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Water productivity, growth, and physiological assessment of deficit irrigated cotton on hyperarid desert-oases in northwest China

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ABSTRACT

Critical water shortage and hyperaridity are the principal reasons, limiting cotton cultivation on desert-oases in northwest China. However, if water dearth is effectively managed then these terrains can also add significant contribution in regional and country's total cotton production due to favorable climate. In that perspective, a 2-years (2015–2016) field study was conducted on cultivable southern periphery of Taklamakan desert to optimize water productivity of deficit drip irrigated cotton through evaluating its water use (ETc), growth, and physiology based water relations. Treatments included four drip irrigation regimes based on 100 (D_{100}), 80 (D_{80}), 60 (D_{60}), and 40% (D_{40}) replenishment of depleted water from field capacity. Results revealed that average ETc ranged from 510 mm at 40% to 1079 mm at 100% water replenishment. Crop growth and pre-dawn leaf water potential (ψ_{pd}) successively declined with reducing irrigation amount. Photosynthesis (A), and stomatal conductance (g_s) of D_{80} plants decreased by 15% at squaring and by only 8% at later stages while, this decline was more vigorous under 60 and 40% water replenishments. The 80% irrigated plants resulted in only 13% yield reduction from D_{100} whereas, the average seed cotton yield varied from 2433 kg ha^{-1} in 40% to 4376 kg ha^{-1} under 100% water replenishment. The maximum irrigation, and crop water use efficiencies (IWUE, WUE) were recorded 0.62 and, 0.48 kg m^{-3}, respectively, which reduced with increasing irrigation amounts. In addition, crop growth and physiological attributes showed linear correlations with ETc and irrigation regimes during yield formation. Following economic evaluation, these results suggested that, irrigating cotton up to 80% field capacity would provide the optimum yield and net income with 20% water saving while, D_{60} could save 40% water but, subject to major yield and profit loss. However, if water is sufficiently available then 100% irrigation can be practiced for maximizing cotton productivity and net gains on desert-oases.

1. Introduction

Rapidly growing world population and continuously depleting arable land resources due to urbanization are leading to serious food security threats worldwide while, affecting more seriously to densely populated developing countries (Li et al., 2017). Parallel to food, the world fiber demand is also increasing that needs more cultivable land and water resources to meet these challenges. Cotton (*Gossypium hirsutum* L.) is one of the most important food, feed, and fiber producing crop that is grown on widespread area in the world (Howell et al., 2004). Xinjiang Uyghur autonomous region in northwest China is an important agricultural zone, and the world leader in cotton production due to its promising climate and plentiful sunshine hours per day during crop season. In addition, by contributing 35% share in national, and about 11% in world's cotton production, the region highlights its significance for this crop (Tang et al., 2010). So far, due to higher yield per unit area, an increasing number of farming communities are engaged with cotton cultivation in the region for higher profit and better livelihood (Wang et al., 2014). As, the climate of Xinjiang is supportive for cotton, the total production of this region can be further enhanced by allocating more area to this crop but, limitation of arable land is concerned. In this scenario, the cultivated area in the region is intensively being expanded by continuous conversion of deserts into desert-oases. Nevertheless, the environmental threats to crops including water scarcity, high evaporative potential, negligible amount of rainfall, and persistent drought predominantly remained serious concerns

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within desert ecosystem (Guo et al., 2009; Zeng et al., 2006; Zhang et al., 2017).

Oases on the southern rim of Taklamakan desert, northwest China, is a new and fragile piece of cultivable land that also has great attraction for cotton cultivation due to suitable climate. This terrain can add a valuable contribution in total cotton production of Xinjiang but, its hyperaridity and an extreme shortage of irrigation water are the serious threats to ecological sustainability (Zeng et al., 2006), which forbid the widespread cultivation of cotton. However, the use of widely adopted deficit irrigation is the most feasible approach to be used for cotton production under such an extreme and water deficit conditions without disturbing ecosystem's stability (Fereres and Soriano, 2007; Howell et al., 2004; Oweis et al., 2011; Ünlü et al., 2011). In deficit irrigation practice, cotton is irrigated below 100% of its evapotranspirational requirement that optimizes yield within irrigation limits by limiting subsoil drainage and percolation (Fereres and Soriano, 2007; Oweis et al., 2011). Since, cotton grows in an indeterminate pattern (Quisenberry and Roark, 1976), its growth rate, biomass accumulation, leaf area, and gas exchange activities are adversely affected by deficit irrigation (Pettigrew, 2004). Photosynthesis is the most important physiological process that determines crop growth and final yield, is highly susceptible to water deficit stress (Deeba et al., 2012; Raines, 2011; Yi et al., 2016). Despite of that, numerous studies have reported the significance of deficit irrigation for cotton under water limited conditions. According to Zhang et al. (1999), a significant quantity of irrigation water can be saved under drought situation by limiting water use with a minimal influence on crop yield. Later, Fereres and Soriano (2007) also reported that deficit irrigation is potentially an efficient technique not only for enhancing water productivity, but also for profitable farm income.

In Xinjiang, mulched drip micro irrigation is commonly used on large scale for cotton cultivation, as, it saves enough water and enhances water productivity (Ibragimov et al., 2007; Wang et al., 2013). Yet, in those regions where aridity and water scarcity issues are more challenging, there, water saving, and use efficiency can be further improved by switching from full to the deficit drip scheme. In that perspective, Thind et al. (2008) found that deficit drip irrigated cotton ensures 25% more water saving with better yield than normal practices. Besides, Dağdelen et al. (2009) and Ünlü et al. (2011) evaluated water use efficiency and yield of cotton using deficit drip irrigation regimes and proposed 75% and 70% levels as optimum for arid and semiarid Mediterranean regions, respectively. Singh et al. (2010) reported that reduced irrigation is the best alternative under water shortage conditions while, 100% water supply gives the maximum net returns, if water availability is of no concern. Later on, Oweis et al. (2011) concluded that, though a negligible yield loss has to be sacrificed but, deficit drip irrigation proved to be an appropriate technique for cotton in water limited regions. Even, several other similar crop water management studies from Xinjiang northwest arid region of China have also reported the improved water use efficiency and profitability of cotton with more water saving under deficit drip irrigation technique (Guan et al., 2013; Kang et al., 2012; Wang et al., 2014; Wang et al., 2013; Yang et al., 2015). As, it is obvious from earlier studies that water limitation in arid regions is a critical issue against profitable cotton production, thus, in desert ecosystem, the situation could be more challenging. However, it was needed to optimize yield and water use efficiency of cotton on a very important cultivable southern rim of the Taklamakan desert through evaluating its growth and physiological based water relations. Since, despite of favorable climate, none of the literature has reported cotton cultivation and agricultural water management studies from this terrain.

The particular objectives were to; (1) examine physiological traits including rate of photosynthesis, stomatal conductance, leaf water potential, and growth response such as leaf area index, crop growth rate, and biomass accumulation, and (2) determine seed cotton yield, yield response factor (k_y), consumptive water demand (ETc), water use efficiencies (WUEs), and yield-ETc relations of deficit drip irrigated cotton under desert ambiance. The outcome of this study would provide necessary information that would help in successful and sustainable cotton production on cultivable terrains of desert ecosystems and in those regions where extreme water scarcity and high evapotranspiration persist due to global climate change.

Table 1
Long term and experimental year's monthly climate data of study site.

Years	Months	T_{max} (°C)	T_{min} (°C)	$T_{avg.}$ (°C)	Rainfall (mm)	R.H (%)
2000–2014	April	24.33	8.09	16.21	0.0	27.0
	May	29.79	12.91	21.35	4.4	32.2
	June	33.92	17.08	25.50	3.7	39.4
	July	38.05	19.42	28.74	1.9	44.7
	August	35.12	18.33	26.73	9.6	55.3
	September	26.83	9.86	18.35	20.8	53.8
	October	20.18	2.92	11.55	0.0	47.1
2015	April	25.89	7.31	16.60	0.0	25.3
	May	30.35	12.76	21.56	5.6	33.1
	June	31.90	15.19	23.55	7.2	38.7
	July	36.90	18.37	27.64	3.8	41.6
	August	32.75	18.39	25.57	0.2	44.1
	September	27.72	10.37	19.05	17.4	52.9
	October	23.22	3.24	13.23	0.0	46.2
2016	April	26.70	10.51	18.61	0.0	26.4
	May	30.14	14.03	22.09	3.4	34.8
	June	34.73	18.35	26.54	1.8	33.2
	July	35.26	18.54	26.90	1.2	41.6
	August	32.07	16.83	24.45	21.8	59.5
	September	28.17	10.91	19.54	29.1	51.7
	October	22.72	3.88	13.30	0.0	44.0

T_{max}, T_{min} and T_{avg}: maximum, minimum, and average temperature, R.H: relative humidity.

2. Materials and methods

This field experiment was carried out on Cele National Station of Scientific Observation for Desert-Grassland Ecosystem (36°51′30″N, 80°44′28″E), Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, during growing seasons of 2015 and 2016. The study area is located on southern rim of the Taklamakan desert, northwest China, which is a warm temperate zone with a continental desert climate. Its mean annual temperature and the maximum evaporative potential are 11.9 °C and 2595 mm, respectively, while, the long term and experimental year's monthly data for climate are provided in Table 1, which were obtained from a metrological unit of the Cele Desert Research Station. The soil type of experimental site was classified as loamy sand/Aeolian sand, and its physical and chemical properties are listed in Table 2.

2.1. *Plant material and experimental layout*

Cotton crop was planted on 20th and 15th of April during 2015 and 2016, respectively, under super high density planting technique, in which the cotton plants are raised in narrow spaces in order to maintain high population density (approx. 200,000 plants ha^{-1}). To check the sideways seepage losses, plastic sheets were installed around each trial unit up to 1.2 m depth. Plants were grown in 30 and 60 cm alternate row spacing with 10 cm planting distance (Fig. 1). Drip lines with inter-emitters distance of 10 cm, were placed between the narrow rows (30 cm) under thin plastic film. The quantities of N:P:K fertilizers used in this trial were 240:120:60 kg ha^{-1}, respectively. All phosphorus (P_2O_5) as di-ammonium phosphate (DAP) and potassium as K_2SO_4 were mixed in soil just before plantation, while nitrogen in the form of urea was dressed at four intervals (¼ at sowing, ¼ at first irrigation, ¼ at squaring, and ¼ at boll formation). Weeds were controlled manually on

Table 2
Soil physical and chemical properties.

Soil layers (cm)	Soil type	F.C (%)	PWP (%)	B.D ($g\,cm^{-3}$)	Total N ($g\,kg^{-1}$)	Total P ($g\,kg^{-1}$)	Total K ($g\,kg^{-1}$)
0–30	LS	19.63	5.0	1.19	0.208 ± 0.05	0.79 ± 0.03	12.71 ± 0.17
30–60	LS	21.09	5.5	1.23	0.179 ± 0.03	0.86 ± 0.04	12.53 ± 0.15
60–90	LS	22.31	6.2	1.25	0.147 ± 0.05	0.80 ± 0.02	14.32 ± 0.22

LS: loamy sand, F.C: field capacity of soil, PWP: permanent wilting point of soil, B.D: soil bulk density, and NPK for total nitrogen, phosphorous, and potassium, respectively.

three instances during the entire growing seasons.

2.2. Irrigation treatments and field measurements

Four drip irrigation levels D_{100}, D_{80}, D_{60} and D_{40} were evaluated in this trial, based on replenishment of depleted soil water from field capacity. Dağdelen et al. (2009) defined depletion as, the difference between soil water content at field capacity and the actual amount of water in rhizosphere at the time of next irrigation. Usually, in normal conditions, cotton crop is irrigated when 40–50% of soil water from field capacity has been evapotranspired (Doorenbos and Kassam, 1979). In the present experiment, when soil water content in control plots reduced to 50% field capacity (FC), then next irrigation was replenished to each treatment as per set criteria. Thus, at each irrigation event, the control plots were irrigated up to 100% field capacity while, the stressed plots were replenished with 80, 60, and 40% of the volume of water applied in control. For that purpose, water depletion from root zone was monitored through regular soil sampling from 30, 60, and 90 cm soil profile on weekly basis and soil water content was determined by gravimetric method (105 °C, 24 h) (Fig. 2). The volume of irrigation applied to each treatment was quantified using equation of Karam et al. (2006) with significant modifications.

$$V = (Dep \times A) \times R \qquad (1)$$

Where 'V' is the volume of applied irrigation (mm), 'Dep' water depletion (mm) from trial units, which is mainly caused by evapotranspiration, 'A' indicates land area of each treatment (m^2), and 'R' is the fraction of water to be replenished (%). Each trial unit received measured amount of water through drip irrigation system equipped with flow measuring gauges (water flow meter). Cumulatively, the treatments D_{100}, D_{80}, D_{60} and D_{40} received irrigation amounts 1040, 832, 624, and 416 mm, respectively, in 2015 and 936, 748, 561, and 374 mm, respectively, during 2016. Water depletion through evapotranspiration from cotton fields was estimated using soil water balance equation of Heerman (1985).

$$\mathrm{ETc} = \mathrm{IR} + \mathrm{P} - \mathrm{DP} \pm \Delta\mathrm{W} \qquad (2)$$

Where; ETc, IR, P, DP, and ΔW, are crop evapotranspiration (mm), applied irrigation amount (mm), total amount of precipitation (mm), amount of deep percolated water (mm), and the change in moisture content below 1.0 m soil depth, respectively. The excess amount of water from field capacity in 0–0.9 m soil profile was recorded as deep percolation (Kanber et al., 1993), and it was equal to zero because, no change in soil water content below 1 m soil depth was observed before and after irrigation. However, net change in soil water content (ΔW) below 1.0 m depth, between the times of plantation to harvesting was considered as ground water contribution. It was recorded through moisture analysis from 1.0 m depth prior to sowing and after harvesting of crop.

2.3. Physiological measurements

The response of physiological traits under extreme desert environment was essential to be known to understand their relationships with crop evapotranspiration (ETc) and yield formation. For that reason, the photosynthetic rate (A) ($\mu mol\,m^{-2}\,s^{-1}$) and stomatal conductance (g_s) ($mmol\,m^{-2}\,s^{-1}$) were measured at three critical growth stages (squaring, peak bloom, and boll formation) using LI-COR Li-6400 portable photosynthetic system by following the protocol of White and Raine (2009). Except squaring, the other two growth stages arrived at different times in all treatments. Blooming and boll formation stages arrived 5 and 8 days, respectively, earlier in D_{40} plots than control. For that reason, these physiological parameters were measured separately from each treatment when it reached the specified growth stages. The measurements were made on young fully expanded photosynthetically active leaves between 11:00 am to 12:30 pm, one day before stress relief (irrigation). Quantum flux for the device was adjusted as per clear sunny conditions and sunlight was used as light source for IRGA sensor head. Reference CO_2 and block temperature were set at 400 $\mu mols\,mol^{-1}$ CO_2 and 25 °C, respectively (Yi et al., 2016). Pre-down leaf water potential MPa at squaring, peak bloom and boll forming stages was measured through pressure chamber (SKPM 1400; Skye Instruments, Llandrindod Wells, UK) technique of Boyer (1967) as described by Argyrokastritis et al. (2015) and Yi et al. (2016).

2.4. Measurement of growth, yield, and water use efficiencies

For the measurement of periodic changes in growth attributes, destructive sampling of cotton plants was initiated at early squaring and continued fortnightly till first picking. Total dry matter (TDM) $kg\,m^{-2}$ and leaf area index (LAI) $m^2\,m^{-2}$ were measured by oven dry method (72 °C, 72 h) and Li-Cor portable leaf area meter, respectively. Later, TDM data were subjected to further calculations for crop growth rate (CGR) $g\,m^{-2}\,d^{-1}$ measurement. The purpose of measuring growth

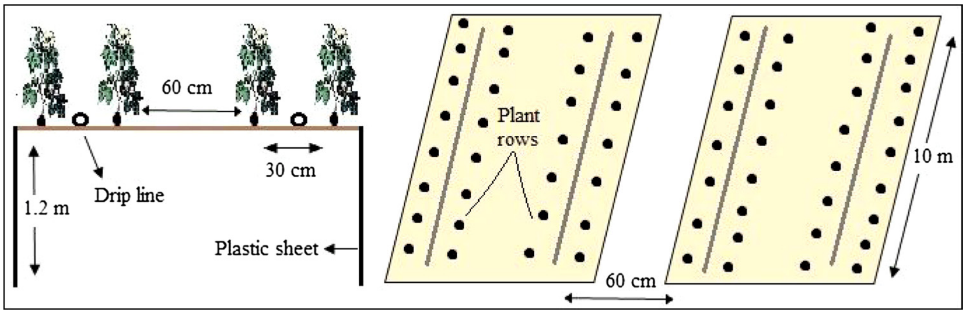

Fig. 1. Field layout of the experiment showing planting geometry and drip lines orientation.

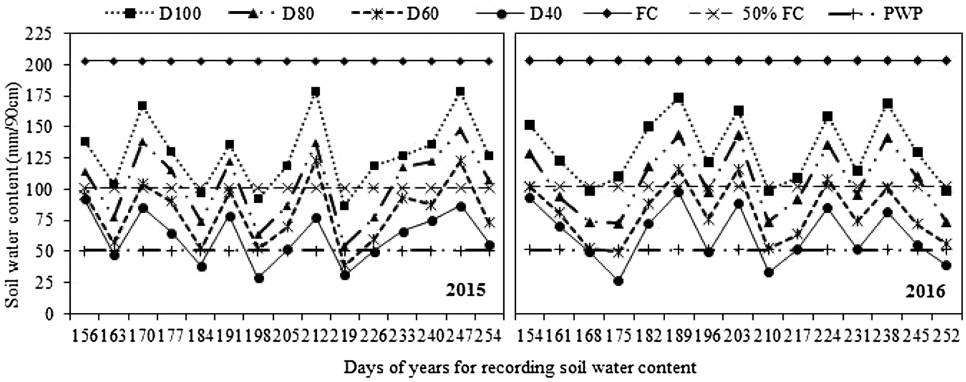

Fig. 2. Weekly changes in soil water content under different drip irrigation regimes during the experimental years. Data presented here are the means of three sampling depths (30, 60, and 90 cm) of each experimental unit. When the soil moisture in D_{100} declined to 50% FC then next irrigation was applied to all treatments, accordingly.

parameters was to evaluate leaf area development and biomass accumulation rates under desert environment and, their correlations with ETc and final yield. Length of crop season under D_{60} and D_{40} was 13 and 15 days, respectively, shorter than D_{100}. However, two hand pickings were made on September 10 and October 02 from each trial unit to quantify seed cotton yield during both trial years. Yield response factor (k_y) was calculated using Stewart's equation (Stewart et al., 1977) as described by Dağdelen et al. (2009).

$$\left(1-\frac{Y_a}{Y_m}\right)=k_y\left(1-\frac{ET_a}{ET_m}\right) \tag{3}$$

In this model equation, Y_a and Y_m are the actual and maximum yields while ET_a and ET_m are the actual and maximum evapotranspiration, respectively. Whereas, 1-(Y_a/Y_m) and 1-(ET_a/ET_m) as a whole expresses the relative yield reduction and evapotranspiration deficits, respectively. The water use efficiency WUE and irrigation water use efficiency IWUE were calculated according to definitions of Zhang et al. (1999).

$$WUE=\frac{Y}{ET} \tag{4}$$

$$IWUE=\frac{Y}{IR} \tag{5}$$

Here, Y is the total yield (kg ha^{-1}) while, ET and IR are the total seasonal evapotranspiration and applied irrigation amounts, respectively.

2.5. Statistical design and data analysis

The treatments were arranged in a randomized complete block design (RCBD) with four replicates. The replications data of each treatment were collected and statistically analyzed using windows application "*Statistix*" v.8.1 (Tallahassee, Florida, USA). The values were expressed as means of four replications with coefficient of variance (CV), and standard error for difference in means (SED) following Fisher's analysis of variance (ANOVA) technique. Subsequently, the least significant difference (LSD) test was applied to treatment means for ranking and comparison at probability $P < 0.05$.

3. Results and discussion

3.1. Crop water use (ETc), yield, and stress response factor (ky)

Data presented in Table 3, summarize the applied irrigation amount, consumptive water use (ETc), water use efficiencies, and obtained seed cotton yields under deficit irrigation treatments, for the years 2015 and 2016. Total amount of rainfall during 1st and 2nd season was recorded 34.2 and 57.3 mm, respectively (Tables 1 and 3). The occurrence of comparatively higher rainfall during 2016 was exceptional, however, it saved one irrigation event. Consequently, the total quantity of irrigation applied in 2016 was lower than the preceding year. The total volume of applied irrigation calculated for both trial years varied between 416 to 1040 mm and 374 to 936 mm, respectively. Comparatively, the irrigation applied to cotton on desert-oases was higher than other regions that can be attributed to extremely dry weather, poor water holding capacity of soil, and frequent wind storms, which facilitated the rapid evaporative loss (Zeng et al., 2006). Likewise, due to high evaporative potential of desert environment, the seasonal crop water use (ETc) was also high that varied from 535 to 1120 mm in the first and 485 to 1037 mm in second season (Table 3). As, it has been already articulated that the occurrence of rainfall in desert-oases was negligible and crop mainly depended on supplemented irrigation, thus, the amount of seasonal irrigation was significantly higher than reported from other regions. Evidently, the irrigation volume and ETc for drip irrigated cotton (708 and 753 mm) reported by Dağdelen et al. (2009), (790 and 878 mm) by Oweis et al. (2011), and (68–383 and 287–584 mm) by Ünlü et al. (2011) from Mediterranean conditions of Turkey, and (498 and 678 mm) by Yang et al. (2015) from Northwest China are significantly lower than the present study. However, cotton compensated its relatively higher water consumption with justifiable seed cotton yield. The maximum yield of 4325 and 4427 kg ha^{-1} was obtained from full irrigation treatment that was followed by D_{80} (3765 and 3870 kg ha^{-1}), and the lowest 2330 and 2536 kg ha^{-1} was recorded from D_{40} in 2015 and 2016, respectively. These results were in line with Papastylianou and Argyrokastritis (2014) (4402 kg ha^{-1}), Onder et al. (2009) (4330 kg ha^{-1}), and Wang et al. (2013) (4674 kg ha^{-1}), respectively. Although, 80% irrigated plants received 20% less water, but they showed better adaptation and reduced yield by only 13%, because, they compensated evapotranspirational deficit by effective use of ground water, which is obvious from ΔW values in Table 3. On the other hand, yield decline under D_{60} and D_{40} was recorded up to 30 and 45%, respectively, that would be due to accelerated shedding of squares and premature bolls due to increasing water deficit stress (Cetin and Bilgel, 2002). Regression analysis indicated a significant linear relationship between seed cotton yield and ETc (Fig. 3a,b) at 5% probability with R^2 values of 0.99 and 1.00 for both crop seasons, respectively. In the same way, yield was also linearly correlated with applied irrigation amount having coefficient of determinant (R^2) 0.99 for both trial years (Fig. 3a, b). These interactions provide a clear understanding on relationship between the amounts of produce per unit of water consumed (ETc), and the amount of water applied. The straight regression lines showing the maximum seed cotton yield at 100% water replenishment are consistent with regression values of Oweis et al. (2011), Dağdelen et al. (2009), and Ünlü et al. (2011) for deficit drip irrigated cotton. Hence, this relationship proves a famous saying "transpiration is a necessary evil", which means that for higher yield, the plant must transpire more water that would eventually need more irrigation.

Crop yield response to water stress (*ky*) indicated a linear increase in relative yield loss ($1 - Y_a/Y_m$), with relative increase in evapotranspiration deficit ($1 - ET_a/ET_m$) (Fig. 4). The slope of regression

Table 3
Seasonal crop water use, seed cotton yield, and water use efficiencies of deficit drip irrigated cotton for the experimental years. The values are means of four replications.

Year	Treatments	Irrigation events	Total IR (mm)	Total P (mm)	ΔW (mm)	Water saving (%)	Water use ETc (mm)	Seed cotton yield (kg ha^{-1})	Relative yield (%)	WUE kg m^{-3}	IWUE kg m^{-3}
2015	D_{100}	10	1040	34.20	46.12 d	0	1120 a	4325 a	100	0.39	0.42 c
	D_{80}	10	832	34.20	89.43 b	20	956 b	3765 b	87	0.39	0.45 bc
	D_{60}	10	624	34.20	94.37 a	40	753 c	3037 c	70	0.41	0.49 b
	D_{40}	10	416	34.20	85.19 c	60	535 d	2330 d	54	0.44	0.56 a
	SED				1.65		1.73	172		0.024 ns	0.030
	CV				2.96		0.28	7.27		8.44	8.93
2016	D_{100}	9	936	57.30	43.52 c	0	1037 a	4427 a	100	0.43 c	0.47 d
	D_{80}	9	749	57.30	68.29 a	20	874 b	3870 b	87	0.44 bc	0.52 c
	D_{60}	9	562	57.30	64.41 a	40	683 c	3206 c	72	0.47 b	0.57 b
	D_{40}	9	374	57.30	53.11 b	60	485 d	2536 d	57	0.52 a	0.68 a
	SED				2.20		2.23	84		0.015	0.020
	CV				5.41		0.40	3.40		4.75	4.80

IR: irrigation, P: precipitation, ΔW: change in soil water content below 1 m soil depth, WUE: crop water use efficiency, IWUE: irrigation water use efficiency, ns: nonsignificant, CV: coefficient of variance, SED: standard error for difference of means.
The values with different letters are significantly ($P < 0.05$) apart according to LSD test. The LSD values for ΔW, ETc, seed cotton yield, WUE, and IWUE are 3.73, 3.92, 391, 0.055, 0.068 and 4.97, 5.04, 190, 0.035, 0.042 for the year 2015 and 2016, respectively.

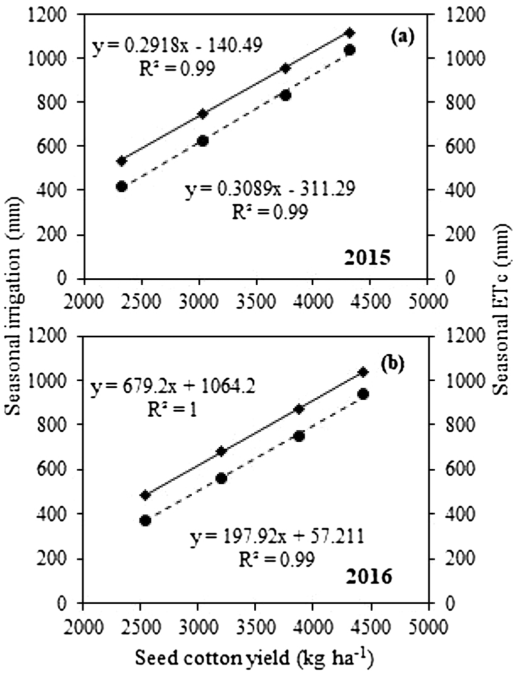

Fig. 3. Correlations of seed cotton yield with applied irrigation amount (dotted line) and the seasonal crop evapotranspiration (solid line) for the year 2015 (a) and 2016 (b). The relationships have been drawn separately for each trial year that clarified a linear increase in seed cotton yield with the increasing irrigation volume and seasonal ETc.

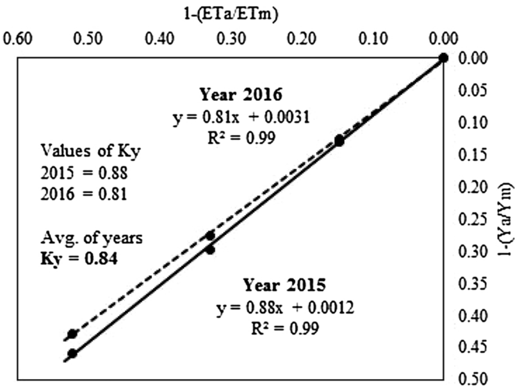

Fig. 4. Yield response factor (*ky*) for deficit drip irrigated cotton under hyperarid desert environment. The *ky* value has been obtained from the mean values of two years data at 5% probability. The continuous line indicates response for year 2015, and the dotted line for 2016.

between relative ET and yield, determined the value of *ky* 0.84 (average of two years). Statistically, this relationship was found significant at 5% probability. According to FAO manual No.56, *ky* is a coefficient that describes relative yield loss due to decline in ETc caused by soil water deficit. The value of *ky* obtained in this study was in agreement with 0.86 and 0.87 reported by Kanber et al. (1996) and Singh et al. (2010) for sprinkler and deficit drip irrigated cotton, respectively. On the other hand, Dağdelen et al. (2009) and Yang et al. (2015) determined comparatively lower values of *ky* (0.78 and 0.65) for drip irrigated cotton in western Turkey and Northwest China, respectively. In the present study, relatively higher value of *ky* could be attributed to hyperaridity and high evaporative potential of desert ambiance that caused more relative yield loss proportional to relative decrease in ETc. In the line of that, it has been formerly reported that, *ky* closer or equal to or greater than unity indicates relative yield reduction proportionately greater than relative decline in crop evapotranspiration (Kirda, 1999).

3.2. Water use efficiency and irrigation water use efficiency

Average water use efficiency (WUE) of both years, ranged from 0.41 to 0.48 kg m^{-3}. Statistically, all treatments performed at par during 2015, whereas, in the following year, deficit water supplies affected WUE significantly ($P < 0.05$). This difference in response between two years can be attributed to significant difference in amount of precipitation during both study years (Tables 1 and 3). In 2016, the highest WUE 0.52 kg m^{-3} was recorded for the lowest irrigation (D_{40}) while, it gradually decreased with increasing irrigation amount, so, the minimum 0.42 kg m^{-3} was recorded from fully irrigated (D_{100}) plots (Table 3). WUE usually indicates the actual yield of a particular crop with respect to amount of water consumed in ETc including irrigation and precipitation (Singh et al., 2010). Thus, it decreases with increasing irrigation volume, which is obvious from Table 3 of the present study. Consistent with these observations, Rao et al. (2016) reported water productivity in the range of 0.38–0.41 kg m^{-3} for deficit irrigated cotton, and Ünlü et al. (2011) reported 0.59 kg m^{-3} (four years average) for well-watered cotton crop. This increase in WUE of deficit drip irrigated cotton would be due to better utilization of ground water by cotton crop under soil water deficit (Rao et al., 2016). Similarly, irrigation treatments significantly ($P < 0.05$) influenced irrigation

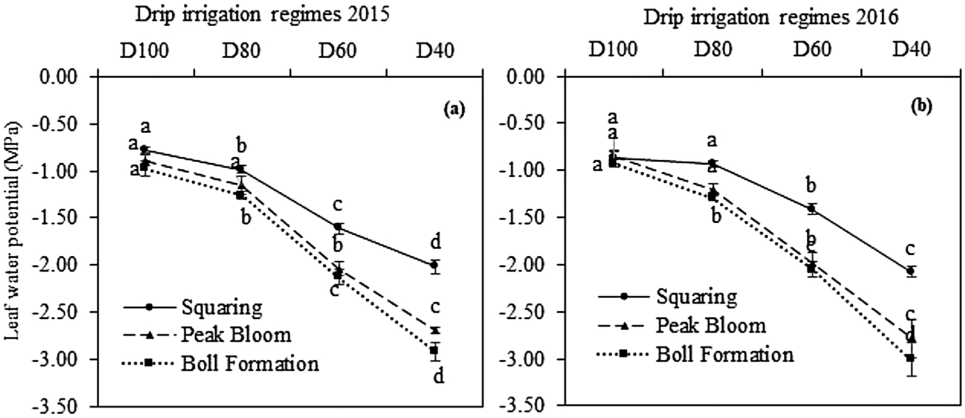

Fig. 5. Effect of deficit drip irrigation on LWP of desert grown cotton at three critical growth stages.The values are means of four replications with standard errors (±) of means. The markers with different letters are significantly apart from each other according to LSD test at 5% probability.

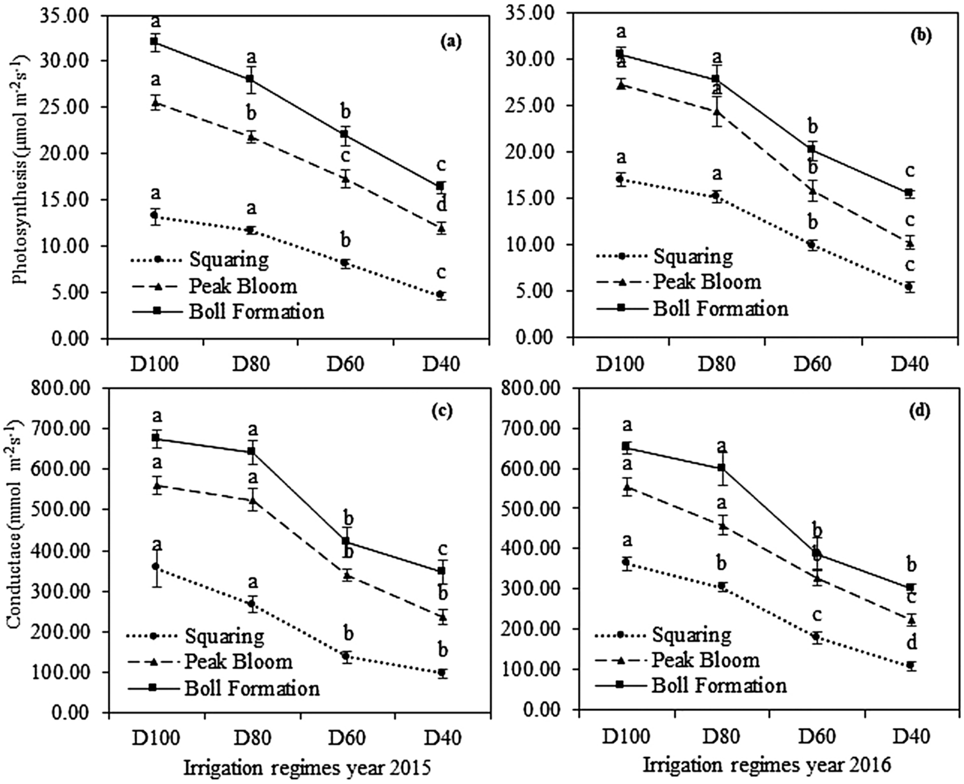

Fig. 6. Effect of deficit drip irrigation on rate of photosynthesis (a, b) and stomatal conductance (c, d) of cotton at three critical growth stages under desert environment. The values are means of four replicates with standard errors (±) of means. Markers with different letters are significantly apart from each other according to LSD test at 5% probability.

water use efficiency (IWUE) of cotton during both crop seasons. The highest IWUE of 0.56 and 0.68 kg m^{-3} was recorded for D_{40}, and the lowest 0.42 and 0.47 kg m^{-3} for well-watered (D_{100}) plots during 1st and 2nd season, respectively. In the present study, the maximum IWUE of cotton was substantially lower than 0.98, 0.81, and 0.81 kg m^{-3} of Dağdelen et al. (2009), Singh et al. (2010), and Kang et al. (2012), respectively. This could be attributed to mighty evaporative potential and hyperarid conditions of desert, due to which the crop irrigation water demand was significantly higher, that resulted the consequences (Table 3). However, Wang et al. (2013) reported quite similar results from deficit irrigated cotton, when they applied stress on late flowering stage.

3.3. Physiological attributes and water stress relations

It is clear from Fig. 5a, and b that deficit drip irrigation supplies significantly affected ($P < 0.05$) leaf water potential (LWP) at each growth stage during the trial years. At squaring, the value of LWP in D_{40} treatment was comparatively less negative than respective stages due to high residual soil moisture during that crop stage. However, at every later growth stage, the LWP of highly stressed (D_{40}) plants was significantly more negative than relatively more irrigated plants, and it reached the minimal values of −2.91 and −3.01 MPa in 2015 and 2016, respectively. In recent investigations, Loka and Oosterhuis (2014) and, Argyrokastritis et al. (2015) reported the maximum negative values of leaf water potential −3.23 and −2.41 MPa, respectively for drought stressed cotton, which are in agreement with these results. This reduction in LWP under reduced water supplies can actually be attributed to reduced conductance of xylem due to soil water deficit stress. Accordingly, Tang et al. (2010) have also reported the reduced xylem flow under soil water deficit and its consequences on LWP and rate of transpiration. Overall under 80% water replenishment, the LWP was moderately reduced that could be due to effective use of groundwater by these plants (Table 3) to compensate their turgor loss.

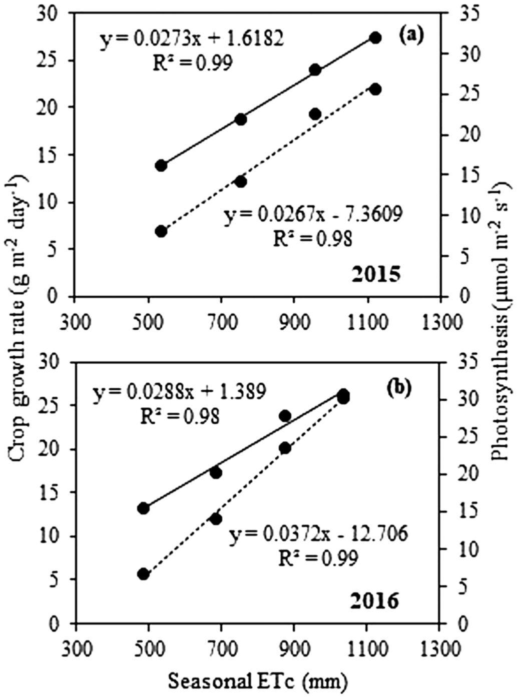

Fig. 7. Correlations of seasonal evapotranspiration with photosynthesis (solid line) and crop growth rate (dotted line) for the year 2015 (a) and 2016 (b). The relationships have been drawn separately for each trial year that clarified a linear increase in growth and photosynthetic rates of cotton with increasing crop evapotranspiration.

Likewise, substantial decline ($P < 0.05$) in photosynthetic performance of cotton was also observed at three critical stages (squiring, peak bloom, and boll formation) with increasing the irrigation deficit stress during 2015 and 2016 (Fig. 6a,b). Relatively, the average rate of carbon assimilation under D_{80}, D_{60}, and D_{40} treatments reduced by 10, 32, and 49%, respectively, compared with full irrigation. These findings are consistent with Yi et al. (2016) who reported a gradual decline in assimilation by 22 and 40%, respectively, under mild and moderate water deficit stress. Besides, it was also noticed that photosynthetic rate of D_{80} plants was statistically at par with control that indicated the suitability of this irrigation level for cotton on water scarce desert-oases. The physiological adaptation of cotton on this irrigation level can be attributed to its effective osmotic adjustment and comparatively better use of groundwater at 20% water deficit stress (ΔW Table 3) under hyperarid environment. In addition, the results clarified a linear positive correlation between photosynthetic rate and seasonal ETc (Fig. 7a,b) with $R^2 = 0.98$ for both trial years. The highest mean assimilation rate of 32.32 $\mu mol\ m^{-2}\ s^{-1}$ was observed when ETc reached the maximum averaging 1079 mm under 100% water replenishment during entire crop season. Similarly, deficit drip irrigation regimes also affected the rate of stomatal conductance (g_s) and resulted in the highest 674.96 and 651.23 $mmol\ m^{-2}\ s^{-1}$ under zero stress in 2015 and 2016, respectively. Based on mean values, g_s decreased by 38 and 50% under D_{60} and D_{40} replenishment, respectively, but, its decline in D_{80} was only 07% that was statistically at par with control (Fig. 6c,d). These results are supported by Deeba et al. (2012) who reported 40, 50, and 95% decrease in stomatal conductance at 75, 50, and 35% relative water content, respectively. Despite of adverse and hyperarid environment of desert, this resemblance of physiological response of cotton with other studies revealed its adaptability to extreme conditions that can be attributed to its stress tolerance ability.

3.4. Growth characteristics and water stress relations

Data presented in Fig. 8a,b show that after seedling establishment, cotton crop started building up leaf area index (LAI) at different rates under different water supplies, and finally diverged after climax due to defoliation of older leaves and development of fruiting bodies. Similar trends have been reported by Tang et al. (2010), Dağdelen et al. (2009), and Karam et al. (2006) from former deficit drip irrigation studies of

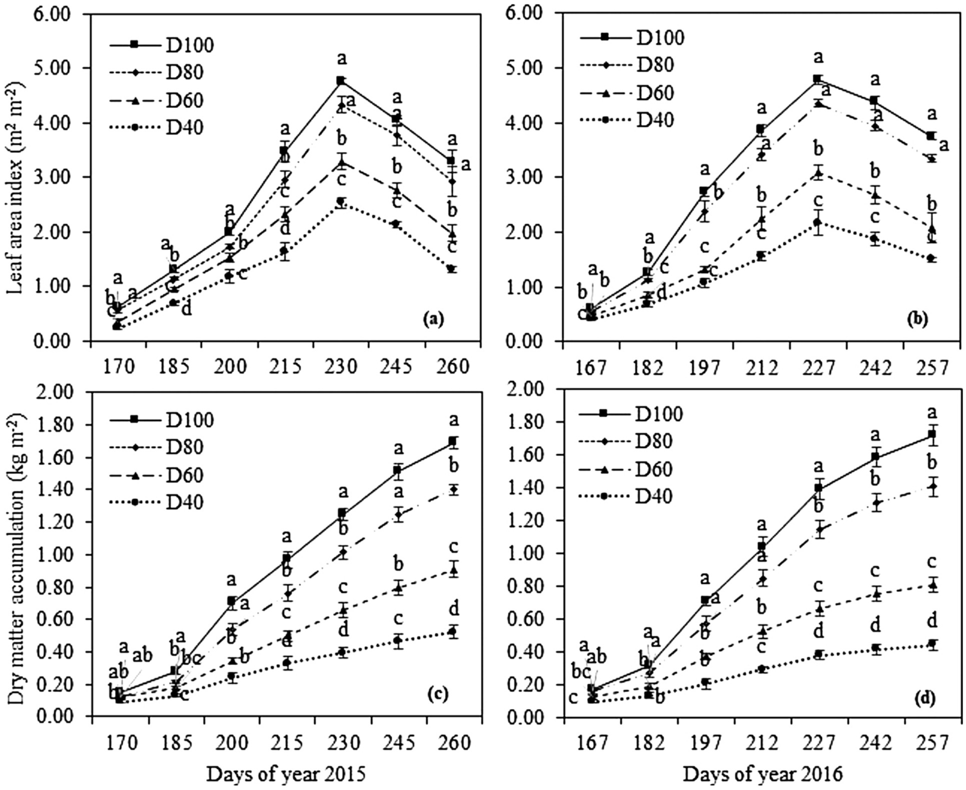

Fig. 8. Periodic changes in leaf area index (a, b) and total dry matter accumulation (c, d) in response to deficit drip irrigation regimes under desert environment. The values are means of four replications with standard errors (±) of means. Markers with different letters are significantly apart from each other according to LSD test at 5% probability.

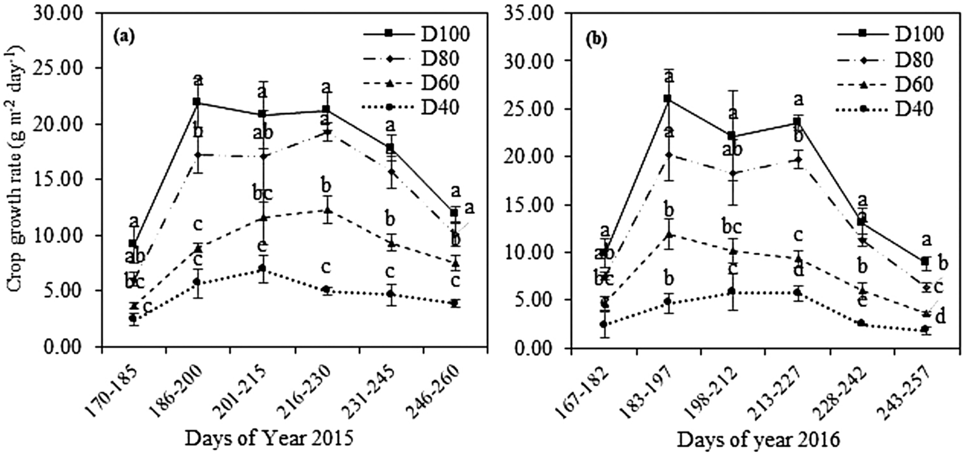

Fig. 9. Periodic changes in growth rate of deficit drip irrigated cotton under desert environment. The values are means of four replications with standard errors (±) of means. The markers with different letters are significantly apart from each other according to LSD test at 5% probability.

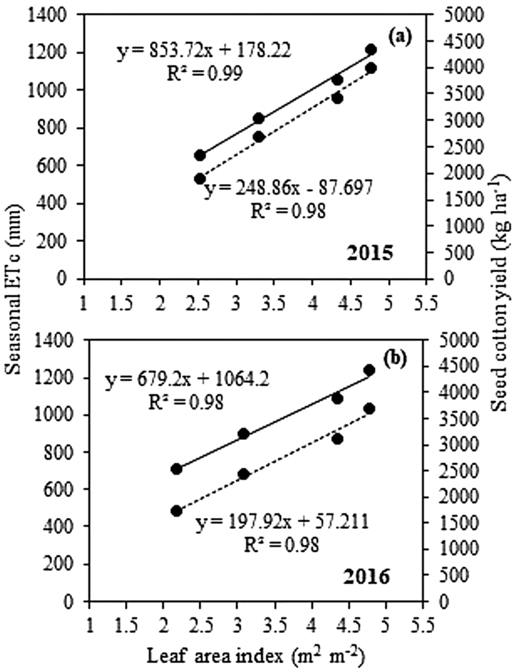

Fig. 10. Correlations of leaf area index with seasonal ETc (dotted line) and seed cotton yield (solid line) for the year 2015 (a) and 2016 (b). The relationships have been drawn separately for each trial year that clarified a linear increase in seed cotton yield and crop evapotranspiration with increasing leaf area index.

cotton. About 115 days after sowing, LAI reached the climax and the maximum 4.76 and 4.79 $m^2 m^{-2}$, and the minimum 2.53 and 2.18 $m^2 m^{-2}$ were recorded for D_{100} and D_{40} water replenishments during both trial years, respectively. These results are quite consistent with Ünlü et al. (2011) and Yang et al. (2015) who reported for well-watered and drought stressed cotton. As, in earlier studies, it has been reported that LAI has direct relationship with amount of irrigation applied (Dağdelen et al., 2009; Ünlü et al., 2011), so, the same response has been observed in current study, specifically under the desert environment. In addition, there existed a significant linear relationship between LAI (at climax) and seed cotton yield with R^2 values of 0.99 (2015) and 0.98 (2016) (Fig. 10a,b) that indicated direct response of yield towards the dynamics of LAI. Similarly, it was also observed that successive increase in LAI substantially enhanced the rate of evapotranspiration, which is illustrated in a linear correlation (Fig. 10a,b). Formerly, Ünlü et al. (2011) also reported similar relationships of LAI with seed cotton yield and ETc as have been devised in the present elucidation.

Periodic changes in above ground total dry matter (TDM) shown in Fig. 8c,d illustrate significant effect of different irrigation levels on this trait. The maximum dry biomass was obtained from fully irrigated (D_{100}) plots, while, it significantly ($P < 0.05$) reduced under deficit irrigation regimes. On an average, TDM of D_{80}, D_{60}, and D_{40} treatments was recorded 17, 50, and 73%, respectively, lower than control (D_{100}). The maximum TDM 1.69 and 1.72 $kg\,m^{-2}$ was recorded for D_{100} treatment in the 1st and 2nd season, respectively. However, as expected, the lowest 0.52 $kg\,m^{-2}$ in 2015 and 0.44 $kg\,m^{-2}$ in 2016 were observed from D_{40} treatment. In accordance with that, Dağdelen et al. (2009) reported the same biomass accumulation pattern of deficit drip irrigated cotton in western Turkey. In addition, the maximum and minimum values of TDM were also in line with Karam et al. (2006) and Yang et al. (2015) for full and deficit irrigated cotton. Results also showed that, throughout vegetative phase, the crop growth rate (CGR) was significantly ($P < 0.05$) lower in highly stressed (D_{40}) plots than in control (D_{100}). Full irrigation accelerated growth rate up to the maximum 21.88 and 25.93 $g\,m^{-2}\,day^{-1}$, while, the least 6.92 and 5.83 $g\,m^{-2}\,day^{-1}$ were recorded from D_{40} treatment in the 1st and 2nd

Table 4
Economic analysis for the irrigation treatments (average of two years).

Treatments	IR $m^3\,ha^{-1}$ (1)	Water price $ m^{-3} (2)	Water cost $ ha^{-1} (3) (1 × 2)	Labour cost $ ha^{-1} (4)	DS cost $ ha^{-1} (5)	[a]Prod. cost $ ha^{-1} (6)	Total cost $ ha^{-1} (7) (3 + 4 + 5 + 6)	Yield kg ha^{-1} (8)	Cotton price $ kg^{-1} (9)	Gross income $ ha^{-1} (10) (8 × 9)	Net income $ ha^{-1} (11) (10-7)
D_{100}	9880	0.04	395.2	1293.9	380.5	1015.6	3085.2	4376	1.3	5688.8	2603.6
D_{80}	7905	0.04	316.2	1133.2	380.5	1015.6	2845.5	3818	1.3	4963.4	2117.9
D_{60}	5930	0.04	237.2	1085.6	380.5	1015.6	2718.9	3122	1.3	4058.6	1339.7
D_{40}	3950	0.04	158.0	1037.1	380.5	1015.6	2591.2	2433	1.3	3162.9	571.7

IR: irrigation amount, DS: drip irrigation system, Prod.: production.

[a] Prod includes all kinds of costs, which were fixed for all treatments such as fertilizers, seeds, and other essential basic inputs.

season, respectively (Fig. 9a,b). These findings are well supported by Wang et al. (2007) who elucidated a substantial decline in CGR with increase in irrigation deficit stress. Usually, the CGR mainly depends on assimilatory activity of plants while, the rate of photo assimilation is susceptible to soil moisture dryness. Thus, the observed decline in CGR under deficit irrigation would be due to decreased assimilation rate (Fig. 6a,b), which has also been confirmed by Zhang et al. (2016). In addition, it can also be attributed to reduced TDM accumulation (Fig. 8c,d), which is a key determinant of crop's vegetative growth, and declines with reducing irrigation supplies (Dağdelen et al., 2009; Ünlü et al., 2011). The detailed analysis indicated a significant linear relationship between CGR and ETc with R^2 value of 0.98 (Fig. 7a,b) under reduced water supplies. In the line of that, Farooq et al. (2009) interpreted that plant growth is usually accomplished through various physiological processes, and transpiration is amongst the most sufferers of water deficit stress which is responsible for direct relationship of ETc with plant's assimilatory activity and eventually with crop growth rate.

3.5. Economic analysis

The profitability of desert grown cotton under deficit drip irrigation regimes was evaluated through economic analysis. Water cost used in this calculation was US$ 0.04 m^{-3} that was subsidized by the local government. The total seasonal irrigation cost for each treatment was variable due to difference in quantities of water applied, while, drip irrigation system and production costs were fixed for all plots. The production cost included seedbed preparation, sowing, fertilizers, and all other essential inputs. Labour cost was also variable, because, except seeding, all other farm activities in Xinjiang are hourly paid, which are associated with survival of plants, boll density, and seed cotton yield (Wang et al., 2014). For that reason, labour cost in the present study gradually decreased with decreasing irrigation quantity. The calculations of all expenses, and gross and net incomes on the basis of two years average data are given in Table 4. Cotton price US$ 1.3 kg^{-1} used for calculation was the average of two years (Xinjiang Statistical Bureau), because, it seldom remains same every year. Since, the area was new for cotton, therefore, no significant pest infestation was found, which saved the additional pest management cost. Thus, the total production cost was comparatively lesser than other cotton dominated drip irrigated regions.

The 100% irrigation replenishment provided the maximum net returns of US$ 2603.5, which successively decreased with decreasing irrigation amount. It can be attributed to higher seed cotton yield under full irrigation, which resulted in higher gross income and eventually the net profit. These interpretations are in agreement with Dağdelen et al. (2009) who reported the highest yield and profit under 100% irrigation. On the other hands, D_{80} provided a reasonable amount of net profit (US $ 2117.9 ha^{-1}) that was about 18% lower than D_{100} but, it also saved 20% precious water for desert ecosystem. This profitability under 80% irrigation was in line with Wang et al. (2014) who reported for deficit drip irrigated cotton from northern part of Xinjiang, China. Contrarily, Dağdelen et al. (2009) reported quite lower net income of 75% drip irrigated cotton from western Turkey, due to higher water and crop production costs. At second level of deficit irrigation (D_{60}), the profit ratio was about 50% lesser than D_{100} due to greater yield loss. Though, 60% irrigation saved 40% water but, compared with other cotton dominated territories of Xinjiang, its profit level would not be acceptable for local farmers to attract them towards desert. However, based on economic analysis it can be interpreted that, if water is abundant then net profit can be maximized by adopting 100% level of drip irrigation, while, 80% replenishment could be the best alternate optimum drip irrigation level under extreme water scarcity in the desert environments.

4. Conclusions

It is concluded that deficit drip irrigation regimes significantly affected growth, physiological, and agronomic attributes of cotton. The crop showed compatibility with climate and topography of oases on the southern border of Taklimakan desert. Due to high evaporative potential (2595 mm annually) of hyperarid desert-oases, crop water demand (ETc) was higher than reported from other arid and semiarid regions and it reached the maximum averaging 1079 mm under full irrigation. The highest average seed cotton yield 4376 kg ha^{-1} was obtained from D_{100} using 988 mm irrigation with zero water saving while, this yield was linearly correlated with seasonal ETc. On an average, at 80% irrigation replenishment, the growth, and gas exchange attributes of cotton performed at par with D_{100}, while, these traits were more adversely affected by 60 and 40% replenishment. Rate of photosynthesis, LAI, and CGR, depicted linear relationships with yield and ETc. Overall in 20% less irrigated (D_{80}) fields, seed cotton yield, crop growth, and assimilation rate reduced by only 9–13%, whereas, in 60% less irrigated (D_{40}) plants, this decline was more than 50%. No doubt, the WUE and IWUE increased with increasing drought stress but the quantity of produce was concerned. The economic analysis indicated maximum profit under full irrigation with zero water saving while, D_{80} saved 20% water and provided a reasonable amount of net profit. Hence, these results suggest the suitability of cotton on desert-oases, and propose 80% level of drip irrigation for optimum yield and net income without affecting desert ecosystem's sustainability. However, if water is amply available, then 100% replenishment should be considered to maximize net returns.

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References

Argyrokastritis, I.G., Papastylianou, P.T., Alexandris, S., 2015. Leaf water potential and crop water stress index variation for full and deficit irrigated cotton in Mediterranean conditions. Agric. Agric. Sci. Procedia 4, 463–470.

Boyer, J., 1967. Leaf water potentials measured with a pressure chamber. Plant Physiol. 42, 133–137.

Cetin, O., Bilgel, L., 2002. Effects of different irrigation methods on shedding and yield of cotton. Agric. Water Manage. 54, 1–15.

Dağdelen, N., Başal, H., Yılmaz, E., Gürbüz, T., Akçay, S., 2009. Different drip irrigation regimes affect cotton yield, water use efficiency and fiber quality in western Turkey. Agric. Water Manage. 96, 111–120.

Deeba, F., Pandey, A.K., Ranjan, S., Mishra, A., Singh, R., Sharma, Y.K., Shirke, P.A., Pandey, V., 2012. Physiological and proteomic responses of cotton (Gossypium herbaceum L.) to drought stress. Plant Physiol. Biochem. 53, 6–18.

Doorenbos, J., Kassam, A., 1979. Yield Response to Water. Irrigation and Drainage Paper 33. pp. 257.

Farooq, M., Wahid, A., Kobayashi, N., Fujita, D., Basra, S., 2009. Plant Drought Stress: Effects, Mechanisms and Management, Sustainable Agriculture. Springer, pp. 153–188.

Fereres, E., Soriano, M.A., 2007. Deficit irrigation for reducing agricultural water use. J. Exp. Bot. 58, 147–159.

Guan, H., Li, J., Li, Y., 2013. Effects of drip system uniformity and irrigation amount on cotton yield and quality under arid conditions. Agric. Water Manage. 124, 37–51.

Guo, H., Zeng, F., Arndt, S.K., Zeng, J., Xing, W., Liu, B., 2009. Influence of floodwater irrigation on vegetation composition and vegetation regeneration in a Taklimakan desert oasis. Sci. Bull. 53, 156–163.

Heerman, D.F., 1985. ET in irrigation management. Proceedings of the National Conference on Advances in Evapotranspiration. Trans. ASAE 323–334.

Howell, T., Evett, S., Tolk, J., Schneider, A., 2004. Evapotranspiration of full-, deficit-irrigated, and dryland cotton on the Northern Texas High Plains. J. Irrig. Drain. Eng. 130, 277–285.

Ibragimov, N., Evett, S.R., Esanbekov, Y., Kamilov, B.S., Mirzaev, L., Lamers, J.P.A., 2007. Water use efficiency of irrigated cotton in Uzbekistan under drip and furrow irrigation. Agric. Water Manage. 90, 112–120.

Kanber, R., Yazar, A., Önder, S., Köksal, H., 1993. Irrigation response of pistachio (Pistacia vera L.). Irrig. Sci. 14, 7–14.

Kanber, R., Onder, S., Unlu, M., Koksal, H., Ozekici, B., Sezen, S., Yazar, A., Koc, K., 1996.

Optimization of surface irrigation methods for cotton and comparison with sprinkler irrigation. Research Report.

Kang, Y., Wang, R., Wan, S., Hu, W., Jiang, S., Liu, S., 2012. Effects of different water levels on cotton growth and water use through drip irrigation in an arid region with saline ground water of Northwest China. Agric. Water Manage. 109, 117–126.

Karam, F., Lahoud, R., Masaad, R., Daccache, A., Mounzer, O., Rouphael, Y., 2006. Water use and lint yield response of drip irrigated cotton to the length of irrigation season. Agric. Water Manage. 85, 287–295.

Kirda, C., 1999. Crop Yield Response to Deficit Irrigation: Report of an FAO/IAEA Co-Ordinated Research Program by Using Nuclear Techniques: Executed by the Soil and Water Management & Crop Nutrition Section of the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture. Springer Science & Business Media.

Li, H., Wu, Y., Huang, X., Sloan, M., Skitmore, M., 2017. Spatial-temporal evolution and classification of marginalization of cultivated land in the process of urbanization. Habitat Int. 61, 1–8.

Loka, D., Oosterhuis, D., 2014. Water-deficit stress effects on pistil biochemistry and leaf physiology in cotton (Gossypium hirsutum, L.). S. Afr. J. Bot. 93, 131–136.

Onder, D., Akiscan, Y., Onder, S., Mert, M., 2009. Effect of different irrigation water level on cotton yield and yield components. Afr. J. Biotech. 8.

Oweis, T.Y., Farahani, H.J., Hachum, A.Y., 2011. Evapotranspiration and water use of full and deficit irrigated cotton in the Mediterranean environment in northern Syria. Agric. Water Manage. 98, 1239–1248.

Papastylianou, P.T., Argyrokastritis, I.G., 2014. Effect of limited drip irrigation regime on yield, yield components, and fiber quality of cotton under Mediterranean conditions. Agric. Water Manage. 142, 127–134.

Pettigrew, W., 2004. Physiological consequences of moisture deficit stress in cotton. Crop Sci. 44, 1265–1272.

Quisenberry, J., Roark, B., 1976. Influence of indeterminate growth habit on yield and irrigation water-use efficiency in upland cotton. Crop Sci. 16, 762–765.

Raines, C.A., 2011. Increasing photosynthetic carbon assimilation in C3 plants to improve crop yield: current and future strategies. Plant Physiol. 155, 36–42.

Rao, S.S., Tanwar, S.P.S., Regar, P.L., 2016. Effect of deficit irrigation, phosphorous inoculation and cycocel spray on root growth: seed cotton yield and water productivity of drip irrigated cotton in arid environment. Agric. Water Manage. 169, 14–25.

Singh, Y., Rao, S.S., Regar, P.L., 2010. Deficit irrigation and nitrogen effects on seed cotton yield: water productivity and yield response factor in shallow soils of semi-arid environment. Agric. Water Manage. 97, 965–970.

Stewart, J.I., Hagan, R., Pruitt, W., Danielson, R., Franklin, W., Hanks, R., Riley, J., Jackson, E., 1977. Optimizing Crop Production Through Control of Water and Salinity Levels in the Soil.

Tang, L.-S., Li, Y., Zhang, J., 2010. Partial rootzone irrigation increases water use efficiency, maintains yield and enhances economic profit of cotton in arid area. Agric. Water Manage. 97, 1527–1533.

Thind, H., Aujla, M., Buttar, G., 2008. Response of cotton to various levels of nitrogen and water applied to normal and paired sown cotton under drip irrigation in relation to check-basin. Agric. Water Manage. 95, 25–34.

Ünlü, M., Kanber, R., Koç, D.L., Tekin, S., Kapur, B., 2011. Effects of deficit irrigation on the yield and yield components of drip irrigated cotton in a mediterranean environment. Agric. Water Manage. 98, 597–605.

Wang, C.-Y., Isoda, A., Li, M.-S., Wang, D.-L., 2007. Growth and eco-physiological performance of cotton under water stress conditions. Agric. Sci. China 6, 949–955.

Wang, Z., Jin, M., Šimůnek, J., van Genuchten, M.T., 2013. Evaluation of mulched drip irrigation for cotton in arid Northwest China. Irrig. Sci. 32, 15–27.

Wang, R., Wan, S., Kang, Y., Dou, C., 2014. Assessment of secondary soil salinity prevention and economic benefit under different drip line placement and irrigation regime in northwest China. Agric. Water Manage. 131, 41–49.

White, S.C., Raine, S.R., 2009. Physiological response of cotton to a root zone soil moisture gradient: implications for Partial Root Zone Drying irrigation. J. Cotton Sci. 13, 67–74.

Yang, C., Luo, Y., Sun, L., Wu, N., 2015. Effect of deficit irrigation on the growth, water use characteristics and yield of cotton in arid Northwest China. Pedosphere 25, 910–924.

Yi, X.P., Zhang, Y.L., Yao, H.S., Luo, H.H., Gou, L., Chow, W.S., Zhang, W.F., 2016. Rapid recovery of photosynthetic rate following soil water deficit and re-watering in cotton plants (Gossypium herbaceum L.) is related to the stability of the photosystems. J. Plant Physiol. 194, 23–34.

Zeng, F., Bleby, T.M., Landman, P.A., Adams, M.A., Arndt, S.K., 2006. Water and nutrient dynamics in surface roots and soils are not modified by short-term flooding of phreatophytic plants in a hyperarid desert. Plant Soil 279, 129–139.

Zhang, H., Wang, X., You, M., Liu, C., 1999. Water-yield relations and water-use efficiency of winter wheat in the North China Plain. Irrig. Sci. 19, 37–45.

Zhang, D., Luo, Z., Liu, S., Li, W., Dong, H., 2016. Effects of deficit irrigation and plant density on the growth: yield and fiber quality of irrigated cotton. Field Crops Res. 197, 1–9.

Zhang, Y., Zhao, W., Fu, L., 2017. Soil macropore characteristics following conversion of native desert soils to irrigated croplands in a desert-oasis ecotone, Northwest China. Soil Tillage Res. 168, 176–186.