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Research Article

Assessment of yield and water use efficiency of drip-irrigated cotton (*Gossypium hirsutum* L.) as affected by deficit irrigation

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Abstract: A field experiment was conducted for 2 consecutive years to evaluate the response of cotton crop to deficit irrigation under drip irrigation conditions. Water use efficiency (WUE), seed cotton yield, and fiber quality parameters were assessed at various irrigation levels. The experiment was set up to apply water at 4 different application rates: 50%, 65%, 80%, and 100% of the soil water depletion. These were abbreviated as DI50, DI65, DI80, and FI, respectively. The total amounts of irrigation water applied were 408 and 773 mm and the average seed cotton yields were 2909 and 5090 kg ha^{-1} for the DI50 and FI treatments, respectively. The highest seed cotton yield was obtained with full irrigation treatment in both years. Values of WUE were 0.65 and 0.70 kg m^{-3} for the FI and DI80 treatments, respectively, in the 2007 season. In the 2008 season, WUE values were 0.65 and 0.72 kg m^{-3} for the FI and DI80 treatments, respectively. The highest values of WUE and irrigation water use efficiency (IWUE) were observed in DI80 (0.71 and 0.75 kg m^{-3}, respectively), and the lowest IWUE in both years was seen with the FI treatment (0.66 kg m^{-3}). The yield response factor (ky) was 1.00 during the entire growing season, based on averages of the 2 years. No significant differences in fiber length, strength, uniformity, elongation, or fineness were observed between the FI and DI80 treatments in the 2008 season. The DI80 treatment showed significant benefits in terms of irrigation water savings and better WUE, indicating an attainable advantage of deficit irrigation employment under water shortage conditions.

Key words: Evapotranspiration, fiber quality, water stress, water use, water-yield relations

Introduction

Crop productivity under irrigated agriculture is usually higher than rainfed dry farming. Like most major field crops, cotton production is adversely affected by water stress (Pettigrew 2004; Dağdelen et al. 2006; Basal et al. 2009). Insufficient soil water content due to water stress during the sensitive growth stages, such as the peak flowering and fruit-setting stages, can lead to a reduced number of fruiting positions, boll shedding, and poorly developed bolls (Aujla et al. 2005). On the other hand, overirrigation of cotton can cause undesired excessive vegetative growth, which may reduce cotton yields (Wanjura et al. 2002; Karam et al. 2006).

Knowing the optimum water requirement of drip-irrigated cotton is essential to achieving a balance between vegetative and reproductive growth in cotton. Fereres and Soriano (2007) reported that substantial water savings could be achieved with little impact on the quality and quantity of the crop yields by using deficit irrigation (DI). Wanjura et al. (2002) found that the maximum yield of drip-irrigated cotton was produced with 740 mm of water, but a 20% deviation from this irrigation level reduced

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yield by only 2.6%. Using 3 irrigation levels and 2 irrigation frequencies on drip-irrigated cotton, Ertek and Kanber (2003) reported that, in a single season, there was no significant difference in yield among crop-pan coefficients of 0.75, 0.90, and 1.05 for a screened evaporation pan. In similar study, Basal et al. (2009) reported that deficit drip irrigation of cotton at 75% of full irrigation requirements did not decrease seed cotton yield or yield components for 2 growing seasons. However, Dağdelen et al. (2006) reported that after irrigating cotton at 5 different rates (full irrigation and 4 deficit rates) for 2 seasons, the total irrigation depth ranged from 257 to 867 mm and the highest yield was obtained with the highest irrigation level.

Cotton acreage increased in Syria from 165,569 ha in 1989 to more than 257,000 ha in 2001, with an average seed cotton yield of 3928 kg ha^{-1} in 2001 (Cotton Bureau Report 2002). However, cotton acreage decreased to 176,000 ha in 2008 due to water shortages (Cotton Bureau Report 2008). Water shortages, increasing production costs, and low water use efficiency (WUE) made the economic profit marginal and challenged the end users. Since cotton is a socioeconomic crop in Syria, increasing the WUE and economic returns requires the adoption of new irrigation methods and management practices.

Until recently, cotton in Syria has been traditionally irrigated by all means of surface irrigation. In the last decade, however, there has been a growing interest in adopting drip irrigation for cotton production (Janat and Somi 2001). Many studies have shown that drip irrigation increased seed cotton yield and WUE significantly, relative to increases obtained with surface irrigation (Janat 2004). In addition, exposing the cotton crop to moderate water stress improved the WUE by almost 15% (Basal et al. 2009).

Achieving greater WUE is a primary challenge and it includes the employment of techniques and practices that deliver irrigation water to the crops more accurately. In this context, a combination of drip irrigation and deficit irrigation may play an important role in increasing WUE. However, to successfully apply DI, an intimate knowledge of crop behavior is required, as crop response to water stress varies considerably. Therefore, the primary objective of this study was to determine the best irrigation level under drip irrigation for optimal yield quantity and quality. A secondary objective was to evaluate the response of other parameters, such as the yield, fiber quality, and WUE of drip-irrigated cotton at different irrigation levels.

Materials and methods

This study was carried out during the growing seasons of 2007 and 2008 at Der-Alhajar Research Station, located southeast of Damascus, Syria (33°21′N, 36°28′E), at 617 m above sea level. The area is located within an arid region in which the total annual precipitation is 120 mm. Some climatic data collected during the course of this study are given in Table 1.

The soil type in the experimental area is sandy clay loam in texture. Water content at field capacity varied from 30.7% to 36.1% by volume, and the wilting point varied from 11.5% to 17.1%. Soil bulk densities ranged from 1.11 to 1.21 g cm^{-3} throughout the 0.6-m soil profile. The total available soil water within the top 0.6 m of the soil profile was 114 mm.

Cotton seeds (*Gossypium hirsutum* L. 'Aleppo-33') were planted on 23 April and 13 April in the 2007 and 2008 seasons, respectively. Plants were thinned to achieve a population density of 9 plants m^{-2}. Irrigation was initiated immediately thereafter with an irrigation interval of 3-4 days. Treatments were designated as full irrigation (FI, which received 100% of the soil water depletion) and those that received 80%, 65%, and 50% of the amount received in the FI treatment on the same day (abbreviated as DI80, DI65, and DI50, respectively). For the FI irrigation, scheduling was carried out using the neutron probe. In the middle of the central row at 0.12 m from the emitter, a neutron probe access tube was installed in each experimental unit. This enabled the monitoring of soil moisture status and provided feedback data for irrigation scheduling. After thinning, the active root depth was 0.30 m until peak flowering. Otherwise, from fruit setting until termination, cotton was irrigated to replenish the extracted water in the upper 0.60 m of soil (Janat 2004). It was also observed by Du et al. (2008) that the main wetting layer for drip-irrigated cotton was approximately 0.40 m below the soil surface in the full-irrigated treatment plots.

Table 1. Climatic data for the experimental years.

Month	T_{min} (°C)	T_{max} (°C)	$T_{average}$ (°C)	RH (%)	Rainfall (mm)
2007					
April	8.6	22.6	16.3	55.6	6.2
May	15.5	31.5	24.0	44.9	24.5
June	17.2	36.0	27.4	43.9	-
July	19.8	37.4	29.4	49.4	-
August	19.2	36.9	27.3	53.8	-
September	17.4	34.3	25.9	50.3	-
October	12.9	27.0	21.5	63.3	-
2008					
April	11.6	28.4	20.6	51.3	-
May	12.5	29.9	22.5	42.9	-
June	17.2	36.5	27.1	41.0	-
July	19.4	37.9	28.7	45.6	-
August	20.4	38.3	29.4	49.6	-
September	18.4	34.5	26.0	47.7	-
October	13.8	27.9	20.7	61.0	6.7

T_{min}: minimum temperature, T_{max}: maximum temperature, $T_{average}$: average temperature, RH: relative humidity.

The experimental unit was 20 × 3.75 m (5 rows per plot). A space of 2.0 m between each plot was maintained in order to minimize water movement among treatments. The drip tape, 16 mm in diameter, had emitters spaced at 0.3 m; the emitter discharge rate was 4 L h^{-1} at an operating pressure of 100 kPa. The dripper interval was determined according to Eq. (1) (Ertek and Kanber 2003):

$$Sd = 0.90 \sqrt{q/I}, \quad (1)$$

where Sd is the dripper interval (m), q is the dripper discharge (L h^{-1}), and I is the infiltration rate (mm h^{-1}), as measured by a cylinder infiltrometer.

Volumes of water applied by irrigation were measured by an inline flow meter. Nitrogen fertilizer (120 kg N ha^{-1}) was injected in 6 equally split applications through the drip system as a solution of urea (46% N) using a proportional-type injector.

Dry matter yield was determined at the physiological maturity stage on the basis of total dry weight of the aboveground vegetative portion only. Different plant parameters, such as plant height and number of mature bolls per plant at the first handpicking, were observed. The seed cotton yield of each plot was determined by 2 handpickings of all treatments in early October, and the second picking was about 10-15 days later for the 2007 and 2008 seasons. All of the harvested seed cotton for each plot was weighed as the final yield in both years, and the earliness percentage was calculated as seed cotton yield at first picking × 100 over total seed cotton yield.

Cotton evapotranspiration (ETc) was calculated using the water balance equation (Kang et al. 2000):

$$ETc = I + P \pm DSW - Dp - Ro, \quad (2)$$

where I is the amount of irrigation water applied (mm), P the precipitation (mm), DSW the soil water content change (mm) in the 0.60-m soil profile, Dp the deep percolation (mm), and Ro the amount of runoff (mm). Since the amount of irrigation water was controlled, runoff was assumed to be zero. Monitoring soil water content in the experimental plots revealed that Dp was negligible below 0.60 m in depth. WUE and irrigation water use efficiency (IWUE) were calculated using the following formulas (Kang et al. 2000):

$$WUE = Y/ETc, \quad (3)$$

$$IWUE = Y/I, \quad (4)$$

where Y is the total seed cotton yield (kg ha^{-1}), ETc is the seasonal evapotranspiration, and I is total irrigation water applied (m^3).

In order to evaluate the sensitivity of the treatments to water stress, yield response factor (ky), defined as the ratio of relative yield decrease to relative evapotranspiration deficit, was calculated from the actual yield (Ya), the maximum yield (Ym), the actual evapotranspiration (ETa), and the maximum evapotranspiration (ETm) using the following formula:

$$1 - Ya/Ym = ky\,(1 - ETa/ETm). \quad (5)$$

Fiber quality indices were determined by a randomly handpicked 20-boll sample collected from each experimental plot and sent for lint testing at the Yarn and Fiber Test Laboratories, Cotton Bureau, Aleppo, Syria. The experimental design was a randomized block design with 6 replicates (Figure 1). All parameters were subjected to analysis of variance (ANOVA), and means were compared using Tukey's HSD test at $P < 0.05$. All statistical analyses were performed using SPSS 11.5 for Windows (SPSS Inc. 2005).

Results

Water use parameters

Soil water content at the soil depth of 0.60 m for the fully irrigated treatment (FI) plot remained close to field capacity after shifting the active root depth to 0.60 m (Figure 2). In general, in the FI treatment, soil water content remained greater when compared with the deficit irrigation treatments (DI80, DI65, and DI50) in both years. Water use parameters of drip-irrigated cotton under different irrigation treatments are shown in Table 2. Values of WUE first increased as ETc decreased, reached a maximum, and then declined again as more severe water deficits reduced the ETc further. The highest WUE was obtained for DI80 in 2007 and 2008, and no significant differences among the other treatments were obtained for either year. Similarly, the highest IWUE was obtained for DI80 for both years, whereas the lowest IWUE was found for FI in both growing seasons. IWUE had higher values than WUE since there was no rainfall during the growing seasons. The amount of irrigation water applied ranged from 405 to 753 mm in the 2007 and 411 to 792 mm in the 2008 season. Seasonal ETc varied between 463 and 762 mm (DI50 and FI treatments) in the 2007 and from 466 to 797 mm (DI50 and FI treatments) in the 2008 season. A ky of 1.00 was obtained based on the averages of the 2 years (Figure 3).

Yield and yield components

Yield components of cotton under different drip irrigation levels are shown in Table 3. Increasing the amount of irrigation water applied improved seed cotton yield for both seasons (Figure 4a). Seed cotton yield varied between 4971 (FI) and 2858 kg ha^{-1} (DI50) in 2007 and from 2959 (DI50) to 5208 kg ha^{-1} (FI) in 2008. A higher portion of cotton was produced at the first picking with the lower water application rate, as indicated by the earliness percentage. Even though seed cotton yield increased with irrigation, the maturity of the crop was delayed for both growing seasons. The delayed crop maturity was demonstrated by the lower earliness percentage in FI. The highest earliness percentage was obtained in DI50 for both growing seasons.

The maximum plant height was observed in FI, and it then decreased as the water application rate decreased. Plant height at first harvest was between 56.8 and 102.0 cm in 2007 and 59.2 and 105.5 cm in 2008, and the differences among treatments were significant ($P < 0.01$). The plotting of seed cotton yield against plant height revealed that there was a

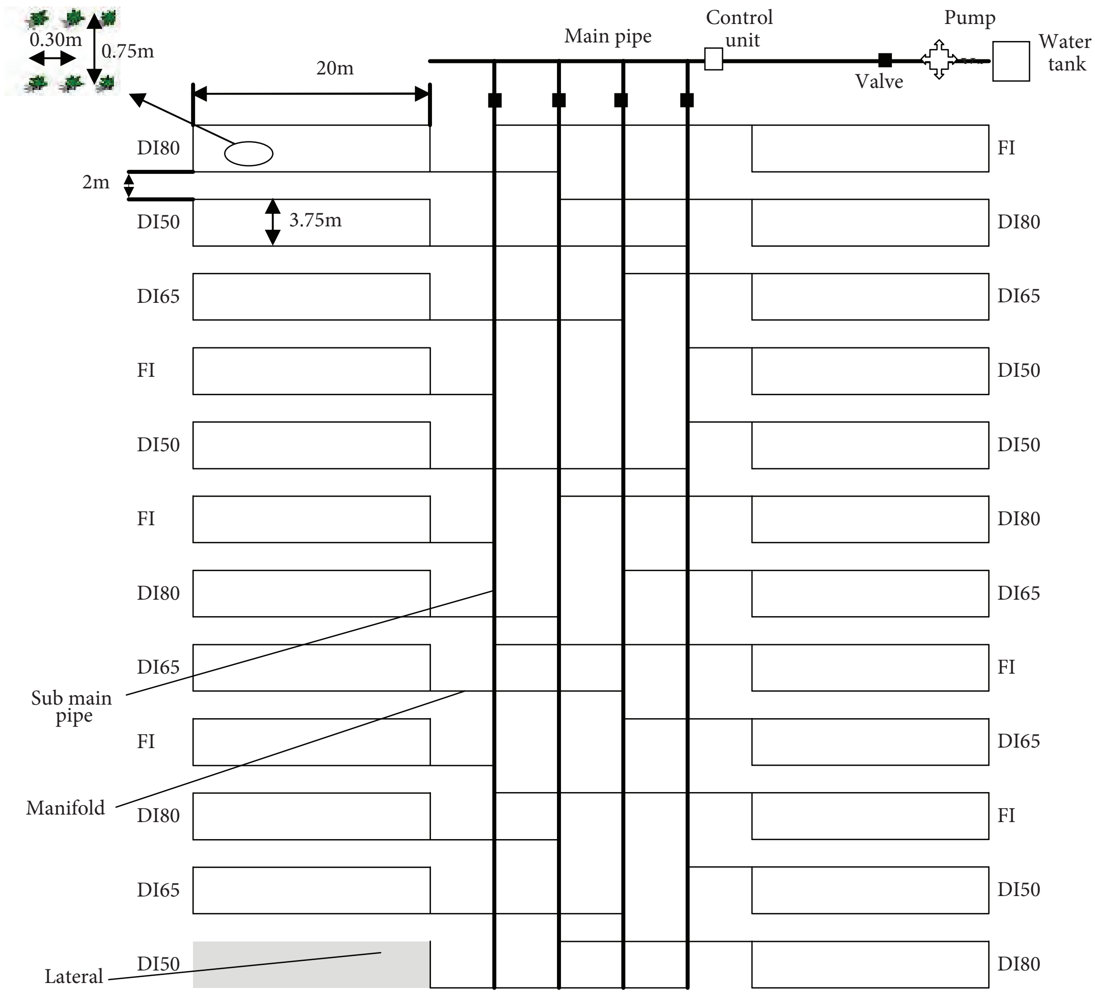

Figure 1. Layout of the experimental design.

strong positive and linear correlation between seed cotton yield and plant height (Figure 4b).

The number of bolls per plant was significantly increased by increasing the rate of irrigation water applied. The FI plants showed the highest number of bolls. The percentage of total bolls for the FI treatment increased by 6%, 19%, and 40% relative to the DI80, DI65, and DI50 treatments, respectively. The reduction in boll number as a result of water stress led to an obvious reduction in seed cotton yield. However, at the time of the first picking for both seasons, there was no significant difference in the number of bolls per plant between the FI and DI80 treatments. Boll weight varied significantly in 2007 only, whereas boll weight for 2008 showed no significant differences among treatments. However, there was a trend toward decreasing boll weight with decreased water application in both years (Figure 5a).

Lint percentage was not affected by different irrigation ratios, and no differences among the treatments were observed in either season. However, a trend of decreasing lint percentage with increased irrigation was observed (Figure 5b). The harvest index (HI, ratio of seed cotton yield to total aboveground biomass) increased as the level of irrigation water applied decreased. However, the differences in HI among treatments were not significant in the 2007 or 2008 growing seasons.

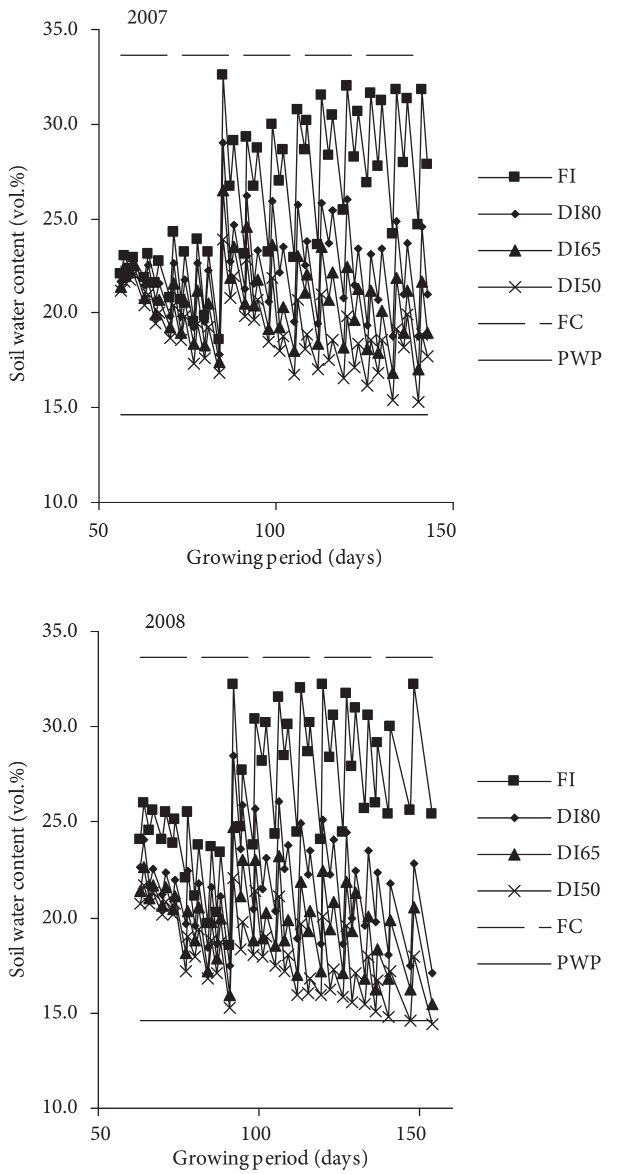

Figure 2. Measured soil water content for different irrigation treatments in 2007 and 2008; FC: field capacity, PWP: permanent wilting point.

Fiber quality

In general, the influence of irrigation level on fiber quality was minimal (Table 4). Cotton fiber quality data indicated that irrigation level had little to no effect on fiber strength (Pressley index and stelometer), uniformity percentage, or fiber elongation. However, there were significant differences in fiber length and fineness among irrigation treatments during the 2007 and 2008 growing seasons. Fiber length increased with increased irrigation water application in both seasons. The highest fiber length was obtained for FI in both seasons. Deficit irrigation treatments also affected micronaire in both growing seasons. Water stress imposed increased fiber micronaire in the 2007 and 2008 growing seasons.

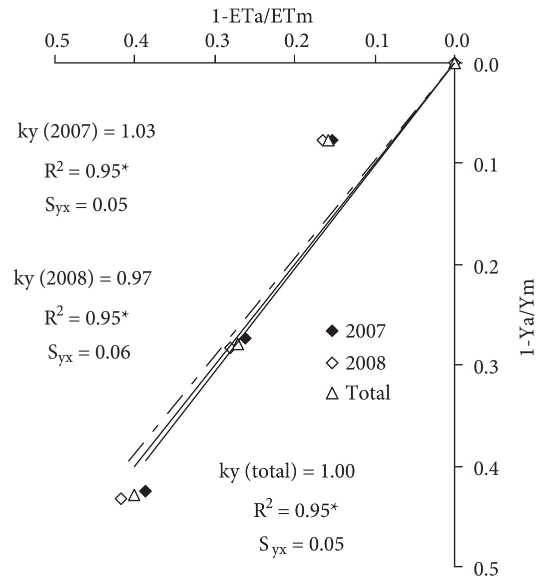

Figure 3. The relationship between relative evapotranspiration deficit and relative yield reduction in 2007 and 2008.

Discussion

Water is the most limiting factor in plant growth and agricultural production in arid areas. In this study, DI maintained high cotton yield when the irrigation amount was reduced by 20%, and, as a result, the WUE was improved. Maintaining control of cotton growth results in a proper balance between leaf production and boll production, attainable through DI (DeTar 2008). Aujla et al. (2008) reported that drip irrigation under paired sown cotton produced similar seed cotton yields during the first year of study, but an increase of 27% was observed during the second year when compared with normally sown cotton. Furthermore, they reported a 25% savings in irrigation water. In addition, Basal et al. (2009) found that deficit irrigation maintained high cotton yields with a 25% reduction in irrigation water applied, which resulted in a substantial increase in WUE.

Our results indicated that the FI treatment produced higher total seed cotton yield than DI

Table 2. Effect of irrigation treatments on water use parameters and yield response factor of drip-irrigated cotton in 2007 and 2008.

Year	Irrigation levels	Irrigation water applied (mm)	ETc (mm)	WUE (kg m^{-3})	IWUE (kg m^{-3})
2007	FI	753	762	0.652 b	0.661 b
	DI80	614	652	0.704 a	0.748 a
	DI65	509	556	0.650 b	0.710 ab
	DI50	405	463	0.617 b	0.706 ab
2008	FI	792	797	0.653 b	0.658 b
	DI80	639	671	0.717 a	0.753 a
	DI65	525	576	0.648 b	0.711 ab
	DI50	411	466	0.635 b	0.720 ab
Mean	FI	773	780	0.653 b	0.659 b
	DI80	627	662	0.710 a	0.750 a
	DI65	517	566	0.649 b	0.710 ab
	DI50	408	465	0.626 b	0.713 ab

For each year, mean values within columns followed by different letters are significantly different at $P < 0.05$.

Table 3. Yield components and harvest index of cotton under different irrigation treatments in 2007 and 2008.

Year	Irrigation levels	Seed cotton yield (kg ha^{-1})	Earliness percentage (%)	Final plant height (cm)	Boll number (per plant)	Boll weight (g)	Fiber percentage (%)	Harvest index
2007	FI	4971 a	83.5 c	102.0 a	10.2 a	6.27 a	40.8	0.307
	DI80	4589 b	89.2 b	88.0 b	9.6 a	5.97 ab	41.3	0.354
	DI65	3615 c	95.0 a	65.8 c	8.3 b	5.70 b	41.7	0.360
	DI50	2858 d	96.6 a	56.8 d	6.3 c	5.63 b	40.7	0.345
2008	FI	5208 a	86.9 b	105.5 a	10.9 a	6.13	40.9	0.306
	DI80	4812 b	89.2 b	92.4 b	10.3 a	6.02	40.9	0.350
	DI65	3733 c	93.1 a	77.7 c	8.8 b	5.72	41.0	0.346
	DI50	2959 d	95.2 a	59.2 d	6.5 c	5.65	41.7	0.338

For each year, mean values within columns followed by different letters are significantly different at $P < 0.05$.

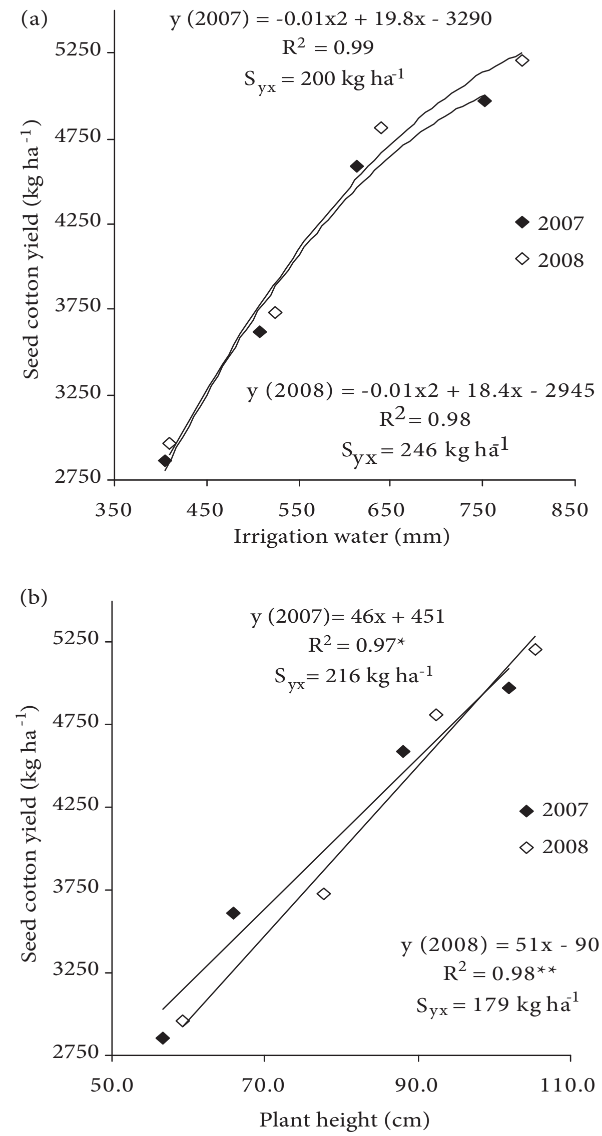

Figure 4. The relationship of seed cotton yield with a) irrigation water and b) plant height in 2007 and 2008.

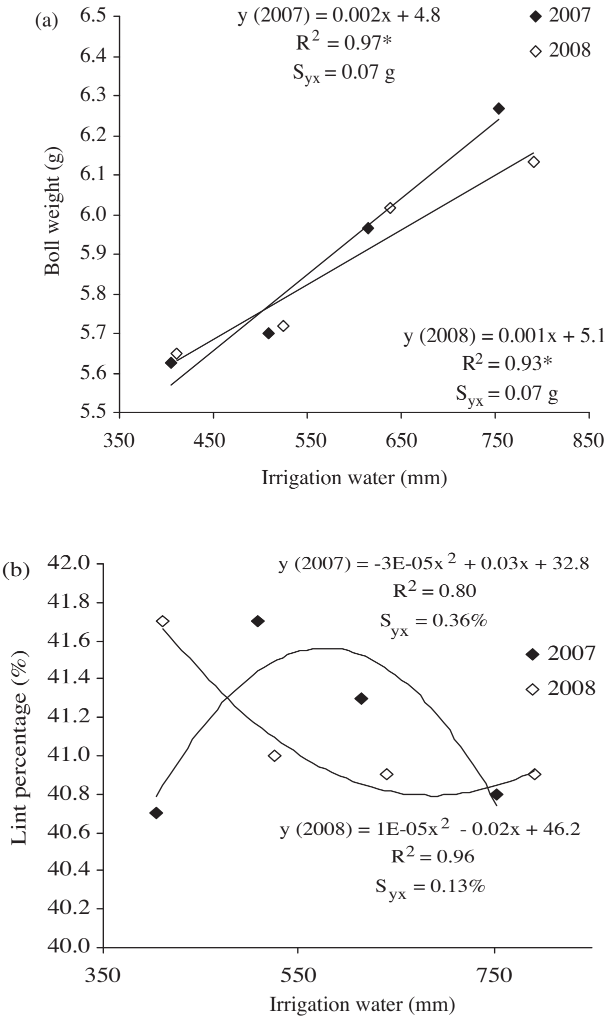

Figure 5. In 2007 and 2008, a) boll weight and b) lint percentage as a function of irrigation water.

treatments averaging 8%, 28%, and 43% for DI80, DI65, and DI50, respectively. However, the WUE and IWUE in the DI80 treatment were higher than those produced with FI in both growing seasons. Deficit irrigation at an 80% level increased the WUE and IWUE by 8% and 13%, respectively, when compared to FI during 2007, and 10% and 14% during 2008. With a marginal reduction in the total yield, the DI80 treatment saved 18.5% and 19.3% of irrigation water in 2007 and 2008, respectively, compared with the FI treatment. This indicated that deficit drip irrigation at around 80% of full irrigation had the potential to save water and could be a proper irrigation level for producing cotton in arid areas. Furthermore, the higher earliness percentage for the DI treatments compared with FI for both seasons indicated that a higher portion of the yield was obtained at the first picking in DI treatments, which could be economically beneficial. The seasonal yield response factors were 0.92 (Dağdelen et al. 2006) and 0.78 (Dağdelen et al. 2009). In this study, an average yield response factor was calculated and found to be 1.00 during the entire growing season.

Similar reports have shown that adequate water supply can increase plant height, number of bolls per plant, boll weight, and seed cotton yields (Pace

Table 4. Fiber quality parameters of cotton under different irrigation treatments in 2007 and 2008.

Year	Irrigation levels	Length (mm)	Uniformity (%)	Pressley index	Stelometer (g tex^{-1})	Elongation (%)	Fineness (micronaire)
2007	FI	31.3 a	52.6	9.7	26.7	4.9	4.5 b
	DI80	30.2 b	53.0	10.1	26.8	5.0	4.7 a
	DI65	29.8 c	52.6	10.2	26.3	4.9	4.8 a
	DI50	29.7 c	52.1	9.9	26.3	4.9	4.8 a
2008	FI	30.5 a	52.2	10.2	28.6	4.5	4.5 c
	DI80	30.2 a	52.4	9.9	28.1	4.4	4.6 bc
	DI65	29.5 b	52.3	10.2	29.3	4.3	4.7 ab
	DI50	29.4 b	52.0	10.2	29.2	4.4	4.8 a

For each year, mean values within columns followed by different letters are significantly different at $P < 0.05$.

et al. 1999; Basal et al. 2009; Dağdelen et al. 2009). In this study, results revealed that cotton plant height, boll number, and weight were controlled by DI. Treatments under DI produced shorter plants, indicating a successful control of vegetative growth in the DI treatments, which is similar to the findings of others (Howell et al. 2004; Pettigrew 2004; Tang et al. 2005; DeTar 2008). However, Aujla et al. (2008) found that cotton plant height was not affected by the quantity of water applied through drip systems.

In general, the amount of irrigation water tended to increase boll production per plant for both growing seasons. Similar trends have been reported for cotton (Ertek and Kanber 2003; Pettigrew 2004; Mert 2005; Onder et al. 2009). Boll weight differed (significantly in 2007 and numerically in 2008) among irrigation treatments, where the highest irrigation water level applied corresponded with the greatest boll mass. Similar results were reported by Gerik et al. (1996) and Basal et al. (2009). However, Pettigrew (2004) found that boll weight did not differ between irrigated and dryland plants. The HI in DI treatments was higher than that of the FI treatment in both seasons. Orgaz et al. (1992) reported that the HI of one cotton cultivar increased significantly over a wide spectrum of water deficits, while the HI of another cultivar did not vary much with water deficits.

Cotton fiber quality is affected by genotype, environment, and the interaction of these 2 factors. The response of lint percentage (gin turnout %) to soil moisture deficits was inconsistent, but, in general, lint percentage decreased with the application of more water. This was similar to the findings of Basal et al. (2009) and Onder et al. (2009), and contrary to those of Pettigrew (2004). Balkcom et al. (2006) reported that cotton produced longer fibers under full irrigated treatment than under all DI treatments. This is similar to the results of this study in both years, except that in 2008 the difference in fiber length between FI and DI80 treatments was not significant. The effect of water stress on fiber length depends on when and for how long the plants have been stressed. Water stress during the fiber elongation stage can shorten fiber length due to a direct mechanical effect on cell enlargement (Pettigrew 2004).

Basal et al. (2009) and, earlier, Pettigrew (2004) reported that any irrigation effect on uniformity was too inconsistent to be definitively assessed. However, our data showed no effect of water level on the uniformity index. The Pressley and stelometer indices (fiber strength) were not affected by different irrigation levels, which is similar to the findings of Pettigrew (2004). Basal et al. (2009) also found no significant differences in fiber strength between fully irrigated cotton and the 75% and 50% levels of irrigation in 1 out of the 2 cultivars tested in their study. Meanwhile, Johnson et al. (2002) reported that fiber strength and available soil water were highly related. Irrigation levels had no effect on fiber elongation in both years, which is in accordance with the findings of others (Pettigrew 2004; Basal et al. 2009). Micronaire increased with increased water stress, which can be attributed to the higher percentage of position 1 bolls on DI plants. There is much inconsistency in reports concerning micronaire response to water stress. Water stress may decrease micronaire (Pettigrew 2004), increase it (Bradow and Davidonis 2000), or have no impact on micronaire at all (Booker et al. 2006). However, numerous studies found that micronaire and irrigation level are negatively correlated (Elms et al. 2001; Balkcom et al. 2006).

In conclusion, full irrigation treatment could be used in areas with no water shortage conditions. Moreover, deficit irrigation at an 80% level produced only marginal yield reduction and had the potential for saving 20% of irrigation water. Consequently, the WUE was improved, indicating a definitive advantage in adopting deficit irrigation for cotton production in arid areas.

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