually build up towards the end of growing season in these treatments.

Bell pepper yield, yield components and quality

Total fresh bell pepper yields, yield components and quality parameters for the different treatments in the experimental years are presented in Table 2. The statistical analysis of the yield and quality parameters are summarized in Table 3 and Figs 4(a)–(i). Statistical evaluations of the results for bell pepper yields and quality parameters obtained during two experimental years showed the prevailing effect of the different weather conditions during the study. For this reason, the yields and quality parameters data obtained in 2016 and 2017 were evaluated separately. Fresh bell pepper yields varied from 45.5 t/ha in PRD_{50} to 75.7 t/ha in I_{100} in DI system; and changed between 54.1 t/ha in PRD_{50} and 74.2 t/ha in I_{100} under SDI system in 2016. In 2017, yields ranged from 45.4 t/ha in PRD_{50} to 70.6 t/ha in I_{100} under DI system, and changed from 46.4 t/ha in PRD_{50} to 71.5 t/ha in I_{100} under SDI system. PRD_{50} produced the lowest yield as 49.8 and 45.9 t/ha, respectively, in the experimental years. Irrigation treatments had significantly different effect on total yield ($P < 0.01$); however, irrigation systems did not have significant effect of yield in the experimental years.

Irrigation regimes had significantly different effect on fruit number per unit area in 2016; however, in the second year both irrigation regimes and irrigation systems had significant effect on fruit numbers (Table 3 and Fig. 4(b)). I_{100} treatment produced greatest number of fruits in the experimental years followed by RDI. PRD_{50} resulted in the lowest number of fruits in the study years. In the first year of the study, the lowest fruit number values were obtained as 1.06×10^6/ha in DI-PRD_{50}, and the highest fruit number values were obtained as 1.63×10^6/ha for DI-I_{100}. In the second year, the lowest fruit number values were found in DI-PRD_{50} as 1.14×10^6/ha for irrigation, and the highest fruit number values were observed both in DI-I_{100} and SDI I_{100} as 1.69×10^6/ha (Table 2).

The yield per plant values for the different irrigation treatments and two drip irrigation methods for both experimental years (2016 and 2017) are given in Table 2. Yields per plant varied from 0.80 kg in PRD_{50} to 1.32 kg in I_{100} in DI system; and changed between 0.95 kg in PRD_{50} and 1.30 kg in I_{100} under SDI system in 2016. In 2017, yields per plant varied from 0.79 kg in PRD_{50} to 1.24 kg in I_{100} under DI system, and changed from 0.81 kg in PRD_{50} to 1.25 kg in I_{100} under SDI system. Both in 2016 and 2017 experimental years, PRD_{50} produced the lowest yield per plant as 0.87 and 0.80 kg, respectively. As indicated in Table 3 and Fig. 4(c), there was no significant difference in yields between the surface- and subsurface-drip irrigation systems in the experimental years. However, irrigation treatments resulted in significantly different yields per plant in 2016 and 2017 growing seasons ($P < 0.01$). In the 2016 development period of the study, higher yield per plant values were obtained as compared to 2017. RDI produced significantly greater yield per plant than I_{75}, I_{50} and PRD_{50} treatments but lower than I_{100} plots in both experimental years.

Full irrigation regimes under both drip systems produced the greatest mean fruit volume in the experimental years. RDI and I_{75} treatments had greater fruit volume values as compared to I_{50} and PRD_{50} but lower than I_{100} treatment. Water stress reduced

https://doi.org/10.1017/S0021859623000205 Published online by Cambridge University Press

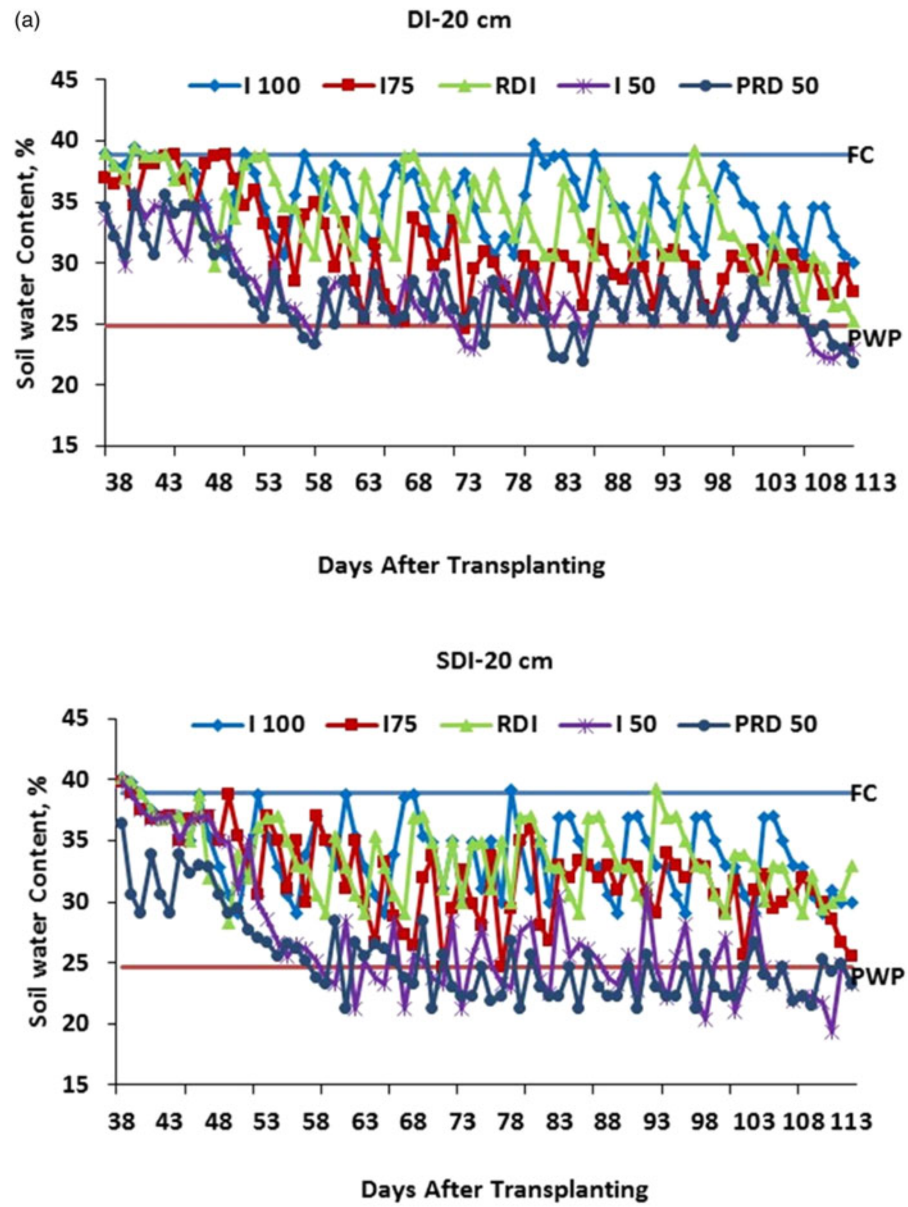

Fig. 3. Soil water storage variation in 20 cm soil depth under the different treatments: (DI-20 cm) SWC in DI in 2016; (SDI-20 cm) SWC in SDI in 2016 (treatments: I_{100}, full irrigation; I_{75}, deficit irrigation; I_{50}, deficit irrigation; PRD_{50}, partial root-zone drying; RDI, regulated deficit irrigation). Soil water storage variation in 20 cm soil depth under the different treatments: (DI-20 cm) SWC in DI in 2017; (SDI-20 cm) SWC in SDI in 2017 (treatments: I_{100}, full irrigation; I_{75}, deficit irrigation; I_{50}, deficit irrigation; PRD_{50}, partial root-zone drying; RDI, regulated deficit irrigation).

the fruit volume in PRD_{50} and I_{50} treatments under both drip systems. Mean fruit volume values varied from 108.3 cm^3 in DI-PRD_{50} to 168.2 cm^3 in DI-I_{100}. In the second years of the study, irrigation regimes on the fruit volume were found to be statistically significant ($P < 0.01$). Mean fruit volume values varied from 90.8 cm^3 in DI-PRD_{50} to 163 cm^3 in DI-I_{100} (Table 2). In the first years of the study, irrigation systems and irrigation systems × irrigation regimes interactions on the fruit volume were found to be statistically significant ($P < 0.05$). Irrigation regimes on the fruit volume were found to be statistically significant ($P < 0.05$) (Table 3 and Fig. 4(d)).

Mean fruit width values varied from 5.58 cm in I_{50} to 6.40 cm in I_{100} under DI, varied between 5.0 cm in I_{50} and 5.97 cm in I_{100} under SDI in 2016; and varied from 5.14 cm in PRD_{50} to 6.36 cm in I_{100} in DI, changed between 5.59 cm in PRD_{50} and 6.24 cm in I_{100} in SDI in 2017 (Table 2). In the first year of the study, irrigation systems and irrigation regimes on the fruit width were found to be statistically significant ($P < 0.01$). In the second year, the effect of different irrigation systems and the irrigation systems, irrigation system × irrigation regimes interaction on the fruit width was found to be significant at $P < 0.05$ and $P < 0.01$, respectively (Table 3 and Fig. 4(e)).

Mean fruit length values varied from 5.69 cm in PRD_{50} to 6.60 cm in I_{100} under DI, varied between 5.48 cm in PRD_{50} and 6.25 cm in I_{100} under SDI in 2016; and varied from 5.71 cm in I_{50} to 6.76 cm in I_{100} in DI, changed between 5.90 cm in PRD_{50} and 6.99 cm in I_{100} in SDI in 2017 (Table 2). In the first years of the study, the effect of irrigation systems and irrigation regimes on the fruit length was found to be statistically significant ($P < 0.01$). In the second year, the effect of different irrigation regimes on the fruit length was found to be significant at $P < 0.01$ (Table 3 and Fig. 4(f)).

Mean fruit weight values changed from 41.2 g in I_{50} to 46.5 g in I_{100} under the DI, varied between 43.5 g in PRD_{50} and 48.0 g in I_{100} under SDI in 2016; and varied from 41.2 g in I_{50} to 47.5 g in I_{100} in DI, changed between 44.6 g in I_{50} and 47.9 g in I_{100} in SDI

https://doi.org/10.1017/S0021859623000205 Published online by Cambridge University Press

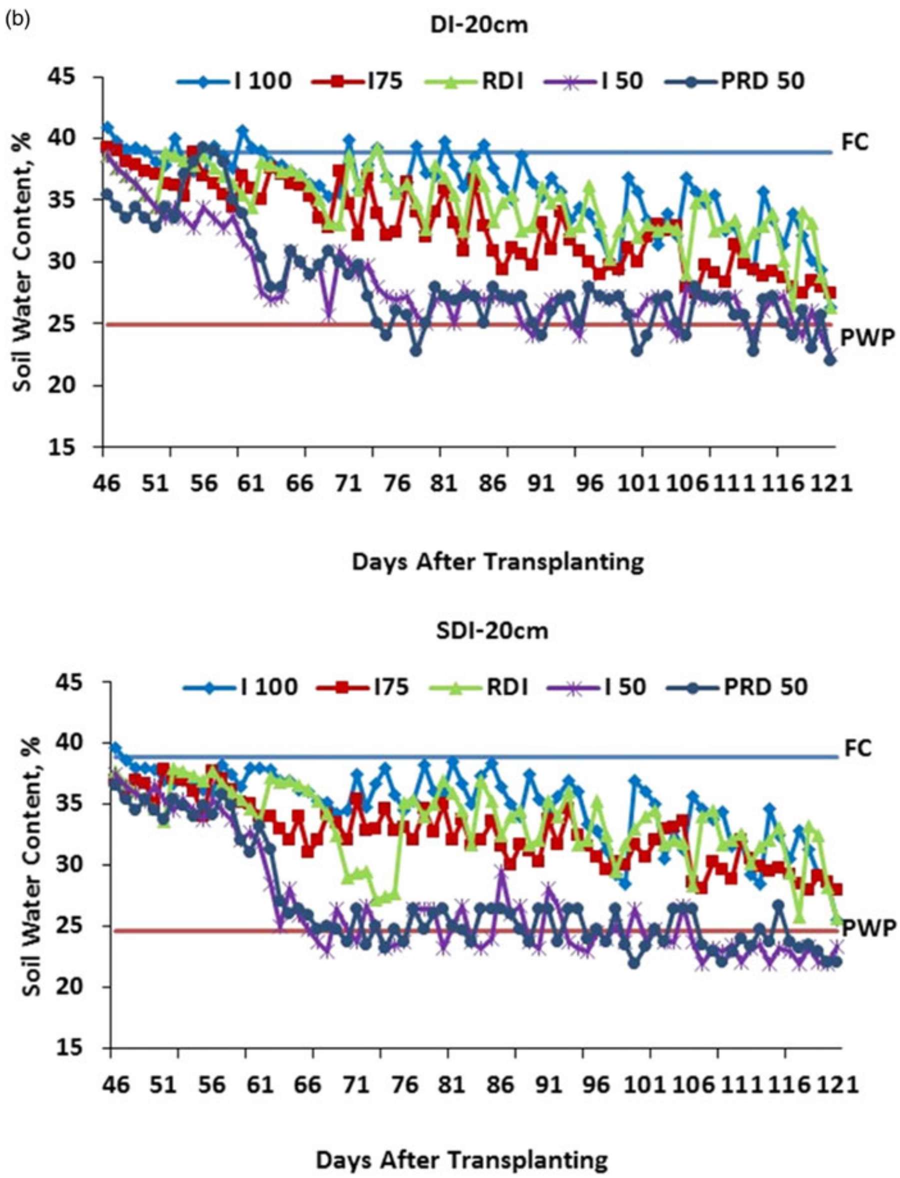

Fig. 3. Continued.

in 2017 (Table 2). In general, fruit weight values decreased with increasing water stress. Both irrigation systems and irrigation regimes had significantly different effect on fruit weight ($P < 0.01$ and $P < 0.05$) (Table 3 and Fig. 4(g)).

Total soluble solute (TSS) values varied from 5.18 g/100 g in I_{100} to 5.61 g/100 g in I_{50} under the DI, and changed between 5.13 g/100 g in I_{75} and 5.33 g/100 g in PRD_{50} in 2016; and varied between 5.10 g/100 g in I_{100} and 5.80 g/100 g in I_{50} in SDI in 2017 (Table 2). In both experimental years, irrigation regimes had significantly different effect on TSS values ($P < 0.01$). Higher TSS values were obtained in water stress treatments of I_{50} and PRD_{50} (Table 3 and Fig. 4(h)).

Plant height values varied between 73 cm in PRD_{50} and 89 cm in I_{100} in DI, and SDI in 2016; varied from 66 cm in PRD_{50} to 83 cm in I_{100} in DI, changed between 67 cm in PRD_{50} and 85 cm in I_{100} in SDI in 2017 (Table 2). Irrigation systems had significant effect on the plant height in the experimental years ($P < 0.01$) (Table 3 and Fig. 4(i)). Water stress reduced the plant height under both drip systems in the experimental years.

Crop water stress index (CWSI)

In this study, the upper limit (UL) and lower limit (LL) equations were developed for the bell pepper following the Idso's empirical approach as: $UL = -0.0099\ VPD + 4.362$; and $LL = -2.1895\ VPD - 0.5539$. Since the slope value in the UL equation was small, UL was taken as 4.36°C. The variations in CWSI prior to irrigations for the different treatments during the growing seasons are shown in Figs 5(a)–(d). Seasonal mean CWSI values for DI treatments in the first year varied from 0.16 in I_{100} to 0.63 in PRD_{50}; for SDI treatments, CWSI varied from 0.13 in I_{100} to 0.61 in PRD_{50}. In the second year, seasonal mean CWSI values for DI treatments varied between 0.13 in I_{100} and 0.58 in PRD_{50}, and for SDI treatments CWSI varied from 0.15 in I_{100} to 0.61 in I_{50} and PRD_{50}. RDI and I_{75} treatments under both drip systems had lower CWSI values than I_{50} and PRD_{50}. In 2016, mean CWSI values for I_{100}, I_{75}, RDI, I_{50} and PRD_{50} were 0.22, 0.31, 0.27, 0.52 and 0.53, respectively, under DI, and corresponding mean CWSI values for these treatments were 0.19, 0.28,

https://doi.org/10.1017/S0021859623000205 Published online by Cambridge University Press

https://doi.org/10.1017/S0021859623000205 Published online by Cambridge University Press

Table 2. Bell pepper total yield, fruit number, yield per plant, fruit volume, fruit width, fruit length, fruit weight, total soluble solid and plant height values under different treatments in the experimental years

Years	Irrigation systems	Irrigation regimes	Total yield (t/ha)	Fruit number (No×10^6/ha)	Yield per plant (kg)	Fruit volume (cm^3)	Fruit width (cm)	Fruit length (cm)	Fruit weight (g)	Total soluble solid (g/100 g)	Plant height (cm)
2016	DI	I_{100}	75.7 a**	1.63 a**	1.32 a**	168.2 a**	6.40 a**	6.60 a**	46.5 a*	5.18 bc**	89.0 a*
		I_{75}	67.4 b	1.31 b	1.00 b	132.0 d	5.88 b	6.06 b	43.7 ab	5.38 b	82.0 c
		I_{50}	51.3 c	1.25 c	0.90 c	114.6 e	5.63 c	5.75 c	41.2 b	5.61 a	79.0 e
		PRD_{50}	45.5 c	1.06 d	0.80 c	108.3 e	5.58 c	5.69 c	42.8 b	5.58 a	73.0 f
		RDI	69.7 ab	1.59 a	1.22 a	143.4 bc	5.94 b	6.47 ab	43.7 ab	5.20 c	83.0 c
	SDI	I_{100}	74.2 a**	1.54 a**	1.30 a**	167.2 a	5.97 a**	6.25 a**	48.0 a*	5.18 bc**	89.0 a
		I_{75}	69.4 b	1.49 b	1.21 b	149.4 b	5.69 b	6.03 b	46.7 ab	5.13 b	83.0 c
		I_{50}	57.7 c	1.24 c	1.01 c	127.3 d	5.00 c	5.55 c	43.6 b	5.31 a	80.8 d
		PRD_{50}	54.1 c	1.09 d	0.95 c	132.8 cd	5.14 c	5.48 c	43.5 b	5.33 a	73.0 f
		RDI	70.6 ab	1.54 a	1.24 a	153.3 b	5.39 b	5.92 ab	46.9 ab	4.97 c	84.8 b
2017	DI	I_{100}	70.6 a**	1.69 a**	1.24 a**	163.0 a**	6.36 a**	6.76 a**	47.5 a**	5.10 c**	83.0 a**
		I_{75}	65.2 a	1.60 a	1.14 a	132.8 b	5.97 c	6.17 bc	45.3 c	5.40 bc	76.0 c
		I_{50}	46.9 b	1.17 b	0.82 b	102.4 c	5.33 e	5.71 d	41.2 d	5.80 ab	67.0 d
		PRD_{50}	45.4 c	1.14 c	0.79 c	90.8 d	5.14 e	6.07 cd	40.8 e	5.50 a	66.0 d
		RDI	67.8 a	1.65 a	1.18 a	130.9 b	5.92 c	6.37 ab	46.1 b	5.20 c	80.0 b
	SDI	I_{100}	71.5 a**	1.69 a**	1.25 a**	157.6 a**	6.24 ab	6.99 a**	47.9 a**	5.20 c**	85.0 a**
		I_{75}	67.7 a	1.63 a	1.18 a	139.3 b	5.96 c	6.64 bc	46.0 c	5.10 bc	77.0 c
		I_{50}	54.5 b	1.40 b	0.95 b	109.1 c	5.66 d	6.06 d	42.1 d	5.40 ab	68.0 d
		PRD_{50}	46.4 c	1.23 c	0.81 c	98.1 d	5.59 d	5.90 cd	41.2 e	5.60 a	67.0 d
		RDI	69.8 a	1.68 a	1.22 a	146.1 b	6.12 bc	6.61 ab	46.8 b	5.00 c	81.0 b

DI, surface drip; SDI, subsurface drip; I_{100}, full irrigation; I_{75}, deficit irrigation; I_{50}, deficit irrigation; PRD_{50}, partial root-zone drying; RDI, regulated deficit irrigation.
Different lowercase letters indicate significant differences. **LSD grouping at $P < 0.01$ level; *LSD grouping at $P > 0.05$, $P > 0.05$; ns, not significant.

https://doi.org/10.1017/S0021859623000205 Published online by Cambridge University Press

Table 3. Statistical analysis results on yield, fruit number, yield per plant, fruit volume, fruit width, fruit length, fruit weight, total soluble solid and plant height of bell pepper under different treatments in the experimental years

Years	Irrigation treatments	Statistical analysis	Total yield (t/ha)	Fruit number (No×10^6/ha)	Yield per plant (kg)	Fruit volume (cm^3)	Fruit width (cm)	Fruit length (cm)	Fruit weight (g)	Total soluble solid (g/100 g)	Plant height (cm)
2016	Irrigation systems	LSD (O.O5) Probability CV(%)	ns	ns	ns	7.4 0.0119* 5.3	0.20 0.0055** 3.8	0.25 0.0420* 4.3	2.18 0.0119* 4.9	ns	ns
	Irrigation regimes	LSD (O.O5) Probability CV(%)	5.57 0.0001** 7.8	1.21 0.0001** 8.5	0.09 0.0001** 7.8	7.69 0.0001** 5.3	0.26 0.0001** 3.8	0.26 0.0001** 4.3	2.30 0.050* 4.9	0.16 0.0001** 2.9	0.71 0.0001** 0.8
	Interaction of irrigation systems and irrigation regimes	LSD (O.O5) Probability CV(%)	ns	ns	ns	10.9 0.0301* 5.3	ns	ns	ns	ns	0.49 0.0284* 0.8
2017	Irrigation systems	LSD (O.O5) Probability CV(%)	ns	0.65 0.0309* 6.3	ns	ns	0.153 0.0385* 2.7	ns	0.45 0.0230* 1.1	ns	1.13 0.0434* 1.6
	Irrigation regimes	LSD (O.O5) Probability CV(%)	4.65 0.0001** 7.4	0.97 0.0001** 6.3	0.08 0.0001** 7.4	9.22 0.0001** 5.5	0.164 0.0001** 2.7	0.462 0.0011** 7.1	0.51 0.0001** 1.1	0.263 0.0005** 4.8	1.2 0.0001** 1.6
	Interaction of irrigation systems and irrigation regimes	LSD (O.O5) Probability CV(%)	ns	ns	ns	ns	0.232 0.0093** 2.7	ns	ns	ns	ns

LSD, least significant difference; CV, coefficient of variation; DI, surface drip; SDI, subsurface drip; I_{100}, full irrigation; I_{75}, deficit irrigation; I_{50}, deficit irrigation; PRD_{50}, partial root-zone drying; RDI, regulated deficit irrigation.
**LSD grouping at $P < 0.01$ level; *LSD grouping at $P > 0.05$, $P > 0.05$; ns, not significant.

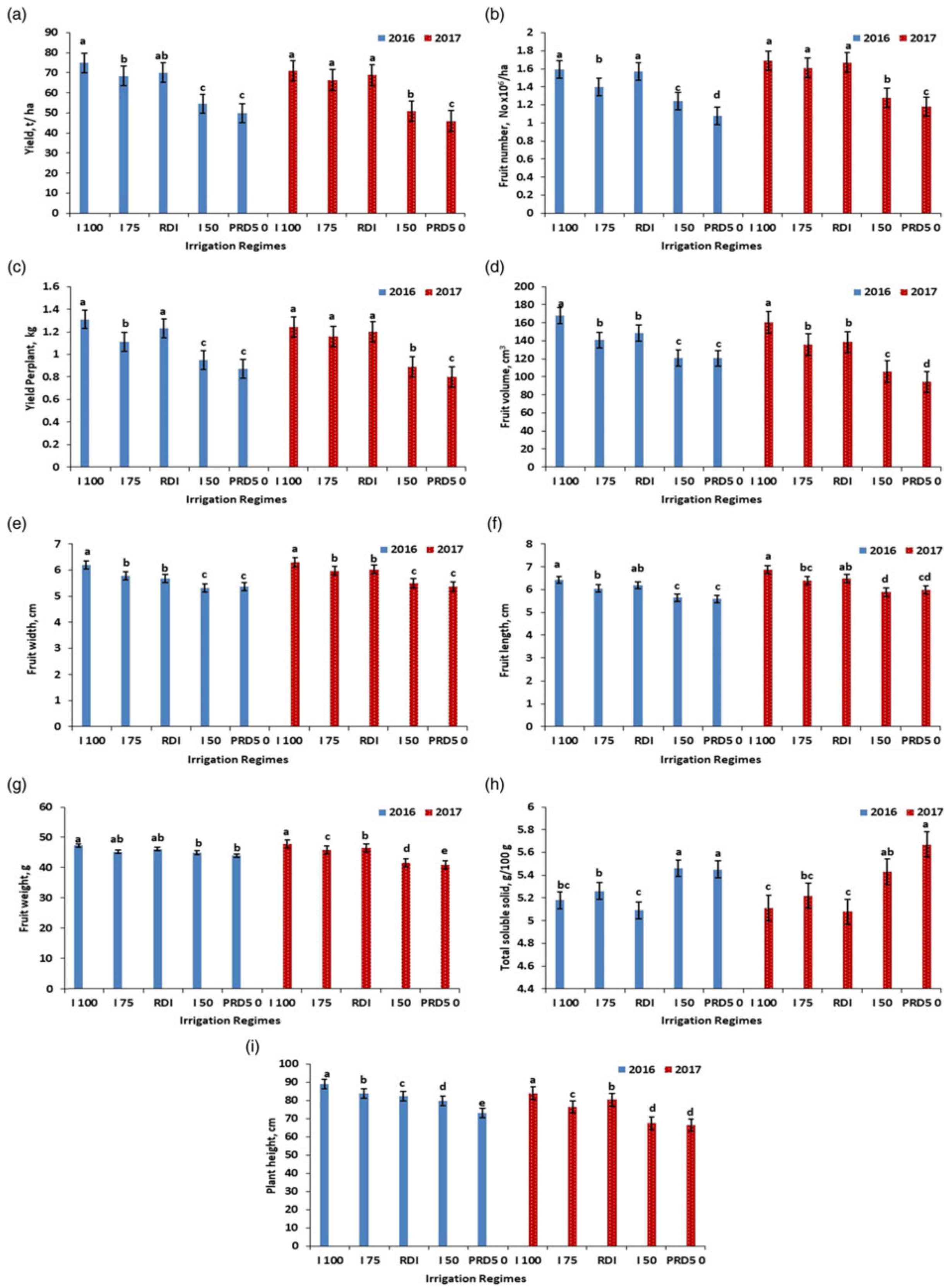

Fig. 4. Comparison of mean values averaged over two drip systems for the different treatments in the experimental years. (a) Yield; (b) fruit number; (c) yield per plant; (d) fruit volume; (e) fruit width; (f) fruit length; (g) fruit weight; (h) total soluble solid; (i) plant height (treatments: I_{100}, full irrigation; I_{75}, deficit irrigation; I_{50}, deficit irrigation; PRD_{50}, partial root-zone drying; RDI, regulated deficit irrigation).

Note. Vertical bars represent standard error among four independent replicates. Different lowercase letters indicate significant differences at $P < 0.01$, except fruit weight in the first year $P < 0.05$.

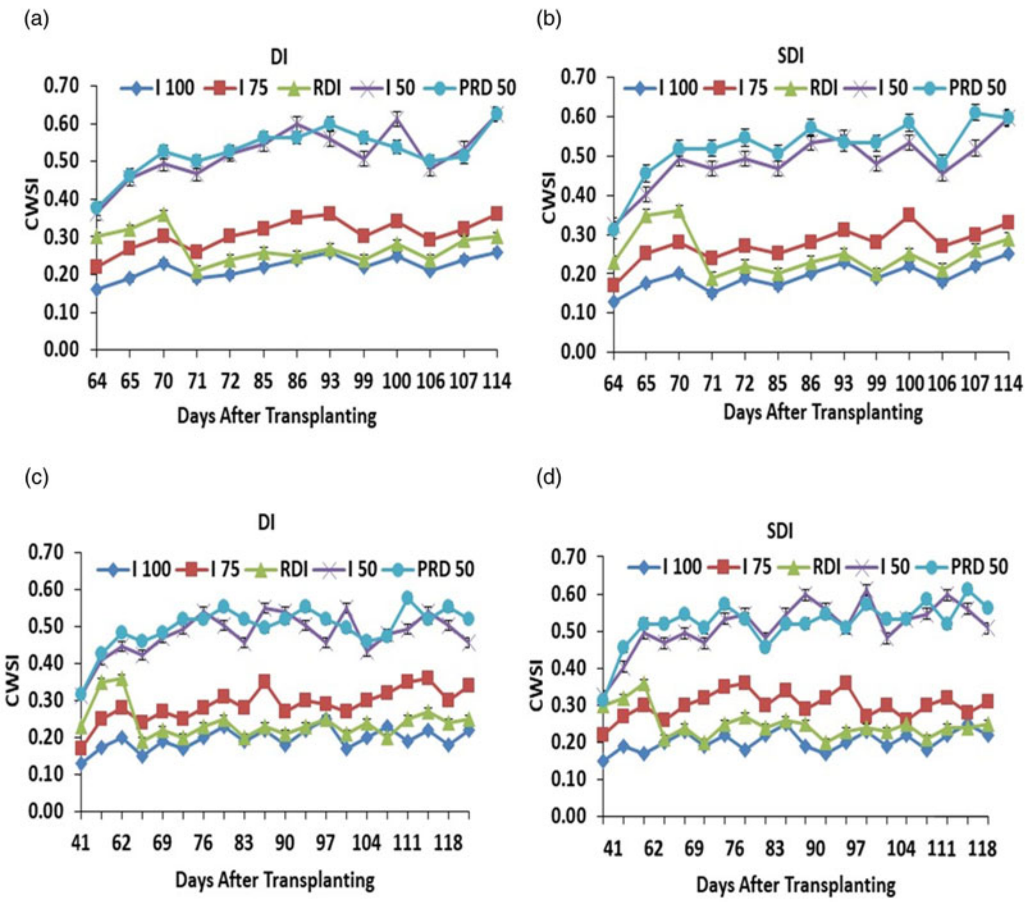

Fig. 5. Crop water stress index (CWSI) variation during the 2016 and 2017 bell pepper growing seasons in all treatments under surface and subsurface drip irrigation: (a) CWSI in DI in 2016; (b) CWSI in SDI in 2016; (c) CWSI in DI in 2017; (d) CWSI in SDI in 2017.
Note. Vertical bars represent the mean ± s.e. ($n = 19$).

0.25, 0.49 and 0.52, respectively, under SDI. In 2017, mean CWSI values for I_{100}, I_{75}, RDI, I_{50} and PRD_{50} were 0.20, 0.29, 0.24, 0.48 and 0.50, respectively, under DI, and mean CWSI values for I_{100}, I_{75}, RDI, I_{50} and PRD_{50} were 0.20, 0.30, 0.25, 0.51 and 0.52, respectively, under SDI.

Relationships between CWSI, yield, yield per plant, total soluble solid, ETa, fruit weight and plant height

The relationships between CWSI (as the independent variable) and bell pepper yield, yield per plant, TSS, ETa, fruit weight and plant height (as the dependent variable) in the experimental years are presented in Figs 6(a)–(f) and 7(a)–(f), respectively. For the growing seasons, the relationship between CWSI and yield had high determination coefficients that yielded $R^2 = 0.98$ for DI and 0.99 for SDI in the first and second years, corresponding values were $R^2 = 0.99$ and 0.95, respectively. The relationship between CWSI and yield per plant was expressed with a significant quadratic equation with high determination coefficients of $R^2 = 0.96$ for DI and 0.99 for SDI in the first and second years, corresponding values were $R^2 = 0.96$ and 0.90, respectively. A second-order polynomial equation best describes the relations between CWSI and TSS with high determination coefficients of $R^2 = 0.97$ for DI and 0.75 for SDI in the first and second years, corresponding values were $R^2 = 0.85$ and 0.90, respectively. The significant relationship between CWSI and ETa was determined with high determination coefficients of $R^2 = 0.99$ for DI and 0.97 for SDI in the first and second years, corresponding values were $R^2 = 0.85$ and 0.80, respectively. The significant relationship between CWSI and fruit weight was determined with high determination coefficients of $R^2 = 0.85$ for DI and 0.99 for SDI in the first and second years, corresponding values were $R^2 = 0.99$ and 0.99, respectively. The significant relationship between CWSI and plant height was determined with high determination coefficients of $R^2 = 0.83$ for DI and 0.77 for SDI in the first and second years, corresponding values were $R^2 = 0.99$ and 0.99, respectively. The relationship obtained between yield and CWSI may be used to predict the yield potential of bell pepper.

Economic evaluation

An economic analysis was carried out based on the 2 years' average data on investment, operation and production costs obtained from the APD in Mersin (APD 2016, 2017), and the results are given in Table 4. Economic analysis showed that the highest net income was generated as US\$32203/ha with the full irrigation treatment under the surface-drip (DI I_{100}) treatment followed by the SDI I_{100} treatment with US\$31474/ha. RDI (US\$29077/ha and US\$29604/ha for DI and SDI) treatment produced relatively higher net return values as compared with I_{50} and PRD_{50} treatments. The lowest net return was generated by DI PRD_{50} treatment with US\$16470/ha.

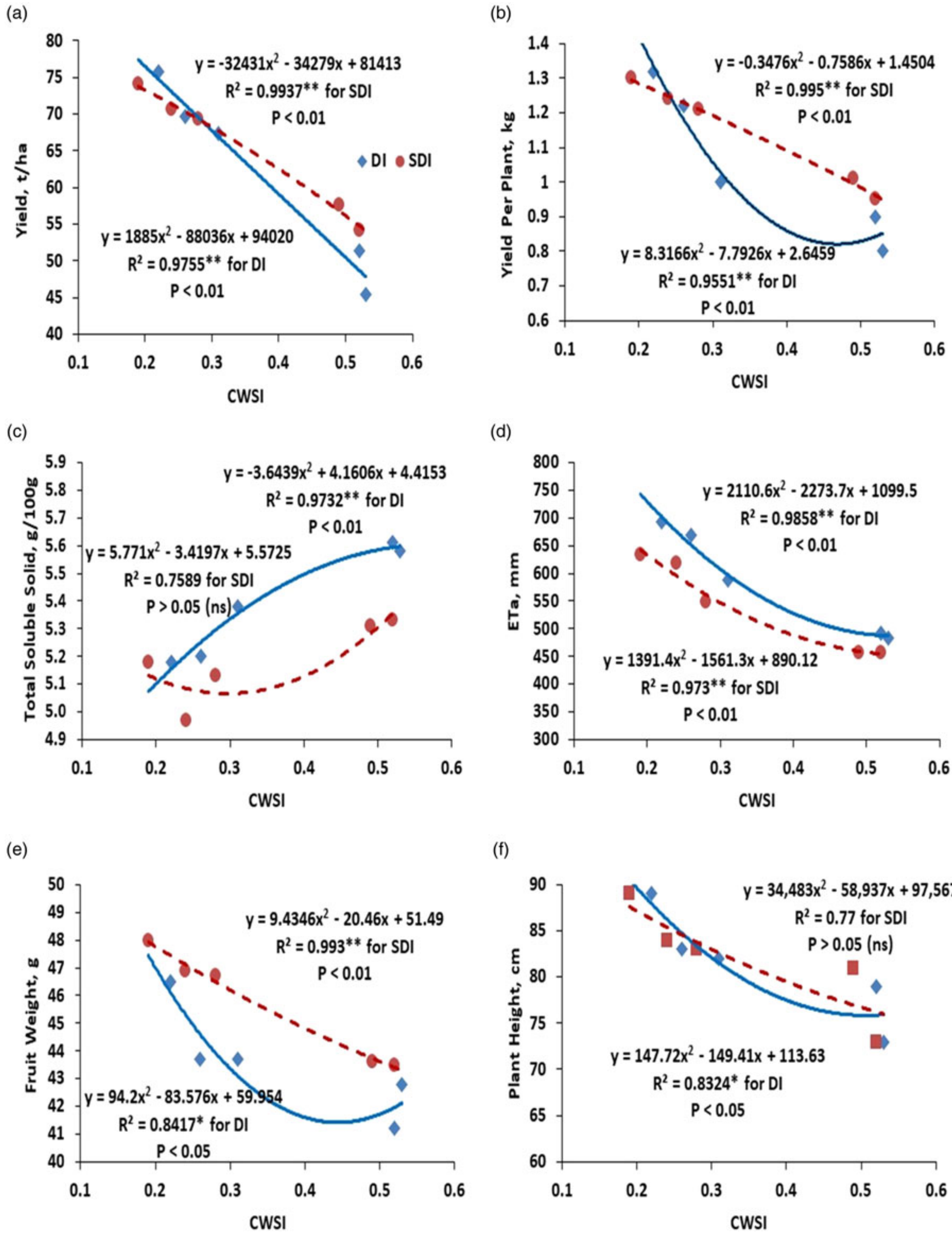

Fig. 6. The relationships between crop water stress index (CWSI) and yield (a), yield per plant (b), total soluble solid (c), evapotranspiration (ETa) (d), fruit weight (e) and plant height (f) in the 2016 growing season.
Note. **LSD grouping at $P < 0.01$ level; *LSD grouping at $P > 0.05$, $P > 0.05$; ns (not significant).

Discussion

The seasonal actual crop ETa values were generally greater in the 2017 than in 2016 due to prevailing greater air temperatures and less amounts of rainfall during the 2017 growing season. Bell pepper plants under surface-drip plots used 8.4 and 4.6% more water than subsurface-drip plots for the I_{100} treatments in 2016 and 2017 seasons, respectively, due to reduced surface evaporation from the SDI plots. Since SDI kept the surface soil dry, it decreased the evaporation, and thereby reduced the water consumption of bell pepper. Similar findings were reported by

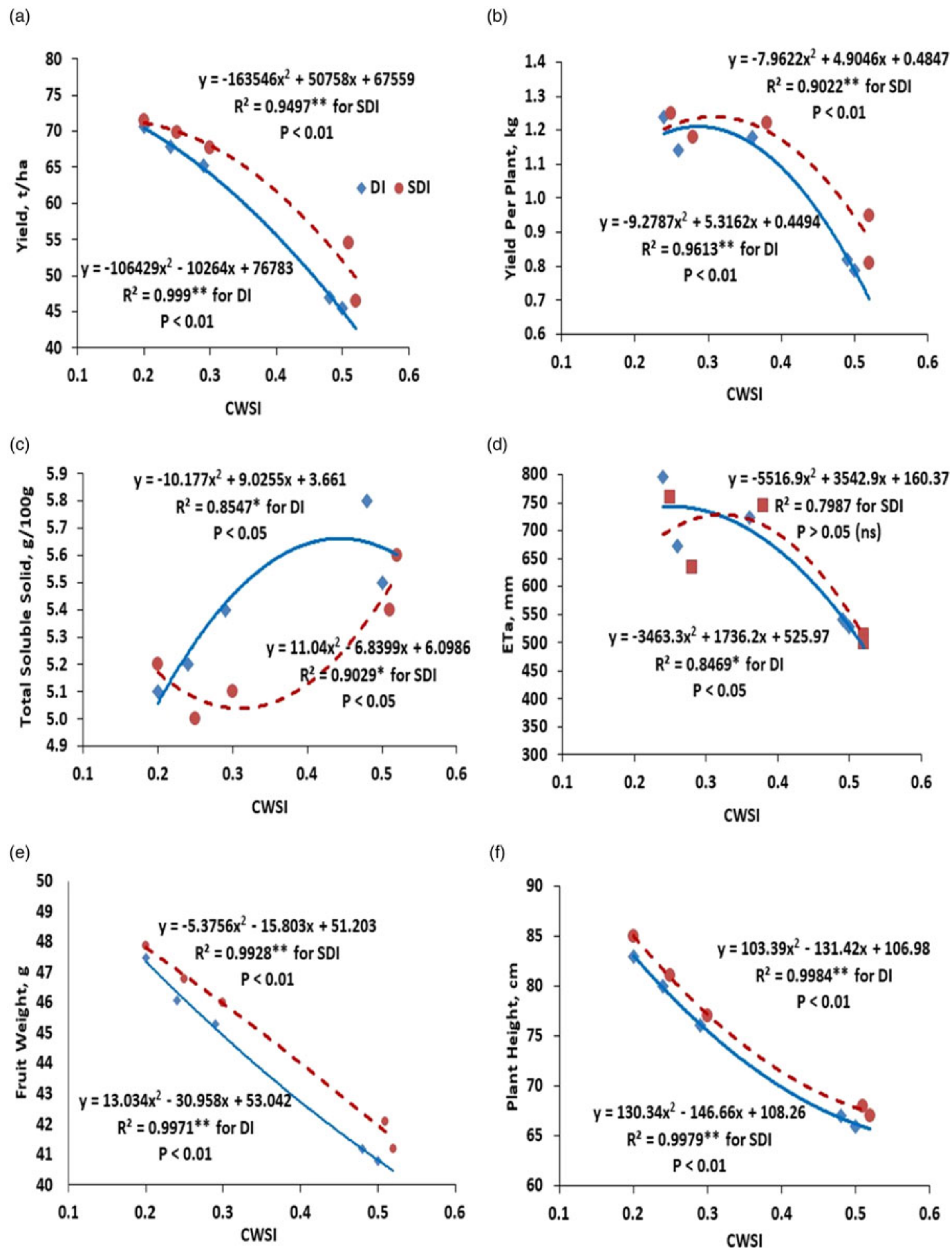

Fig. 7. The relationships between crop water stress index (CWSI) and yield (a), yield per plant (b), total soluble solid (c), evapotranspiration (ETa) (d), fruit weight (e) and plant height (f) in the 2017 growing season.
Note. **LSD grouping at $P < 0.01$ level; *LSD grouping at $P > 0.05$, $P > 0.05$; ns, not significant.

Kong *et al.* (2012) that seasonal actual crop water use (ETa) of bell pepper under SDI plots was lower than under DI plots. They reported that the minimum and maximum ETa were found for DI plots (362–451 mm) and SDI plots (301–438 mm), respectively. Crop water use decreased with increasing water stress as observed in I_{50} and PRD_{50} treatments in which SWC gradually decreased below 50% of available water just after flowering growth stage and fell below 50% level during fruit set and maturation periods. Several studies on drip irrigated bell pepper documented that the ETa values varied from 715 to 1412 mm in SDI treatment;

Table 4. Economic analysis of the different irrigation treatments under the surface and subsurface irrigation systems

Irrigation systems	DI					SDI				
Irrigation regimes	I_{100}	I_{75}	I_{50}	PRD_{50}	RDI	I_{100}	I_{75}	I_{50}	PRD_{50}	RDI
Irrigation water (mm) (1)	596	473	347	347	544	554	438	321	321	512
Irrigation water (m^3/ha) (2)	5960	5060	3590	3590	5700	6180	4770	3350	3350	5830
Irrigation duration (h) (3)	68.5	54.5	40.0	40.0	63.0	63.5	50.5	37.0	37.0	59.0
Labour cost for irrigation ($/h) (4)	3	3	3	3	3	3	3	3	3	3
Total cost for irrigation labour ($) (3 × 4) (5)	206	164	120	120	189	191	152	111	111	177
Water price ($/$m^3$) (6)	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017
Water price ($/ha) (2 × 6) (7)	89.4	70.9	52.1	52.1	81.6	83.0	65.6	48.2	48.2	76.7
Bell pepper production costs (8)	6485	6845	6845	6845	6845	6845	6845	6845	6845	6845
Irrigation system cost per unit area ($/ha) (9)	2400	2400	2400	2400	2400	2900	2900	2900	2900	2900
Annual cost for the irrigation system ($/ha) (9/6 yıl) (10)	400	400	400	400	400	363	363	363	363	363
Annual total cost ($/ha/year) (5 + 7 + 8 + 10) (11)	7540	7479	7417	7417	7516	7481	7425	7367	7367	7461
Bell pepper yield (kg/ha) (12)	75 700	67 400	51 300	45 500	69 700	74 200	69 400	57 700	54 100	70 600
Bell pepper sales price ($/kg) (13)	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53
Gross income per ha ($/ha/year) (12 × 13) (14)	39 743	35 385	26 933	23 888	36 593	38 955	36 435	30 923	28 403	37 065
Net income ($/ha/year) (14–11) (15)	32 203	27 906	19 515	16 470	29 077	31 474	29 010	22 926	21 036	29 604

DI, surface drip; SDI, subsurface drip; I_{100}, full irrigation; I_{75}, deficit irrigation; I_{50}, deficit irrigation; PRD_{50}, partial root-zone drying; RDI, regulated deficit irrigation.
Numbers in parenthesis represent column numbers, and how the values in each column are calculated.
It is charged over 1$ = 3.33 TL in pricing.

and 765 to 1475 mm in DI treatments in Southeast Anatolia region of Turkey (Kirnak *et al.*, 2003); ETa values ranged between 309 and 528 mm in Mediterranean region of Turkey (Sezen *et al.*, 2006); ETa ranged between 322 and 796 mm in Thrace region of Turkey (Demirel *et al.*, 2012); varying between 493 and 592 mm (Tanaskovik *et al.*, 2016); Karam and Nangia (2016) determined seasonal ETa using weighing lysimeter as 506 mm for bell pepper for a total growing period of 112 days from transplantation to third harvest. Present findings comply with most of the earlier findings reported.

Water stress significantly reduced fresh bell pepper yields in both experimental years ($P < 0.05$). Bell pepper yields were greater in 2016 growing season than that those in 2017. The reason for this difference in yield between the years could be attributed to higher temperatures prevailed during flowering stage in 2017. As indicated in Table 3, there was no significant difference in yields between the surface- and subsurface-drip irrigation systems in the experimental years. Although there is no significant difference in yield values between the two irrigation systems, all treatments except I_{100} produced greater yield under SDI than DI. However, irrigation treatments resulted in significantly different yields in 2016 and 2017 growing seasons ($P < 0.01$). Since there was no significant difference between the two drip systems regarding the yield values, statistical comparisons of the mean yields were made on yields averaged over the two drip systems (Fig. 4(a)). In both growing seasons, I_{100}, RDI and I_{75} treatments resulted in similar yields except I_{75} in 2017, and significantly greater yields than I_{50} and PRD_{50}. I_{75} treatment produced significantly greater yield than PRD_{50} and I_{50}. Although PRD_{50} and I_{50} treatments received the same amount of irrigation water, I_{50} resulted in higher yields than PRD_{50}. PRD_{50} reduced yields by 30.9 and 28.5% in DI and SDI systems, respectively, in 2016; and the corresponding yield reduction was 36.5 and 35.1% in 2017. Water stress occurring in I_{50} and PRD_{50} significantly reduced bell pepper yield under both drip systems. As mentioned earlier, SWC in these two treatments remained below 50% available water level during most of the growing seasons. RDI saved 5 and 12% water (average value 8.5%) as compared with I_{100} under DI; and 10 and 6% (averaged over 2 years 8.0%) under SDI system, respectively, in the experimental years. I_{75} treatment resulted in an average water saving of 20.6 and 26.7% for DI and SDI, respectively. Average yield reductions of 6.8 and 9.9% were observed for I_{75} under SDI and DI, respectively, as compared to I_{100}. Delfine *et al.* (2002) demonstrated that photosynthetic limitations in bell pepper plants growing in the field and subjected to moderate stress conditions were mainly due to decreasing stomatal conductance. Thus, lower yields obtained from I_{50} and PRD_{50} treatments were because of the water stress that reduces the stomatal conductance. Many studies confirmed that reductions in water supplied during pepper growth have an advance effect on final yield. For high yield, an adequate water supply is required during the whole crop cycle (Delfine *et al.*, 2002; Dorji *et al.*, 2005; Sezen *et al.*, 2006; González-Dugo *et al.*, 2007); Sezen *et al.* (2006) have reported drip irrigated bell pepper yield varying from 21.0 to 35.3 t/ha in Mediterranean region of Turkey.

TSS of pepper fruit and fruit size are important parameters to evaluate fruit quality. The results revealed that irrigation regimes had significantly different effect on TSS values ($P < 0.01$) in both experimental years. Higher TSS values were obtained in water stress treatments of I_{50} and PRD_{50}. Hsiao (1993) stated that restricted plant size and reduced assimilate availability at the time of fruit development and maturation caused by water stress, as the major causes of the reduced number of fruits, thus lower yields. The water deficit during the period between flowering and fruit development reduced final fruit production (Jaimez *et al*., 2000; Fernandez *et al*., 2005 and Dorji *et al*., 2005; Sezen *et al*., 2006). It was observed in the present study that in general, fruit weight values decreased with increasing water stress. Both irrigation systems and irrigation regimes had significantly different effect on fruit weight ($P < 0.01$ and $P < 0.05$). Full irrigation regimes under both drip systems produced the greatest mean fruit volume in the experimental years. RDI and I_{75} treatments had greater fruit volume values as compared to I_{50} and PRD_{50} but lower than I_{100} treatment. Water stress reduced the fruit volume in PRD_{50} and I_{50} treatments under both drip systems. Reduction in the yield of bell pepper under DI might be due to the reduction in fruit size and numbers (Fernandez *et al*., 2005). Reduction in pepper fruit size and numbers appears as the controlling factor for fruit yield (Sara *et al*., 2017). In the present study, DI significantly reduced crop yield in terms of fresh mass of fruit per plant.

Dorji *et al*. (2005) compared traditional drip system irrigation to DI (I_{50}) and PRD drip system irrigation for hot pepper irrigation and found that water savings with I_{50} and PRD_{50} were about 50% of traditional drip irrigation. However, the I_{80} and I_{60} treatments caused significant reductions in pepper yields through a reduction in fruits number per square metre and average fruit weight in comparison with I_{100} treatment. The RDI method can save a substantial amount of water and maintain yield in bell pepper production. Similar data were reported by Kang *et al*. (2001) in hot pepper grown under water stress. The findings of the present study confirm these findings by Nagaz *et al*. (2012) and Kang *et al*. (2001). Gadissa and Chemeda (2009) concluded that in areas where water shortage prevails depth of irrigation can be lowered up to 75% of its full supply for the production of green pepper under the normal planting method with 25% water saving and 22.8% yield reduction. Thus, RDI and I_{75} irrigation treatments can save substantial irrigation water while producing similar yields with full irrigation under the Mediterranean climatic conditions.

The experimental results indicated that I_{100} treatment resulted in lowest CWSI, and I_{50} and PRD_{50} resulted in the highest CWSI in the experimental years. In general, as the irrigation water applied increased, CWSI decreased. The SWC was consistent with the CWSI values in I_{50} and PRD_{50}, which had the largest soil water stress levels and greater CWSI values, while the highest irrigation level (I_{100}) had the smallest soil water stress levels and lower CWSI values. Slightly lower CWSI values were determined in SDI plots than those in DI plots; however, the difference between the CWSI values in SDI and DI treatments was not significant. As shown in Figs 5(a)–(d), CWSI values increased gradually towards the end of season in all treatments. RDI and I_{75} treatments under both drip systems had lower CWSI values than I_{50} and PRD_{50}. Mean CWSI values for RDI averaged over 2 years were 0.26 for DI and 0.25 for SDI; and for I_{75}, mean CWSI values were 0.30 and 0.29.

The CWSI has been used in numerous studies on irrigation management. In most of the studies on effects of water stress on vegetables, CWSI increased with increased levels of water stress. Overall, the CWSI is responsive to water stress and has the potential to determine crop responses to water stress. Aladenola and Madramootoo (2014) reported that average maximum CWSI thresholds of 0.3 and 0.4 for loamy sand and clay soil, respectively, can be used to schedule irrigation, beyond which the bell pepper will suffer stress. Sezen *et al*. (2019) reported similar results that the full irrigation treatment had lower CWSI (0.25–0.27) for red pepper under the Mediterranean climatic conditions. In the present study, an average CWSI value of 0.20 was found for full irrigated bell pepper under DI and SDI systems.

In general, the CWSI correlated significantly ($P < 0.01$) and negatively with yield, yield per plant, TSS, ETa, fruit weight and plant height indicating that the yield of bell pepper declined with increasing CWSI values. All these relations are best described by significant second-order polynomial equations. In the most studies, CWSI results are consistent with yield results, and yield varied linearly with the CWSI in eggplant (Bozkurt Çolak *et al*., 2015), broccoli (Erdem *et al*., 2010), pepper (Aladenola and Madramootoo, 2014; Sezen *et al*., 2014). Linear equations developed for each crop can be used to predict the yield of the crop when the crop is subjected to different levels of water stress.

Conclusions

The main focus of this study was to investigate physiological and yield response of bell pepper to various DI strategies applied with surface- and subsurface-drip systems under the Mediterranean climatic conditions. RDI appeared to be a good alternative to full irrigation since it produced statistically similar yield to I_{100} treatment in both experimental years under both drip systems. The highest net income was generated with the full irrigation treatment under the surface-drip (DI I_{100}) treatment followed by the SDI I_{100} and RDI treatments. An average CWSI value of approximately 0.20 just before irrigation can be used for irrigation scheduling of bell pepper to achieve high bell pepper yields. In general, the CWSI correlated significantly ($P < 0.01$) with bell pepper yield, yield per plant, TSS, ETa, fruit weight and plant height indicating that bell pepper yield declined with increasing CWSI values. In conclusion, RDI is recommended along with conventional DI (I_{75}) in Mediterranean area.

Author contributions. Y. B. C. and A. Y. conceived and designed the study. M. Y., E. G. and A. A. conducted data gathering. S. T. performed statistical analyses. Y. B. C. and A. Y. wrote the article.

Financial support. The authors would like to thank the Turkish Scientific and Technical Research Council (TUBITAK) for its financial support for the project TUBITAK ERA-NET-215O951.

Conflict of interest. None.

Ethical standards. Not applicable.

References

Abdelkhalik A, Pascual B, Nájera I, Domene MA, Baixauli C and Pascual Seva N (2020) Effects of deficit irrigation on the yield and irrigation water use efficiency of drip irrigated sweet pepper (*Capsicum annuum L.*) under Mediterranean conditions. *Irrigation Science* **38**, 89–104.

Aladenola O and Madramootoo C (2014) Response of greenhouse-grown bell pepper (*Capsicum annuum L.*) to variable irrigation. *Canadian Journal of Plant Science* **94**, 303–310.

APD (2016) Production and crop sale prices in Mersin, Agricultural Provincial Directorate, Ministry of Agriculture and Forestry, Mersin APD, Turkey.

APD (2017) Production and crop sale prices in Mersin, Agricultural Provincial Directorate, Ministry of Agriculture and Forestry, Mersin APD, Turkey.

Bozkurt Colak Y (2021) Leaf water potential for surface and subsurface drip irrigated bell pepper under various deficit ırrigation strategies. *Chilean Journal of Agricultural Research* **81**, 491–506.

Bozkurt Çolak Y, Yazar A, Çolak İ, Akça H and Duraktekin G (2015) Evaluation of crop water stress index (CWSI) for eggplant under varying irrigation regimes using surface and subsurface drip systems. *Agriculture and Agricultural Science Procedia* **4C**, 372–382.

Bozkurt Çolak Y, Yazar A, Gönen E and Eroğlu EÇ (2018) Yield and quality response of surface and subsurface drip irrigated eggplant and comparison of net returns. *Agricultural Water Management* **206**, 165–175.

Chai Q, Gan Y, Zhao C, Xu HL, Waskom RM, Niu Y and Siddique KH (2016) Regulated deficit irrigation for crop production under drought stress. A review. *Agronomy for Sustainable Development* **36**, 3.

Chartzoulakis K and Maria B (2015) Sustainable water management in agriculture under climate change. *Agriculture and Agricultural Science Procedia* **4**, 88–95.

Cohen Y, Alchanatis V, Saranga Y, Rosenberg O, Sela E and Bosak A (2017) Mapping water status based on aerial thermal imagery: comparison of methodologies for upscaling from a single leaf to commercial fields. *Precision. Agriculture* **18**, 801–822.

Costa JM, Ortuño MF and Chaves MM (2007) Deficit irrigation as a strategy to save water: physiology and potential application to horticulture. *Journal of Integrative Plant Biology* **49**, 1421–1434.

DeJonge KC, Taghvaeian S, Trout TJ and Comas LH (2015) Comparison of canopy temperature-based water stress indices for maize. *Agricultural Water Management* **156**, 51–62.

Delfine S, Tognetti R, Loreto F and Alvino A (2002) Physiological and growth responses to water stress in field-grown bell pepper (*Capsicum annuum L.*). *Journal of Horticultural Science and Biotechnology* **77**, 697–704.

Demirel K, Genc L and Sacan M (2012) Effects of different irrigation levels on pepper yield and quality parameters in semi-arid conditions. *Journal of Tekirdag Agricultural Faculty* **9**, 7–15.

Dorji K, Behboundian MH and Zegbe-Dominguez JA (2005) Water relations, growth, yield and fruit quality of hot pepper under deficit irrigation and partial rootzone drying. *Scientia Horticulturae* **104**, 137–149.

Dukes MD, Zotarelli L and Morgan KT (2010) Use of irrigation technologies for vegetable crops in Florida. *Horttechnology* **20**, 133–142.

English M and Nuss GS (1982) Designing for deficit irrigation. *Journal of the Irrigation and Drainage Division* **108**, 91–106.

Erdem Y, Arin L, Erdem T, Polat S, Deveci M, Okursoy H and Gültas HT (2010) Crop water stress index for assessing irrigation scheduling of drip irrigated broccoli (*Brassica oleracea L. var. italica*). *Agricultural Water Management* **98**, 148–156.

Evett SR, Stone KC, Schwartz RC, O'Shaughnessy SA, Colaizzi PD, Anderson SK and Anderson DJ (2019) Resolving discrepancies between laboratory-determined field capacity values and field water content observations: implications for irrigation management. *Irrigation Science* **37**, 751–759.

Fereres E and Soriano MA (2007) Deficit irrigation for reducing agricultural water use. *Journal of Experimental Botany* **58**, 147–159.

Fereres E, Francisco O and Victoria GD (2011) Reflections on food security under water scarcity. *Journal of Experimental Botany* **62**, 4079–4086.

Fernandez MD, Gallardo M, Bonachela S, Orgaz F, Thompson RB and Fereres E (2005) Water use and production of a greenhouse pepper crop under optimum and limited water supply. *The Journal of Horticultural Science and Biotechnology* **80**, 87–96.

Ferrara A, Lovelli S, Di Tommaso T and Perniola M (2011) Flowering, growth and fruit setting in greenhouse bell pepper under water stress. *Journal of Agronomy* **10**, 12–19.

Gadissa T and Chemeda D (2009) Effects of drip irrigation levels and planting methods on yield and yield components of green pepper (*Capsicum annuum*, L.) in Bako, Ethiopia. *Agricultural Water Management* **96**, 1673–1678.

Galindo A, Collado-González J, Griñán I, Corell M, Centeno A, Martín-Palomo MJ, Girón IF, Rodríguez P, Cruz ZN, Memmi H, Carbonell-Barrachina AA, Hernández F, Torrecillas A, Moriana A and Pérez-López D (2018) Deficit irrigation and emerging fruit crops as a strategy to save water in Mediterranean semiarid agrosystems. *Agricultural Water Management* **202**, 311–324.

González-Dugo V, Orgaz F and Fereres E (2007) Responses of pepper to deficit irrigation for paprika production. *Scientia Horticulturae* **114**, 77–82.

Gonzalez-Dugo V, Testi L, Villalobos FJ, López-Bernal A, Orgaz F, Zarco-Tejada PJ and Fereres E (2020) Empirical validation of the relationship between the crop water stress index and relative transpiration in almond trees. *Agricultural and Forest Meteorology* **292–293**, 108128.

Han M, Zhang H, DeJonge KC, Comas LH and Gleason S (2018) Comparison of three crop water stress index models with sap flow measurements in maize. *Agricultural Water Management* **203**, 366–375.

Hsiao TC (1993) Growth and productivity of crops in relation to water stress. *Acta Horticulturae* **335**, 137–148.

Idso SB, Jackson RD, Pinter PJ Jr, Reginato RJ and Hatfield JL (1981) Normalizing the stress-degree-day parameter for environmental variability. *Agricultural and Forest Meteorology* **24**, 45–55.

Irmak S, Djaman K and Rudnick D (2016) Effect of full and limited irrigation amount and frequency on subsurface drip-irrigated maize evapotranspiration, yield, water use efficiency and yield response factors. *Irrigation Science* **34**, 271–286.

Jackson RD, Idso SB, Reginato RJ and Pinter PJ (1981) Canopy temperature as a crop water stress indicator. *Water Resources Research* **17**, 1133–1138.

Jaimez RE, Vielma O, Rada F and Garcia-Nunez C (2000) Effects of water deficit on the dynamics of flowering and fruit production in capsicum. Chinese Jacque in a tropical semiarid region of Venezuela. *Journal of Agronomy and Crop Science* **185**, 113–119.

Jones HG and Vaughan RA (2010) *Remote Sensing of Vegetation: Principles, Techniques, and Applications*. Oxford, New York: Oxford University Press.

Kang S, Zhang L, Hu X, Li Z and Jerie P (2001) An improved water use efficiency for hot pepper grown under controlled alternate drip irrigation on partial roots. *Scientia Horticulturae* **89**, 257–267.

Karam F and Nangia V (2016) Improving water productivity in semi-arid environments through regulated deficit irrigation. *Annals of Arid Zone* **55**, 79–87.

Katimbo A, Rudnick DR, DeJonge KC, Lo TH, Qiao X, Franz TE, Nakabuye HN and Jiaming Duan J (2022) Crop water stress index computation approaches and their sensitivity to soil water dynamics. *Agricultural Water Management* **266**, 107575.

Kirnak H, Kaya C, Taş I and Higgs D (2003) Responses of drip irrigated bell pepper to water stress and different nitrogen levels with or without mulch cover. *Journal of Plant Nutrient* **26**, 263–277.

Kong Q, Li G, Wang Y and Huo H (2012) Bell pepper response to surface and subsurface drip irrigation under different fertigation levels. *Irrigation Science* **30**, 233–245.

Kumar S and Rai M (2005) *Chile in India*. India: Chile Pepper Institute Newsletter (XXII), pp. 1–3.

Lamm FR and Camp CR (2007) Design, operation, and management, subsurface drip irrigation. In Lamm FR, Ayars JE and Nakayama FS (eds), *Microirrigation for Crop Production*. Amsterdam: Elsevier, pp. 473–551.

Lamm FR and Rogers D (2017) Longevity and performance of a subsurface drip irrigation system. *American Society of Agricultural and Biological Engineers* **60**, 931–939.

List RJ (1971) *Smithsonian Meteorological Tables*. revised Edn. Smithsonian Misc Collections, vol. **114**. Washington, DC: Smithsonian Institute.

Maes WH and Steppe K (2012) Estimating evapotranspiration and drought stress with ground-based thermal remote sensing in agriculture: a review. *Journal of Experimental Botany* **63**, 4671–4712.

Marsal J, Mata M, Arbones A, Del Campo J, Girona J and Lopez G (2008) Factors involved in alleviating water stress by partial crop removal in pear trees. *Tree Physiology* **28**, 1375–1382.

MGM (2019) *General Directorate of Meteorology of Turkey*. Ankara, Turkey: Weather data.

Nagaz K, Masmoudi MM and Mechlia NB (2012) Effects of deficit drip-irrigation scheduling regimes with saline water on pepper yield, water productivity and soil salinity under arid conditions of Tunisia. *Journal of Agriculture and Environment for International Development – JAEID* **106**, 85–103.

Romero-Trigueros C, Alarcon JJ, Nortes PA, Bayona JM, Maestre-Valero J and Nicolas E (2020) Medium-long term effects of saline reclaimed water and regulated deficit irrigation on fruit quality of citrus. *Journal of the Science of Food and Agriculture* **100**, 1350–1357.

Sara M, Sayyed HT, Mohammad P and Hamid Z (2017) Physiological responses of pepper plant (*Capsicum annuum* l.) to drought stress. *Journal of Plant Nutrition* **40**, 1453–1464.

Sezen SM, Yazar A and Eker S (2006) Effect of drip irrigation regimes on yield and quality of field grown bell pepper. *Agricultural Water Management* **81**, 115–131.

Sezen SM, Yazar A, Dasgan Y, Yucel S, Akyıldız A, Tekin S and Akhoundnejad Y (2014) Evaluation of crop water stress index (CWSI) for red pepper with drip and furrow irrigation under varying irrigation regimes. *Agricultural Water Management* **143**, 59–70.

Sezen SM, Şengül H, Baytorun N, Daşgan Y, Akyildiz A, Tekin S, Onder D, Agcam E, Akhoundnejad Y and Gügercin Ö (2015) Comparison of drip and furrow irrigated red pepper yield, yield components, quality and net profit generation. *Irrigation Drainage* **64**, 546–556.

Sezen SM, Yazar A and Tekin S (2019) Physiological response of red pepper to different irrigation regimes under drip irrigation in the Mediterranean region of Turkey. *Scientia Horticulturae* **245**, 280–288.

Steduto P, Hsiao TC, Fereres E and Raes D (2012) Crop yield response to water – FAO irrigation and drainage paper No. 66. FAO, Rome.

Tanaskovik V, Cukaliev O, Kanwar SR, Heng LK, Markoski M and Spalevic V (2016) Nitrogen fertilizer use efficiency of pepper as affected by irrigation and fertilization regime. *Notulae Botanicae Horti Agrobotanici Cluj-Napoca* **44**, 525–532.

Yahaya O, Alao F and Odigie CJ (2012) Yield, crop-water-use evaluation for pepper production under irrigated cultivation in Akure, Nigeria. *Global Journal of Science Research Agriculture & Biology* **12**, 18–22.

Yazar A, Howell AT, Dusek DA and Copeland KS (1999) Evaluation of crop water stress index for LEPA Irrigated Corn. *Irrigation Science* **18**, 171–180.

Zhang H (2003) *Improving Water Productivity Through Deficit Irrigation: Examples From Syria, the North China Plain and Oregon, USA*. Colombo, Sri Lanka: International Water Management Institute.

Zotarelli L, Dukes MD, Scholberg JMS, Femminella K and Muñoz-Carpena R (2011) Irrigation scheduling for green bell peppers using capacitance soil moisture sensors. *Journal of Irrigation and Drainage Engineering* **137**, 73–81.