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Improving Water Productivity in Semi-arid Environments through Regulated Deficit Irrigation

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Abstract: A twelve-year experiment (1998-2009) was conducted at Tal Amara Research Station in Lebanon to determine the effects of deficit irrigation on yield and water productivity in six annual crops; maize (1998-1999), soybean (2000-2001), cotton (2001-2002), sunflower (2002-2003), bell pepper (2005) and eggplants (2008-2009). Deficit irrigation was applied by exposing the crop to a certain level of water stress either during a particular growth period or throughout the whole growing season. At harvest, 1 m^2 quadrates were sampled randomly from the different irrigation treatments to determine yield (Y) and water productivity (WP) as the ratio of yield to evapotranspiration (ET). Results showed that deficit irrigation caused in all crops less yield but resulted in higher WP compared to the well-irrigated control. For soybean, deficit irrigation at mature seeds was more profitable compared to full bloom and seed enlargement. Moreover, flowering was sunflower most critical growth stage and therefore deficit irrigation should be avoided at this stage, while it can be acceptable at seed formation. For cotton, timing deficit irrigation at first open boll has been found to provide the highest lint yield with maximum WP, in comparison to deficit irrigation at early boll loading and mid boll loading. For maize, deficit irrigated-treatments at 80% and 60% of crop evapotranspiration produced less seed yield but resulted in higher WP than the well-irrigated control. In bell pepper and eggplants, deficit irrigation at 80% of ETc was recommended to obtain higher yield and optimized WP. We concluded that deficit irrigation resulted in water saving with the least yield reduction, and thereby considered optimal strategy for irrigation under semi-arid conditions.

Key words: Deficit irrigation, crop evapotranspiration, water productivity, lysimeter, yields.

The relative amount of water available to agriculture is declining worldwide due to the rapid population growth and the greater incidence of drought in recent years caused by climate change and different human activities. Competing agricultural, municipal and industrial water usage will eventually threaten food security (UNWWAP, 2003; World Bank, 2006). Continued successful management of the limited amount of water available for agricultural uses depends upon better agronomic practices and enhanced understandings of water productivity, defined as the crop productivity output per unit of water consumed (Howell *et al*., 1998; Jones, 2004).

Optimal scheduling of water application is critical to make the most efficient use of water for crop production. This requires that water application is kept at the optimum level to achieve maximized returns. Deficit irrigation - the deliberate and systematic under-irrigation of crops (English *et al*., 1990; Jurriens and Wester, 1994) is one way of optimizing water use efficiency (WUE) to achieve higher crop yields per unit of irrigation water (Saeed *et al*., 2008; Domínguez *et al*., 2012a). It is applied by eliminating irrigation that has the lower impact on yield (English, 1990; English *et al*., 1990; English and Raja, 1996; DaCosta and Huang, 2006; Geerts and Raes, 2009). Using the deficit irrigation approach, the crop is exposed to a certain level of water stress either during a particular growth period or throughout the whole growing season (English, 1990; Pereira *et al*., 2002; Karam *et al*., 2003, 2005, 2006, 2007, 2009, 2011; Fereres and Soriano, 2007).

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The resulting yield reduction may be small compared with the benefits gained by diverting the saved water to irrigate other crops (Kirda, 2002; Kirnak *et al*., 2002).

The objectives of this long-term research were to determine water use and yield in six annual crops with contrasting response to deficit irrigation; maize, soybean, cotton, sunflower, bell pepper and eggplants. The ultimate objective is to assess water productivity response to different irrigation regimes and propose irrigation management strategies for the studied crops under the semiarid Lebanon's Bekaa Valley.

Materials and Methods

Field studies aiming at examining the response of maize (*Zea mays* L.), soybean (*Glycine max* L. Merril), cotton (*Gossypium hirsutum* L.), sunflower (*Helianthus annuus* L.), bell pepper (*Capsicum annuum* L.) and eggplants (*Solanum melongena* L.) to deficit irrigation were conducted during the period of 1998-2009 at Tal Amara Research Station in the Central Bekaa Valley of Lebanon (33°51'44'' N lat., 35°59'32'' E long, altitude 905 m a.s.l.). Tal Amara has a well-defined hot, dry season from May to September and very cold for the remainder of the year. Long-run data indicate an average seasonal rain of 592 mm, with 95% of the rain occurring between November and March. Crops were grown on deep and fairly-drained soil, characterized by dominant clay content (44%). Measured field capacity (-0.33 bar) and permanent wilting point (-15 bars) averaged 29.5% and 16.0% by weight. Extractable plant water is estimated at 190 mm for 1 m rooting depth and a bulk density of 1.41 g cm^{-3}.

Hybrid maize (cv. *Manuel*) was sown on 19 May in 1998 and 25 May in 1999 at 10 plants m^{-2}. Soybean hybrid (cv. Asgrow 3803) was sown on 10 May 2000 and 25 April 2001 at a density of 12 plants m^{-2}. Cotton (cv. AgriPro AP 7114) was sown on 5 May in 2001 and on 13 May in 2002 at a density of 10 plants m^{-2}. Sunflower (cv. Arean) was sown on 20 May 2003 and 10 May 2004 at a density of 10 plants m^{-2}. Seeds of bell pepper (cv. Mercury F1) were germinated in peat on 12 April 2005 in a controlled nursery. The seedlings were then transplanted in the field on 31 May 2005 at a density of 4 plants m^{-2}. Seeds of eggplant (cv. Baladi) were sown on 12 April 2008 and 30 April 2009 in pots, using peat moss and germinated in a controlled greenhouse at Tal Amara Research Station and transplantation took place on 28 May 2008 and 11 June 2009 at the rate of 4 plants m^{-2}.

For all crops except soybean, evapotranspiration (ET_{crop}) was measured using a set of two drainage no suction-type lysimeters of 4 m² surface area (2 m × 2 m) by subtracting the volume of drainage from the irrigation amount. The lysimeters, 1.2 m deep, 24 m apart, aligned N-S, are situated in the middle of 1-ha field (200 m N-S by 50 m W-E) (Karam *et al*., 2003). For soybean, ET_{crop} was measured by a weighing lysimeter of 16 m² surface area (4 m × 4 m) and 1.2 m deep, containing the same clay soil as in the drainage lysimeters (Fig. 1). Both drainage and weighting lysimeters were cultivated with crops at the same density as in the surrounding experimental field. Reference evapotranspiration ($ET_{rye\ grass}$) was measured in a set of two rye-grass drainage lysimeters of 4 m² surface area (2 m × 2 m) and 1 m depth cultivated with rye grass (*Lolium perenne*). The lysimeters are 24 m distant, aligned W-E, and located inside the meteorological park of the Research Station, 50 m apart of the experimental plots (Fig. 2). ET_{crop} and $ET_{rye\text{-}grass}$ were calculated for a given interval as the difference between irrigation (I) and drainage (Dr), assuming the variation of the soil water storage (ΔS) is 0 (all terms are expressed in mm)

$$ET_{(crop,\ rye\_grass)} = I - D_r \pm \Delta S \qquad ...(1)$$

Crop coefficients (K_c) in the different crop growth stages were derived as the ratio ($ET_{crop}/ET_{rye\text{-}grass}$). Soil water content in the lysimeters

Fig. 1. A view of the weighing lysimeter at Tal Amara Research Station (courtesy: F. Karam, 2005).

Fig. 2. A view of the rye grass drainage lysimeters at Tal Amara Research Station (courtesy: F. Karam, 2005).

and experimental plots was estimated weekly using digital tensiometers (0-200 cbar) (Watermark, Soil Moisture Meter, IRROMETER COMPANY, Inc.) installed in two replicates in each lysimeter at 30 and 60 cm of the soil depth. Table 1 illustrates full and deficit-irrigated treatments for the crops under study.

Ambient weather data (solar radiation, air temperature, wind speed at 2 m height, air temperature at dew point and relative humidity) were daily recorded from an automated weather station (AURIA 12E, DEGREANE, France) 50 m apart from the experimental site (Fig. 3). The weather station was established within 10 m of the rye-grass lysimeters in a standard meteorological park of 40 m N-S × 40 m W-E size, cultivated with rye grass of the same physiological traits as in the lysimeters. The weather station is automatically linked to an internal data logger, which discharges at 10-min interval the registered meteorological

Table 1. Irrigation treatments of the different crops under study

Crop	Years	Treatment	Period of deficit irrigation/level of deficit irrigation as % of ET_{crop}
Maize	1998 and 1999	I-100	No irrigation restriction during the growing period
		I-80	Deficit irrigation at 20% of crop evapotranspiration (from 6-leaf stage onwards)
		I-60	Deficit irrigation at 40% of crop evapotranspiration (from 6-leaf stage onwards)
Soybean	2000 and 2001	C	No irrigation restriction during the growing period
		S-1	Deficit irrigation at full bloom stage (R2)
		S-2	Deficit irrigation at seed enlargement stage (R5)
		S-3	Deficit irrigation at mature seeds stage (R7)
Cotton	2001 and 2002	C	No irrigation restriction during the growing period
		S-1	Deficit irrigation at first open boll stage (R2)
		S-2	Deficit irrigation at early boll loading stage (R5)
		S-3	Deficit irrigation at mid boll loading stage (R7)
Sunflower	2003 and 2004	C	No irrigation restriction during the growing period
		S-1	Deficit irrigation at early flowering stage (F1 stage)
		S-2	Deficit irrigation at mid flowering stage (F3.2 stage)
		S-3	Deficit irrigation at early seed formation stage (M0 stage)
Bell pepper	2005	C	No irrigation restriction during the growing period
		WS-80	Deficit irrigation at 20% of crop evapotranspiration (ET_{crop})
		WS-60	Deficit irrigation at 40% of crop evapotranspiration (ET_{crop})
		WS-40	Deficit irrigation at 60% of crop evapotranspiration (ET_{crop})
Eggplants	2008	C	No irrigation restriction during the growing period
		WS-V	Deficit irrigation at vegetative growth
		WS-F	Deficit irrigation at flowering stage
		WS-R	Deficit irrigation at fruit ripening stage
Eggplants	2009	C	No irrigation restriction during the growing period
		WS-80	Deficit irrigation at 20% of crop evapotranspiration (ET_{crop})
		WS-60	Deficit irrigation at 40% of crop evapotranspiration (ET_{crop})
		WS-40	Deficit irrigation at 60% of crop evapotranspiration (ET_{crop})

Fig. 3. A view of the automatic weather station and meteorological park at Tal Amara Research Station (courtesy: F. Karam, 2005).

Fig. 4. A view of the experimental field at Tal Amara Research Station (courtesy: F. Karam, 2009).

data via electronic cable to a computer situated in the monitoring unit 500 m apart from the experimental site. Data were stored in an Excel file and were used to compute potential evapotranspiration according to the FAO Penman-Monteith method (ETp-PM), as well as maximum daily vapor pressure deficit (VPD) (Allen *et al*., 1998).

Water was distributed to the plots uniformly and simultaneously using a drip irrigation system, consisting of 16 mm diameter polyethylene (PE) distribution lines with 40 cm spaced drippers, each with an irrigation capacity of 4 L ha^{-1} at a pressure of 100 kPa. Drip irrigation lines were 0.7 m apart, equally spaced in the planting rows. A view of the experimental plots is given in Fig. 4. Water for irrigation was pumped from a 150 m deep well situated within the research station domain and was filtered using a 15 cm diameter screen filter with a 150 mesh screen (0.105 mm opening diameter). Water was stored in an upstream concrete reservoir with a storage capacity of 3750 m^3. Water was then pressurized into a network of DN (nominal diameter) 100 mm distribution pipes. Water flowed to the plots through a manifold (DN 50 mm) instrumented with manual valves, flow meters, pressure regulators, and air vents on each irrigation supply line. The system had fertigation equipment installed in the mainline for applying fertilizers. In addition, a flushing valve was installed at the downstream end of each plot. Irrigations were applied two times a week with typical application depths of about 25-30 mm per irrigation.

Applied irrigation amounts were calculated using the soil water measurements by the digital tensiometers. Actual soil water deficit (SWD) was calculated as:

$$SWD = q_{FC} - \theta_t \qquad ...(2)$$

where, q_{FC} and θ_t are volumetric soil water content at field capacity and at a given time t, respectively. Irrigation volume that should be applied to the soil to restore field capacity was then calculated as:

$$V_1 = SWD \times RD \times A \qquad ...(3)$$

where, V_1 is net irrigation volume (m^3), SWD is the soil water deficit ($m^3\ m^{-3}$), RD is root depth (m) and A is the plot area (m^2). Gross irrigation volume (V_2) was obtained by dividing net irrigation volume (V_1) calculated in Eq. (3) by the irrigation application efficiency at farm level (E_u):

$$V_2 = V_1/E_u \qquad ...(4)$$

E_u is unit farm irrigation efficiency. E_u is the product of the efficiency of the irrigation system (E_{is}) and the distribution uniformity (DU). In our case, E_u was equal to 0.9 (drip irrigation with 95% of irrigation system efficiency and 95% of distribution uniformity).

At physiological maturity, all individual plants in the 1 m^2 sampling quadrates were harvested to determine above ground biomass production (B) and yield (Y). In maize, soybean and sunflower, water productivity was calculated as the ratio of grain/seed yield at dry basis to evapotranspiration (Y/ET) and as aboveground dry biomass (0% humidity) to evapotranspiration (B/ET). In cotton, water productivity at lint-basis (WP_l) was calculated as lint yield to the amount of water evapotranspired from the crop. For bell peppers and eggplants, water productivity was calculated as the ratio of fruit yield at both fresh and dry bases and evapotranspiration. Water productivity was expressed in kg m^{-3} (1 kg m^{-3} = 1 g m^{-2} mm^{-1}).

Results and Discussion

Table 2 illustrates evapotranspiration, yield, biomass and water productivity at yield (WP_y) and biomass basis (WP_b) of the different crops under full and deficit irrigation treatments. Maize seasonal evapotranspiration reached on the lysimeter 952 mm in 1998 and 920 mm in 1999. Average across years, water productivity at grain basis (WP_y) varied from 1.61 kg m^{-3} on the control to 1.66 and 1.87 kg m^{-3} on deficit-irrigated treatments I-80 and I-60, respectively, thus showing increases of 3% and 14%, respectively, with comparison to well-irrigated control. Moreover, average water productivity at biomass basis (WP_b) varied from 2.81 kg m^{-3} on the control to 2.89 and 3.10 kg m^{-3} on deficit-irrigated treatments I-80 and I-60, respectively. Soybean seasonal evapotranspiration totaled 800 mm in 2000 and 725 mm in 2001. Average seed-related water productivity (WP_y) varied from 0.47 kg m^{-3} on the well-irrigated treatment to values from 0.39 to 0.55 kg m^{-3} on deficit-irrigated treatments, while at biomass basis WP_b varied from 1.07 kg m^{-3} on the control to 1.08-1.17 kg m^{-3} on deficit-irrigated treatments. Table 2 shows that average seed yield of deficit-irrigated treatment S1 that had irrigation cutoff at full bloom stage (R2) decreased by 4% with comparison to the control, while WP_y increased by 14%. Average across years (2001 and 2002), cotton evapotranspiration reached 590 mm on the full-irrigated control with average total growing period of 148 days between sowing and boll dehiscence and lint yield of 457 kg ha^{-1}. The highest water productivity at lint basis (WP_l) was encountered in S1 treatment that had irrigation cutoff at first open boll and averaged 1.3 kg m^{-3}, followed by S2 (1.1 kg m^{-3}), S3 (1.0 kg m^{-3}), and the control (0.8 kg m^{-3}). These values are very close to those obtained by Gilham *et al*. (1995) who estimated water productivity of cotton at lint basis to range from 0.3 to 1.0 kg m^{-3}. Sunflower seasonal evapotranspiration attained an average of 729 mm for a total growing period of 130 days from sowing to harvest. Average water productivity at seed basis (WP_y) varied from 0.74 kg m^{-3} on the control to values from 0.71 to 0.83 kg m^{-3} on deficit-irrigated treatments, while at dry biomass basis WP_b varied from 2.73 kg m^{-3} on the control to values ranging from 2.92 to 3.03 kg m^{-3} on the deficit-irrigated treatments. For bell pepper, seasonal evapotranspiration as measured on the weighing lysimeter was 506 mm for a total growing period of 112 days from transplantation to third harvest. Fresh harvested bell peppers on the well-irrigated treatment yielded 28.3 t ha^{-1}, while on deficit irrigated treatment (WS1) they were 31.9 t ha^{-1}. Water productivity at fresh pepper yield varied from 5.92 kg m^{-3} on the control to values varying between 7.16 and 7.78 kg m^{-3} on deficit-irrigated treatments. Eggplants seasonal evapotranspiration reach an average of 580 mm for a total growing period of 120 days from transplantation to harvest. In 2008, the production of fresh eggplants was observed to have its maximum on the control (33.4 t ha^{-1}), while deficit irrigation at vegetative (V), flowering (F) and ripening (R) stages decreased fresh yield by 20-30%. In 2009, deficit irrigation at 80, 60 and 40% of crop evapotranspiration decreased significantly fresh yield, but water productivity was found to increase from 5.73 kg m^{-3} on the well-irrigated control to values between 5.9 and 8.9 kg m^{-3} on the deficit-irrigated treatments.

Results of this long-term research showed that deficit irrigation at mature seeds (R7) in soybean was more profitable compared to full bloom (R2) and seed enlargement (R5). Seed-related water productivity (WP_y) of deficit-irrigated treatments S1 and S3 were higher than the control, but S2 treatment had WP_y 17% lower than the control. On the other hand, results demonstrated that flowering was the most critical stage of sunflower to deficit irrigation and therefore deficit irrigation at this stage should be avoided, while it can be acceptable at seed formation (M0 stage). Deficit irrigation at early flowering (F1 stage) and mid flowering (F3.2 stage) reduced seed yield by 25% and 14%, respectively, with comparison to the control. However, deficit irrigation at early seed formation (M0 stage) was found to increase slightly seed yield in WS3 treatment (5.5 t ha^{-1}) compared to the control (5.63 t ha^{-1}). For cotton, timing deficit irrigation at first open

Table 2. Evapotranspiration, yield, biomass and water productivity at yield (WP_y) and biomass basis (WP_b) of the different crops

Crop	Variety	Year	Treatment	ET (mm)	Yield (t ha^{-1})	Biomass (t ha^{-1})	WP_y (kg m^{-3})	WP_b (kg m^{-3})
Maize(1)	Manuel	1998	Lysimeter	952.0	15.2	28.6	1.60	3.00
			I-100	863.0	14.5	27.3	1.68	3.16
			I-80	664.0	11.6	21.8	1.74	3.28
			I-60	575.0	10.8	18.6	1.88	3.23
		1999	Lysimeter	920.0	13.4	21.5	1.46	2.34
			I-100	833.0	12.8	20.5	1.54	2.46
			I-80	616.0	11.5	17.6	1.86	2.65
			I-60	556.0	10.4	16.5	1.87	2.97
Soybean(2)	Asgrow 3803	2000	Lysimeter	800.0	3.38	7.96	0.42	1.00
			C	720.0	2.82	6.88	0.39	0.96
			S-1	596.0	2.50	5.66	0.42	0.95
			S-2	632.0	1.76	6.21	0.28	0.98
			S-3	647.0	2.57	6.64	0.40	1.03
		2001	Lysimeter	725.0	3.65	8.23	0.50	1.14
			C	652.0	3.59	7.65	0.55	1.17
			S-1	541.0	3.65	6.53	0.67	1.21
			S-2	580.0	2.93	7.38	0.51	1.27
			S-3	567.0	3.43	7.50	0.60	1.32
Cotton(3)	AgriPro AP7114	2001	Lysimeter	-	-	-	-	-
			C	578.0	0.423	-	0.70	-
			S-1	474.0	0.653	-	1.40	-
			S-2	538.0	0.568	-	1.10	-
			S-3	543.0	0.540	-	1.00	-
		2002	Lysimeter	-	-	-	-	-
			C	602.0	0.490	-	0.80	-
			S-1	483.0	0.624	-	1.30	-
			S-2	532.0	0.586	-	1.10	-
			S-3	569.0	0.554	-	1.00	-
Sunflower(4)	Arena	2003	Lysimeter	-	-	-	-	-
			C	688.0	5.46	19.2	0.79	2.79
			S-1	534.0	3.95	16.6	0.74	3.10
			S-2	579.0	4.63	17.6	0.80	3.03
			S-3	629.0	5.59	19.6	0.89	3.12
	Arena	2004	Lysimeter	-	-	-	-	-
			C	769.1	5.26	20.5	0.68	2.67
			S-1	598.0	4.06	16.4	0.68	2.73
			S-2	647.0	4.65	18.2	0.72	2.82
			S-3	700.0	5.41	20.6	0.77	2.95
Bell pepper(5)	Mercury	2005	Lysimeter	506.0	-	-	0.00	-
			C	478.0	28.3	-	5.92	-
			WS-80	427.0	31.9	-	7.47	-
			WS-60	360.0	28.0	-	7.78	-
			WS-40	275.0	19.7	-	7.16	-

Table 2. Cont...

Crop	Variety	Year	Treatment	ET (mm)	Yield (t ha^{-1})	Biomass (t ha^{-1})	WP$_y$ (kg m^{-3})	WP$_b$ (kg m^{-3})
Eggplants⁽⁶⁾	Baladi	2008	Lysimeter	-	-	-	-	-
			C	570	33.0	-	5.79	-
			WS-V	430	21.4	-	4.98	-
			WS-F	490	24.7	-	5.04	-
			WS-R	470	22.1	-	4.70	-
	Baladi	2009	Lysimeter	-	-	-	-	-
			C	590	33.8	-	5.73	-
			WS-80	470	27.7	-	5.89	-
			WS-60	290	19.5	-	6.72	-
			WS-40	150	13.4	-	8.93	-

(1) Karam *et al*. (2003); (2) Karam *et al*. (2005); (3) Karam *et al*. (2006); (4) Karam *et al*. (2007); (5) Karam *et al*. (2009); (6) Karam *et al*. (2009).

boll has been found to provide the highest lint yield with maximum water productivity, in comparison to deficit irrigation at early boll loading and mid boll loading. In addition, results revealed that cotton lint yields were reduced as irrigation amounts increased. For maize, deficit irrigated-treatments at 80% and 60% of crop evapotranspiration produced less seed yield but resulted in higher water productivity than the well-irrigated control. This increase in water productivity might be due to a larger decline in plant transpiration because of reduced green leaf area as a consequence of water stress, which probably has also reduced evaporation from dry soil (Karam, 2003).

In bell pepper, deficit irrigation at 80% of ET$_{crop}$ was recommended to obtain higher yield (32 t ha^{-1}) of fresh bell peppers and higher water productivity (7.47 kg m^{-3}). Relative to plants grown in WS1 treatment, marketable fruit yield and water productivity of the full-irrigated treatment was reduced by 11% by 20%, respectively. For eggplants, obtained results suggested that applying deficit irrigation for 2 weeks prior to flowering (WS-F) resulted in water saving of the same magnitude as the WS-80 treatment (20-25%) with the least yield reduction, while deficit irrigation at vegetative growth (WS-V) and fruit ripening (WS-R) resulted in greater decreases in fresh yield. Even though deficit irrigation at vegetative growth and fruit ripening resulted in significant reductions in fresh yield (30-35%), water productivity was found to decrease by 14-18%, when compared to the full-irrigated treatment.

Through this experimental work, we have learnt that improvement of water productivity requires information not only on water consumption by crops, but also on the sensitivity of crops to water stress. With the ever limitation in water resources for agricultural uses, irrigation strategies that focus on deficit irrigation as a way to optimize water productivity and achieve higher crop yields per unit of irrigation water are advisable in scarce water resources environments (Saeed *et al*., 2008; Domínguez *et al*., 2012a). By eliminating irrigation that has the lower impact on yield, the resulting yield reduction may be small compared with the benefits gained by diverting the saved water to irrigate other crops (English, 1990; English *et al*., 1990; English and Raja, 1996; Kirnak *et al*., 2002; DaCosta and Huang, 2006; Geerts and Raes, 2009). In addition, deficit irrigation has potential benefits resulting from reduced irrigation costs (English and Raja, 1996).

Conclusions

This long-term research demonstrated that a target yield can always be obtained under deficit irrigation. Results showed that while maize has a limited capacity to adjust grain yield in response to water availability, soybean has a high capacity to compensate the effects of water stress applied early-in-the e-season. Cotton, an indeterminate species, has a larger capacity to adjust the number of dehiscent bolls under stressful conditions. Sunflower, was shown to have an aptitude to tolerate moderate water stresses. For bell pepper, a mild water stress can be a good choice to save 20% of irrigation water with an increase of 10% in yield. For eggplants, deficit irrigation resulted in negative effects on fresh yield. However, applying deficit irrigation for 2 weeks prior to flowering resulted in water saving of the same magnitude as reducing water application by 20% with the least yield reduction.

Water savings due to deficit irrigation demonstrate that the reduction in irrigation supply from the well-irrigated strategy permits the allocation of the given supply of irrigation water to a proportional larger area. Hopefully, the findings of this research will offer new opportunities for involving irrigation managers and farmers in adopting deficit irrigation practices in dry regions.

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