

Responses of yield, water use efficiency and quality of short-season cotton to irrigation management: interactive effects of irrigation methods and deficit irrigation

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Abstract Transplanted short-season cotton followed by winter wheat is widely cultivated in the North China Plain (NCP). However, data and guidelines on irrigation water management for the short-season cotton cultivation are lacking. In order to determine optimal irrigation practices for transplanted cotton in the NCP, a field experiment with surface drip and border irrigation was conducted in 2011, 2012 and 2013 seasons. Four irrigation treatments, namely full drip (DT), full border (BT), deficit drip (DDT) and deficit border (DBT) irrigation treatments, were evaluated on the basis of vegetative growth, evapotranspiration (ET), cotton yield, water use efficiency (WUE) and fiber quality. Results showed that the average seasonal ET ranged from 358 to 449 mm. Compared to the border irrigation, the drip irrigation improved vegetative growth, and the deficit irrigation inhibited vegetative growth compared with the full irrigation. DT produced the highest seed cotton yield of 3164 kg ha⁻¹, while the minimum seed cotton yield of 2459 kg ha⁻¹ was produced in the DBT. On average, DDT produced the largest WUE of 0.83 kg m⁻³, while the smallest in BT. On average, 33.4 % of the irrigation water was saved by DT compared to BT, and drip irrigation increased seed cotton yield by 11.5 %. In addition, drip irrigation tended to increase the fiber length and optimize the

micronaire value. Deficit irrigation significantly decreased the fiber strength and reduced the fiber length. Overall, the DT is recommended as the optimal irrigation strategy for the short-season cotton in the NCP.

Introduction

The North China Plain (NCP) is one of the most important grain and cotton production regions in China (Dong et al. 2006; Mao 2013). In recent years to cope with food safety and to improve the comprehensive economic benefits of cotton, the winter wheat–cotton intercropping system was gradually eliminated due to its non-mechanized, vigorous and time-consuming cultivation practices. In this region, cotton cultivation is now being adjusted to incorporate seedling development in the greenhouse and mechanical transplanting to a field by a cotton seedling planter (Mao 2013). It is beneficial for mechanized cultivation of cotton. Therefore, the short-season cotton, which was transplanted after winter wheat harvesting, is gradually becoming the main pattern of cotton planting (Mao 2013). However, the optimal irrigation method and scheduling for the short-season cotton are still unclear.

The conventional irrigation methods practiced in cotton production in the NCP are border and furrow irrigation with low water use efficiency (Kang et al. 2012). Drip irrigation has been suggested as a means to supply most types of crops with frequent and uniform applications of water. This method is adaptable over a wide range of topographic and soil conditions (Cetin and Bilgel 2002; Dağdelen et al. 2009). Various water application methods with different irrigation scheduling for cotton have been studied to optimize yield and irrigation water use in different regions of the world. Howell et al. (1989) tested drip and furrow

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methods for cotton irrigation and found no yield differences between these methods. Mateos et al. (1991) found that the advantage of one method over the other varied from year to year. Cetin and Bilgel (2002) reported that seed cotton yield and WUE for sprinkler irrigation decreased by 7 and 39 %, respectively, compared to furrow irrigation. However, drip irrigation produced 21 % more seed cotton yield and increased WUE by 26 % over the furrow method over 4 years of research in Turkey (Cetin and Bilgel 2002). Ibragimov et al. (2007) indicated that drip irrigation saved 18–42 % of the irrigation water and increased irrigation WUE by 35–103 % compared to furrow irrigation in Uzbekistan. Similar results were reported by Smith et al. (1991), Aujla et al. (2005), Jalota et al. (2006) and Wang et al. (2007).

Similarly, many studies have reported that deficit irrigation significantly affects cotton growth, yield and fiber quality (Johnson et al. 2002; Ertek and Kanber 2003; Pettigrew 2004; Dağdelen et al. 2009; Önder et al. 2009; Ünlü et al. 2011; Guan et al. 2013). Önder et al. (2009) tested four levels of deficit irrigation treatments for two growing seasons. They found that deficit irrigation decreased ET, total seed cotton yield, boll mass, lint percentage and leaf area index. Ertek and Kanber (2003) found no significant difference in cotton yield under treatments with different irrigation amounts based on crop-pan coefficients in a higher-yield season with lower shedding rate. However, in a lower-yield season, deficit irrigation produced significantly lower yields than the wettest treatment. They also found that deficit irrigation increased shedding and decreased the number of bolls. There was a significant ($P < 0.01$) inverse linear relationship between the shedding rate and the boll number. However, boll mass and opened boll number on a per-plant basis and the harvest index were increased by deficit irrigation, indicating that cotton has a high capability to adapt to water stress conditions (Ertek and Kanber 2003; Ünlü et al. 2011). The timing of irrigations or rainfall can also impact the number of bolls on a cotton plant; infrequent irrigation can cause an increase in shedding and a drop in yield (Ertek and Kanber 2003). Ertek and Kanber (2003) also pointed out that plants can compensate for higher water stress at the end of the season because the yield at this period does not depend on shedding, and boll maturation is less affected by water stress. Furthermore, water stress affects lint quality in some ways; especially during the fiber elongation period, water stress results in a decrease in fiber length due to the direct mechanical and physiological processes of cell expansion (Pettigrew 2004; Dağdelen et al. 2009). Dağdelen et al. (2009) found that deficit irrigation not only reduced the yield but also reduced the fiber length and strength. Johnson et al. (2002) found that fiber strength and elongation factors were correlated with soil water content. Ünlü et al. (2011) reported

that some lint properties, such as lint length, lint uniformity and micronaire, were reduced when soil moisture deficits increased, but there were no statistically significant differences between different irrigation treatments on these quality components of cotton lint.

Conventional cotton cultivated in the early spring in the NCP has a different growth trend than the winter wheat–cotton continuous cropping conditions. The hot summer with high air temperature causes high evapotranspiration for the short-season cotton in its growing season, and soil water content in the plowing layer is low, near the permanent wilting point after the winter wheat harvesting. Therefore, irrigation water management plays an important role in achieving high yield and quality in the transplanted short-season cotton in this region. Several studies for the short-season cotton cultivation have mainly focused on the optimal parameters of seedling raising, such as seedling raising method (Liu et al. 2010), plant density (Fang et al. 2011) and seeding age at transplanting (Wang et al. 2010), and on the comprehensive benefits between the short-season cotton and the wheat–cotton intercropping in the NCP (Ma et al. 2010; Wang et al. 2011). However, little attempt has been made to assess the effects of different deficit irrigation regimes and different irrigation methods, growth, yield and quality of the short-season cotton in the NCP (Liu et al. 2012). Therefore, the main objectives of this research were (1) to measure crop growth, ET, seed yield, WUE and fiber quality of the short-season cotton under full irrigation and deficit irrigation; (2) to compare these responses between surface drip irrigation and border irrigation; and (3) to determine suitable irrigation practices associated with greater yield, irrigation WUE and fiber quality.

Materials and methods

Experimental site

The field experiment was carried out in 2011, 2012 and 2013 at the experimental station (35°19'N, 113°53'E and 73.2 m) of Farmland Irrigation Research Institute, located in Xinxiang, Henan, North China Plain. The site is in a warm temperate climate with an annual mean air temperature of 14.2 °C, annual sunshine duration of 2286 h, frost-free days of 220 d, precipitation of 546 mm and potential evaporation of 2000 mm on the basis of a 60-year average of data taken at Xinxiang Weather Station near the experimental field. The groundwater table is more than 5 m deep at the experimental site, and the site has fluvo-aquic soil (Eutric Cambisols). The soil texture is sandy loam, with a mean bulk density of 1.38 g cm⁻³, mean field capacity of 24 % (gravimetric water content) and mean permanent wilting point of 8 % (gravimetric water content) at the 0- to

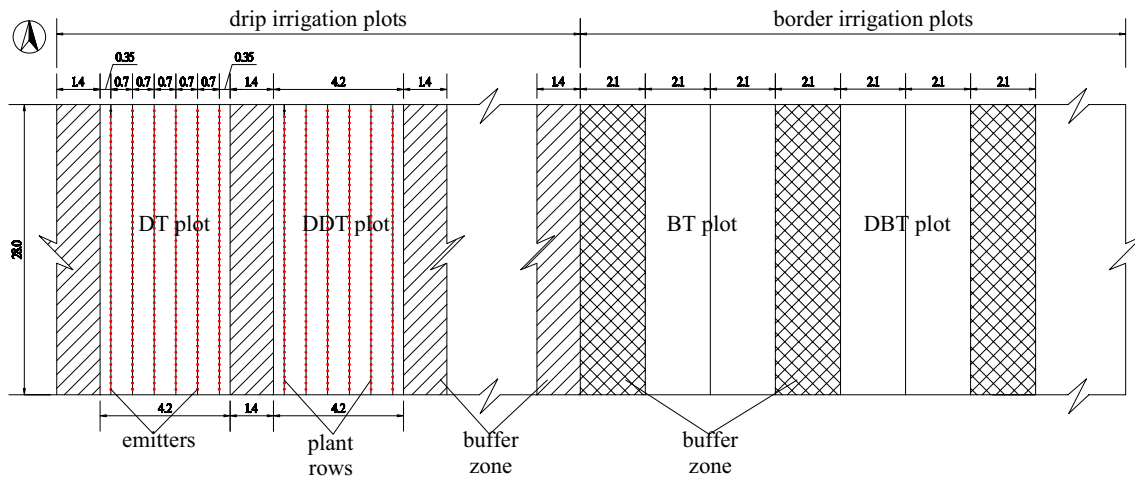


Fig. 1 Layout of experimental plots

100-cm layer. Soil available N, P and K contents were 44.9, 3.2 and 121.1 mg kg⁻¹, respectively, and the organic matter content was 12.9 g kg⁻¹ at the 0- to 60-cm layer.

Experimental design

The experimental design was split plots with three replications. Main plots and subplots were assigned for two irrigation methods (drip and border irrigation) and two different irrigation schedules (full and deficit irrigation). The layout of the experimental plots is shown in Fig. 1. Each subplot was 117.6 m² (28 m × 4.2 m) in area and included six cotton rows. Of the six rows, the inner four rows of each subplot were investigated for individual experimental treatment effects.

A fraction of field capacity (θ_f) was adopted as a starting point to determine the full irrigation amount treatments (DT: drip irrigation; BT: border irrigation). Irrigation was scheduled when the soil water content in the root zone approached 70 % of θ_f for three main plant growth periods (Liu et al. 2011): the seedling stage, the squaring stage and the flowering and boll setting stage (Table 1). No irrigation was applied at the boll opening stage. The irrigation treatments were started on the day the seedlings were transplanted in each growing season.

The irrigation amounts were 30 and 75 mm for the DT and BT treatments, respectively. The irrigation amount for the deficit drip irrigation treatment (DDT) was applied at a rate of 50 % of that applied to the full drip irrigation treatment (DT) on the same day.

The irrigation amount for the deficit border irrigation treatment (DBT) was applied only once after the cotton seedling was transplanted (Table 1). The crop evapotranspiration of the DBT treatment mainly depended on rainfall and soil

Table 1 Irrigation date, amount per application and total irrigation amount of four treatments during the three growing seasons of the short-season cotton

Season	Date	Amount per application (mm)			
		DT	DDT	BT	DBT
2011	09/06/2011	25	25	76.4	76.4
	21/06/2011	30	15	70.9	
	15/07/2011	30	15		
	16/07/2016			65.3	
	25/07/2011	30	15		
	31/08/2011	30	15		
	Total irrigation amount	145	85	212.6	76.4
2012	05/06/2012	30	30	73	73
	17/06/2012	30	15	86.4	
	25/07/2012	30	15		
	27/07/2012			80.1	
	09/08/2012	30	15		
	28/08/2012	30	15		
	Total irrigation amount	150	90	239.5	73
2013	06/06/2013	30	30	77.3	77.3
	19/06/2013	30	15		
	17/08/2013	30	15		
	21/08/2013			93.5	
	26/08/2013	30	15		
	Total irrigation amount	120	75	170.8	77.3

water profile storage throughout the growing season. The two adjacent plots were maintained with a 2.1-m separation to minimize water movement among the treatments. A subplot with border irrigation includes one intermediate border for easy flooding, that is, each subplot in border irrigation

includes two strips, with border length and breadth of 28 and 2.1 m, respectively (consisting of three cotton rows).

Polyethylene (PE) laterals, each having a 16 mm diameter, were laid close to each cotton row to maintain 0.7-m spacing between the rows. The inline emitter discharge rate was 2.0 L h⁻¹, with emitters spaced at 0.20 m distance, under an operating pressure of 100 kPa. The amount of irrigation water applied in each treatment was measured by a water meter.

Agronomic management

During the three seasons, cotton (*Gossypium hirsutum* L. cv. Zhongmiansuo 50) seedlings were raised at the beginning of May (Julian Day: 125) by sowing seeds in substrate (turf: vermiculite: perlite = 5:4:1). The seedlings were transplanted by hand on June 8, 2011 (Julian Day: 159), June 5, 2012 (Julian Day: 156), and June 6, 2013 (Julian Day: 157), in the three seasons after the winter wheat harvest. The row-to-row spacing was maintained at 0.70 m, and the plant population density was 67.5 thousand plants per hectare (plant-to-plant spacing was approximately 21 cm) for all treatments.

A locally recommended fertilizer was adopted in the study for all treatments. A compound fertilizer (N: P: K: 18, 18 and 18 % composite) was applied at a rate of 70 kg ha⁻¹ as the base fertilizer. The remaining N to achieve 60 kg ha⁻¹ (urea, N 46 %) was applied at the squaring stage. All treatments had similar pest control and other agricultural management.

The bolls were harvested by hand three times each season. The sampling area in each subplot was 5 m × 2.8 m (i.e., 4 rows with the length of 5 m). The first harvest was conducted when approximately 10 % of the bolls opened in the middle of September. The second harvest took place when approximately 70 % of the remaining bolls opened at the beginning of October. When the remaining bolls on the plants were open, the last harvest was conducted at the middle of October before winter wheat was sown.

Measurements

During the growing season, the soil moisture in the root zone of 0–100 cm at a depth interval of 20 cm in all treatment plots was determined at the interval of 5–7 days by the gravimetric method (oven-dry basis, 105 °C, 8–10 h). Soil samples were collected manually by soil auger from the center of each treatment plot.

Similarly, evapotranspiration (ET, mm) was calculated using the soil water balance equation (Allen et al. 1998; Hillel 1998):

$$ET = P + I_r + U - R - D_w - \Delta W \quad (1)$$

where P is precipitation (mm), I_r is irrigation amount (mm), U is upward capillary rise into the root zone (mm), R is runoff (mm), D_w is downward flux moved below the root zone (mm), and ΔW is the change in soil water stored in the 0- to 100-cm layer (mm). D_w was calculated based on the relation of unsaturated water conductivity using the volumetric soil moisture at 1 m in the soil profile (Zhang et al. 2006; Gao et al. 2015). Assuming no incoming or outgoing flux other than that produced by unit gradient at the bottom of the layer, outflow from a layer can be expressed as:

$$L \frac{d\theta}{dt} = -K(\theta) \quad (2)$$

where L is layer thickness (L), θ is the average volumetric soil water content of the layer (L³ L⁻³), t is time (T), and K is unsaturated hydraulic conductivity (L T⁻¹). The unsaturated hydraulic conductivity predicted from Van Genuchten's (1980) model for soil moisture–pressure relation.

In the experimental area, the upward flow was negligible because the groundwater table was 5 m below the root zone depth and saw no runoff ($R = 0$) in all of the growing seasons. Thus, Eq. (1) can be changed to:

$$ET = P + I_r - D_w - \Delta W \quad (3)$$

The average crop coefficients (K_c) at the different growing stage were calculated using the following equation:

$$K_c = ET/ET_0 \quad (4)$$

where ET_0 is reference crop evapotranspiration (mm) (Allen et al. 1998).

Water use efficiency (WUE, kg m⁻³) was calculated using the following equation:

$$WUE = \frac{Y}{10 \times ET} \quad (5)$$

where Y is the seed yield (kg ha⁻¹), and ET is the total evapotranspiration (mm).

The plant height and leaf area index (LAI) as an indicator of plant vegetative growth were measured manually by ruler (1-mm accuracy) at 20-day intervals from July 5 to August 15 for the three growing seasons. Five plants from the inner row of each treatment plot were randomly selected and labeled for the measurement of plant height and LAI. LAI was calculated using the following equation:

$$LAI = C \times D \times \frac{1}{n} \sum_{i=1}^n \sum_{j=1}^m L_{ij} \times B_{ij} \quad (6)$$

where L_{ij} is the length of the j th leaf on plant i (m), B_{ij} is the breadth of the j th leaf on plant i (m), m is number of leaves in the i th plant, and n is the number of plants measured from each plot (here $n = 5$). D is the plant population density (plant m⁻²), and in this study, $D = 6.75$ plant m⁻².

C is the conversion coefficient of the leaf area, and in this study, it is 0.85 as calculated by ArcGIS of the GIS software for the cotton variety (Chen et al. 2012).

The average number of bolls per plant was recorded from each plot before the first harvesting. The seed cotton yield was determined by considering the four center rows of 5-m length as sample areas from each treatment plot at every harvest, and the average biomass per boll in each plot was calculated by dividing the total seed yield by the total number of bolls. The seed cotton from each harvest was ginned to determine the lint percentage of each treatment plot. Fiber length, fiber uniformity, fiber fineness (micronaire), fiber elongation and fiber strength were measured using a high volume instrument (HVI) system at the Cotton Institute, Chinese Academy of Agricultural Sciences.

The meteorological data were obtained from a standard automatic weather station located at a distance of 50 m from the experimental field. The meteorological variables included sunshine duration, atmospheric temperature, relative humidity, wind speed and precipitation throughout the growing season. Monthly mean meteorological data for (a) precipitation, (b) sunshine duration and (c) atmospheric temperature of the three growing seasons compared with the 60-year mean values are shown in Fig. 2.

Data analysis

Analysis of variance (ANOVA) was performed for the seed yield, WUE and fiber quality parameters using the GLM procedure from SPSS 16.0 software (SPSS 2007), and mean values were compared for any significant differences using the Duncan's multiple range tests at a significance level of $P_{0.05}$.

Results

Irrigation water amount (I_r) and soil water dynamics

I_r for seedling preparation was much less than the total irrigation amount from transplantation to harvesting, so the I_r of this period was not considered in this study. Irrigation applied just after transplantation with drip irrigation was 25, 30 and 30 mm in 2011, 2012 and 2013, respectively, and the value was 75 mm for the border irrigation plots (Table 1). During the three growing seasons, the DT and DDT were irrigated five times in 2011 and 2012, while four times in 2013. The BT was irrigated three times in 2011 and 2012 and two times in 2013 (Table 1). All treatments received less water in 2013 due to heavy rainfall in July and August. The seasonal irrigation amount ranged from 73 to 240 mm for the short-season cotton. On average, the DT,

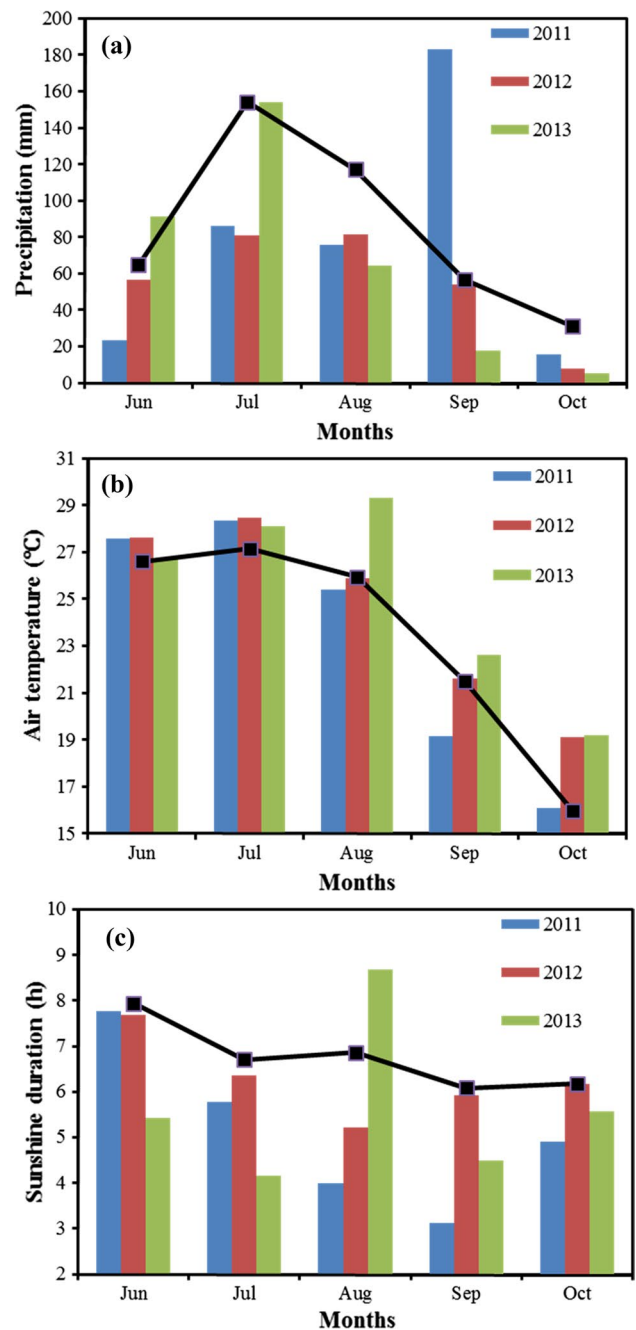
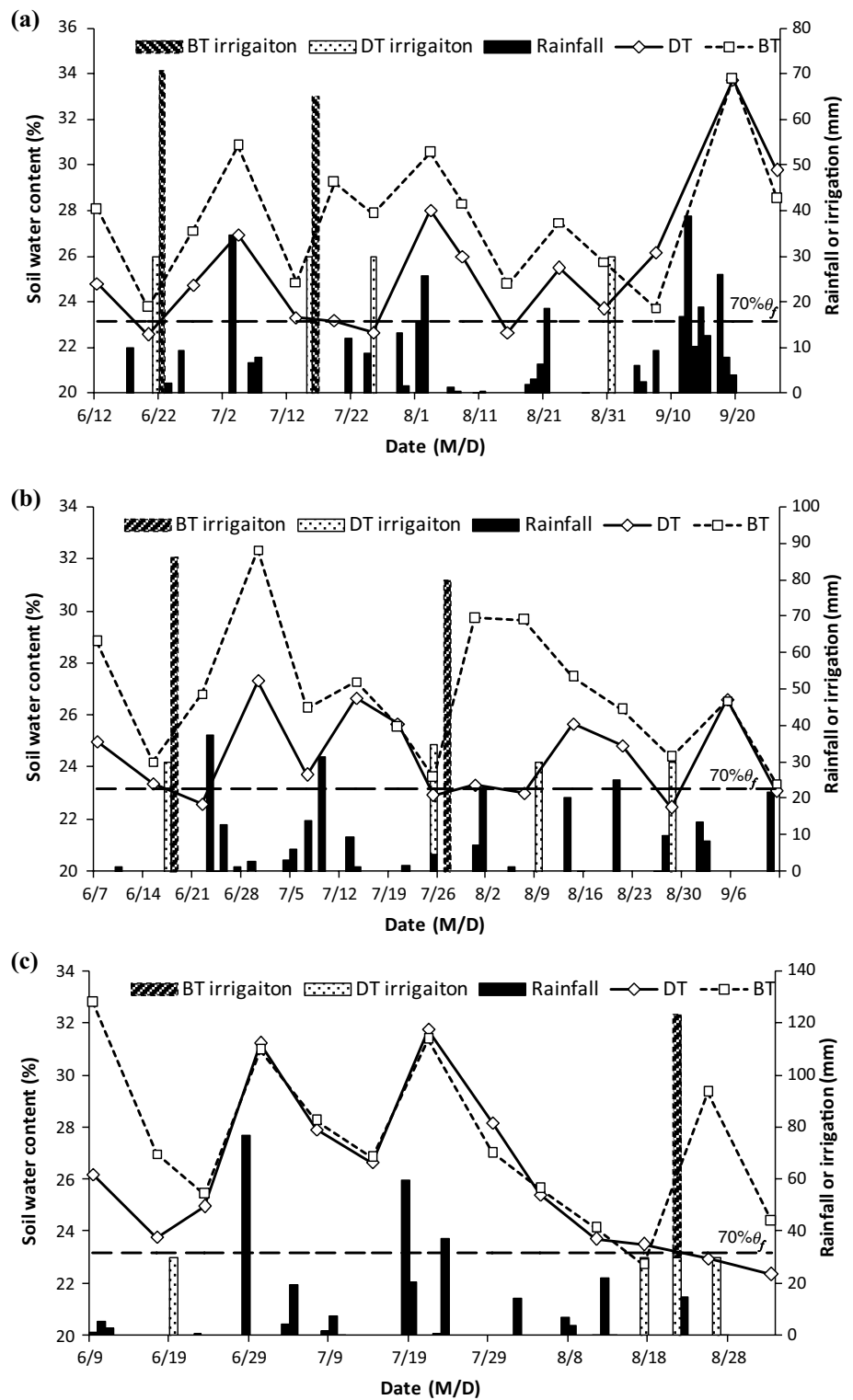


Fig. 2 Monthly mean meteorological data for the 2011, 2012 and 2013 short-season cotton growing seasons at the Farmland Irrigation Research Institute (FIRI), Xinxiang, China. **a** Precipitation in the three seasons and the 60-year mean. **b** Air temperature in the three seasons and the 60-year mean. **c** Sunshine duration in the three seasons and the 60-year mean

DDT and DBT saved irrigation water by 33.4, 60.0 and 63.6 %, respectively, compared to the BT.

Variation of average soil moisture in the 0- to 60-cm soil layer and distribution of rainfall and irrigation water amount after the first irrigation in different treatments in

Fig. 3 Changes of average value of soil water content at 0–60 cm, rainfall and irrigation amount during the growing season of cotton in 2011 (a), 2012 (b) and 2013 (c) for the treatments of DT and BT



the three seasons are presented in Fig. 3. Changes in soil moisture at the bolls opening stage are not shown in Fig. 3 as no irrigation was applied at this growing stage. Soil moisture in the BT was higher than 70 % of θ_f in the three seasons except for August 8, 2013, and soil moisture in the

DT was lower than that in the BT. However, soil moisture in the DT was kept in the control range (70 % of $\theta_f \pm 2$ %) at irrigation time. The seasonal average, soil moisture in the DT was lower than that in the BT by 2.10, 2.42 and 1.34 % in 2011, 2012 and 2013, respectively. Smaller

amounts of drainage demonstrated that soil in the drip irrigation treatments could hold more rainfall than the border irrigation treatments after heavy rainfall occurred (Table 2). For example, irrigation was applied on July 15 and July 16, 2011, for the DT and BT treatments, and soil moisture measured on July 19 in the DT was lower than that in the BT by 6.1 %, which was the largest difference of soil moisture between the DT and BT treatments. Therefore, soil in the 0–60 cm depth in the DT had more storage capacity than soil in the BT. Additionally, downward soil water movement was reduced in the DT, increasing rainfall use efficiency.

Crop evapotranspiration (ET) and coefficient (K_c)

In general, the largest ET occurred in the flowering and bolls stage, and relatively lower ET values were observed in the seedling and bolls opening stages (Table 2). The highest seasonal ET was observed in the BT and ranged from 406 mm (in 2011) to 463 mm (in 2012). The DT had lower ET, which varied from 370 mm (in 2011) to 430 mm (in 2013). The lowest ET was measured in the DDT in 2011, while in the DBT in 2012 and 2013. These small differences in ET among the three seasons could be due to variations in climatic factors. The average seasonal ET of the three growing seasons ranged from 358 to 449 mm. ET for the DT, DDT and DBT decreased by 11.3, 20.3 and 19.9 %, respectively, compared to the BT. With the drip irrigation method, the deficit irrigation consumed 10.1 % less water than the full irrigation. In summary, the drip irrigation and deficit irrigation scheduling decreased ET for the short-season cotton.

Variation of average crop coefficient (K_c) at different growing stages was similar to the corresponding ET (Table 2). The largest K_c of the short-season cotton was obtained in the middle stage, while the relative lower K_c was observed in the early and the end stage. There were differences in crop coefficient between different treatments at seedling stage, squaring stage and bolls opening stage. Compared with the BT, the K_c of the short-season cotton in the DT was decreased by 24.9, 17.9 % and 5.7 at seedling stage, squaring stage and bolls opening stage, respectively. Little difference was observed at the bolls opening stage between the treatments due to no irrigation applied at this growth stage. Moreover, the K_c values of deficit irrigation treatments were lower than that in the full drip and border irrigation treatments.

Plant growth and development

Plant height and leaf area index (LAI) in the different treatments are presented in Table 3. The vegetative growth parameters, namely plant height and LAI, were

significantly affected by the irrigation methods and irrigation scheduling. For the full irrigation treatment, the DT significantly improved plant height on 5 July in 2011 and 2013 in comparison with the BT and significantly improved plant height on 25 July for each year in comparison with the BT. However, the DT significantly increased LAI only on 25 July in 2011 and on 5 July in 2013, no significant difference was measured between the DT and BT treatments on other dates for each year. On average for the three growing seasons, the maximum difference between the two treatments was found on 5 July, when the DT treatment increased plant height and LAI by 16.7 and 21.1 %, respectively, compared to the BT treatment. On 25 July, the difference decreased, and the DT treatment increased plant height and LAI by 9.3 and 8.5 %, respectively, compared to the BT treatment. There were no significant differences between the DT and BT treatments in plant height and LAI on 15 August in the three growing seasons. Both deficit irrigation treatments exhibited smaller plant height than did the full irrigation treatments. For the drip irrigation methods, the DDT did not significantly decrease plant height and LAI compared to the DT in 2012 and 2013, but the difference was significant ($P < 0.05$) in 2011. For the border irrigation methods, the DBT significantly decreased plant height on 25 July and 15 August in 2011 and 2012, but the differences were not significant on 5 July in 2011 and 2012. The DBT significantly decreased LAI on 15 August in 2011 and 2012. However, the DBT did not significantly decrease plant height and LAI compared to the BT on all dates in 2013. In summary, drip irrigation methods improved plant height, while deficit irrigation inhibited plant height and LAI.

Cotton yield and yield components

The seed cotton yield, number of bolls per plant, boll mass and lint percentage for the 3 years of study are summarized in Table 4. The seed cotton yield varied from year to year and treatment to treatment. The highest seed cotton yield was obtained from the DT treatment and ranged from 2801 (in 2011) to 3434 kg ha⁻¹ (in 2012) for the three seasons, but was only significantly different from the DDT treatment in 2011. Yield in the DDT treatment varied from 2525 (in 2011) to 3329 kg ha⁻¹ (in 2012). The lowest seed cotton yield was found in the DBT treatment, which ranged from 2136 (in 2011) to 2809 kg ha⁻¹ (in 2013). Compared to the BT treatment, the DBT significantly decreased seed cotton yield in 2011 and 2012, but the differences were not significant in 2013 (Table 5). On average for the three growing seasons, the DBT treatment produced a yield 13.3 % lower than the BT. For the full irrigation treatment, the DT treatment significantly increased seed cotton yield in comparison with the BT in 2011 and 2012. On average for the

Table 2 Evapotranspiration (ET, mm), reference crop evapotranspiration (ET₀, mm), crop coefficient (K_c) and drainage (mm) in different growth stages and over the whole season of the short-season cotton over the three seasons

Growth stage	Item	2011					2012					2013					
		DT	DDT	BT	DBT	DT	DDT	BT	DBT	DT	DDT	BT	DBT	DT	DDT	BT	DBT
The seedling stage	ET (mm)	67 ± 4.8b	60 ± 4.1b	85 ± 5.9a	70 ± 3.2b	65 ± 5.2b	58 ± 3.1b	83 ± 7.3a	64 ± 4.2b	75 ± 6.8bc	68 ± 4.1c	108 ± 9.3a	85 ± 4.5b				
	ET ₀ (mm)	119				134								124			
	K _c	0.56	0.51	0.71	0.59	0.48	0.43	0.61	0.48	0.6	0.55	0.87	0.68				
	Drainage (mm)	0	0	0	0	0	0	7 ± 0.5a	0	0	0	0	0				
The budding stage	ET (mm)	86 ± 2.9b	77 ± 4.9c	97 ± 6.3a	90 ± 6.9ab	81 ± 7.3b	71 ± 5.6b	106 ± 3.2a	72 ± 6.5b	65 ± 4.3b	71 ± 3.7ab	78 ± 5.1a	71 ± 5.0ab				
	ET ₀ (mm)	100				101				87							
	K _c	0.86	0.77	0.97	0.9	0.8	0.71	1.05	0.71	0.74	0.81	0.9	0.82				
	Drainage (mm)	0	0	6 ± 1.1a	0	0	0	0	0	21 ± 1.3a	5 ± 0.5c	23 ± 2.2a	16 ± 3.5b				
The flowering and bolls stage	ET (mm)	172 ± 0.2b	145 ± 3.9c	177 ± 1.2a	139 ± 6.8d	180 ± 9.7b	154 ± 2.2c	207 ± 8.9a	134 ± 7.3d	205 ± 6.8a	197 ± 9.0a	206 ± 7.5a	197 ± 10.2a				
	ET ₀ (mm)	155				171				199							
	K _c	1.11	0.93	1.14	0.89	1.05	0.9	1.21	0.78	1.03	0.99	1.04	0.99				
	Drainage (mm)	21 ± 1.1b	9 ± 0.8c	30 ± 3.5a	11 ± 1.3c	0	0	0	0	38 ± 5.2ab	35 ± 4.1ab	43 ± 6.1a	32 ± 3.7b				
The bolls opening stage	ET (mm)	45 ± 5.3a	42 ± 4.6a	47 ± 3.8a	40 ± 4.1a	69 ± 3.8a	58 ± 2.6b	68 ± 5.1a	53 ± 4.7b	79 ± 7.0a	68 ± 6.2ab	65 ± 6.7ab	61 ± 2.2b				
	ET ₀ (mm)	67				101				109							
	K _c	0.67	0.62	0.69	0.6	0.69	0.58	0.68	0.53	0.72	0.62	0.6	0.56				
	Drainage (mm)	0	0	0	0	0	0	0	0	0	0	0	0				
The whole growth season	ET (mm)	369 ± 9.0b	324 ± 112c	406 ± 8.4a	339 ± 9.3c	395 ± 5.6b	342 ± 8.3c	463 ± 7.7a	323 ± 5.5c	424 ± 12.5b	404 ± 9.7c	456 ± 13.6a	414 ± 8.8bc				
	ET ₀ (mm)	441				507				519							
	K _c	0.8	0.71	0.88	0.74	0.75	0.65	0.89	0.62	0.78	0.75	0.85	0.76				
	Drainage (mm)	21 ± 1.1b	9 ± 0.8c	36 ± 3.8a	11 ± 1.3c	0	0	7 ± 0.5a	0	59 ± 3.9a	40 ± 3.2c	66 ± 5.0a	48 ± 1.8b				

Letters indicate statistical significance at P_{0.05} level within the same row based on Duncan's multiple range test for each season; the row means followed by the same letter are not significantly different at the P_{0.05} level for each season

Table 3 Plant height and leaf area index of the short-season cotton during vegetation growth in different treatments in 2011, 2012 and 2013 seasons

Season	Treatment	Plant height (cm)			Leaf area index (m ² m ⁻²)		
		5 Jul	25 Jul	15 Aug	5 Jul	25 Jul	15 Aug
2011	DT	19.4 ± 1.1a	59.0 ± 2.8a	77.0 ± 3.2a	0.27 ± 0.04a	1.90 ± 0.12a	3.15 ± 0.35a
	DDT	17.6 ± 0.9b	47.6 ± 1.5c	57.5 ± 2.6c	0.20 ± 0.04ab	1.14 ± 0.20c	2.57 ± 0.20b
	BT	16.2 ± 1.7b	51.9 ± 2.3b	76.9 ± 1.5a	0.24 ± 0.03ab	1.67 ± 0.06b	3.07 ± 0.18a
	DBT	16.1 ± 2.0b	46.0 ± 2.7c	73.1 ± 1.0b	0.14 ± 0.03b	1.43 ± 0.32bc	2.63 ± 0.10b
2012	DT	23.6 ± 1.0a	71.4 ± 2.7a	77.4 ± 3.0a	0.36 ± 0.04a	2.21 ± 0.31a	2.89 ± 0.30a
	DDT	21.5 ± 1.6ab	69.3 ± 2.3ab	73.4 ± 3.7ab	0.30 ± 0.05a	2.00 ± 0.26a	2.72 ± 0.12a
	BT	21.9 ± 2.4ab	66.4 ± 1.9b	79.6 ± 2.8a	0.38 ± 0.04a	2.12 ± 0.23a	2.94 ± 0.35a
	DBT	20.2 ± 1.2b	61.6 ± 1.6c	70.5 ± 2.5b	0.36 ± 0.01a	1.66 ± 0.10b	2.43 ± 0.15b
2013	DT	38.1 ± 2.9a	75.5 ± 2.5a	78.7 ± 3.4a	0.75 ± 0.10a	2.68 ± 0.48a	3.28 ± 0.42a
	DDT	37.0 ± 1.1a	76.1 ± 2.5a	77.4 ± 2.6a	0.59 ± 0.09ab	2.37 ± 0.23a	3.01 ± 0.31a
	BT	31.3 ± 2.3b	69.9 ± 1.9b	74.3 ± 2.9a	0.52 ± 0.16b	2.47 ± 0.25a	2.92 ± 0.28a
	DBT	29.5 ± 2.2b	69.5 ± 3.0b	72.1 ± 5.7a	0.54 ± 0.10b	2.67 ± 0.36a	3.07 ± 0.40a
Irrigation methods		0.043*	0.003**	0.523ns	0.041*	0.624ns	0.287ns
Irrigation scheduling		0.045*	0.021*	0.015*	0.015*	0.024*	0.035*

ns not significant; * significant at $P < 0.05$; ** significant at $P < 0.01$ using Duncan's multiple range test

Letters indicate statistical significance at $P_{0.05}$ level within the same column based on Duncan's multiple range test for each season; the column means followed by the same letter are not significantly different at the $P_{0.05}$ level for each season

Table 4 Seed yield and yield components of the short-season cotton in different treatments in 2011, 2012 and 2013 seasons

Season	Treatment	Seed yield (kg ha ⁻¹)	Number of bolls per plant	Boll mass (g)	Lint percentage	Lint yield (kg ha ⁻¹)
2011	DT	2801 ± 45a	11.4 ± 0.2a	3.63 ± 0.16a	39.29 ± 0.52bc	1100 ± 17a
	DDT	2525 ± 82b	10.6 ± 0.3b	3.54 ± 0.08a	41.65 ± 0.61a	1051 ± 34a
	BT	2457 ± 67b	11.4 ± 0.4a	3.19 ± 0.22b	38.39 ± 0.43c	943 ± 25b
	DBT	2136 ± 108c	9.7 ± 0.4c	3.26 ± 0.11b	39.60 ± 0.41b	846 ± 43c
2012	DT	3434 ± 173a	11.1 ± 0.3a	4.58 ± 0.23a	39.63 ± 9.63b	1361 ± 69a
	DDT	3329 ± 71a	10.7 ± 0.4a	4.61 ± 0.10a	40.41 ± 0.20a	1345 ± 28a
	BT	2986 ± 100b	10.9 ± 0.2a	4.06 ± 0.14b	39.16 ± 9.16b	1169 ± 41b
	DBT	2434 ± 68c	8.8 ± 0.6b	4.11 ± 0.20b	40.86 ± 0.86a	995 ± 28c
2013	DT	3257 ± 177a	11.3 ± 0.4a	4.26 ± 0.22a	38.13 ± 0.41b	1242 ± 67a
	DDT	2990 ± 157ab	10.6 ± 0.5a	4.17 ± 0.18a	38.93 ± 0.32a	1164 ± 61ab
	BT	3069 ± 134ab	10.9 ± 0.3a	4.18 ± 0.13a	38.09 ± 0.45b	1169 ± 55ab
	DBT	2809 ± 162b	10.9 ± 0.2a	3.82 ± 0.15b	38.69 ± 0.38ab	1087 ± 59b

Letters indicate statistical significance at $P_{0.05}$ level within the same column based on Duncan's multiple range test for each season; the column means followed by the same letter are not significantly different at the $P_{0.05}$ level for each season

three growing seasons, the drip irrigation method produced relatively greater seed cotton yield, and a deficit irrigation schedule reduced the seed cotton yield significantly (Table 5).

The irrigation treatments also significantly affected the number of bolls per plant, boll mass and lint percentage (Table 4). The DBT treatment significantly ($P < 0.05$) reduced the production of bolls per plant by 14.9 % in 2011 and 19.5 % in 2012 compared to the BT, but no significant differences were observed between these two treatments in

Table 5 Statistical analysis of seed cotton yield in 2011, 2012 and 2013 seasons

Types	Irrigation methods	Irrigation scheduling
2011	0.022*	0.005**
2012	0.005**	0.011*
2013	0.103ns	0.076ns
Mean	0.003**	0.002**

ns not significant; * significant at $P < 0.05$; ** significant at $P < 0.01$ using Duncan's multiple range test

2013 due to the heavier precipitation during the boll setting stage. Similarly, the DDT also showed a significant ($P < 0.05$) reduction in bolls per plant by 7.8 % in 2011 in comparison with the DT treatment, and it tended to reduce the number of bolls per plant but with no statistically significant differences observed in 2012 and 2013. However, considering the full irrigation treatments, the irrigation methods had no significant influence on the number of bolls per plant but had significant influence on the boll mass in the 2011 and 2012 growing seasons. The DT produced 13.6 and 12.9 % higher boll mass than the BT in 2011 and 2012, respectively, while no significant differences were found in 2013. The deficit irrigation had no significant effect on the boll mass in the 2011 and 2012 growing seasons, but the DBT treatment significantly reduced boll mass compared to the BT treatment in 2013. In addition, the deficit irrigation significantly affected the lint percentage in all three growing seasons. The DBT treatment increased the lint percentage by 1.2 % in 2011, 1.7 % in 2012 and 0.5 % in 2013 compared to the BT treatment. The DDT increased the lint percentage by 2.4 % in 2011, 0.8 % in 2012 and 0.8 % in 2013 compared to the DT. Drip irrigation tended to increase the lint percentage and produced more lint yield to a certain extent.

Water use efficiency

The ET, I_r and WUE of the short-season cotton in the different treatments in the three seasons are presented in Table 6. There were statistically significant differences between the treatments for WUE. The deficit irrigation treatments significantly increased WUE in 2012 compared with the full irrigation treatments, but no significant differences were seen in 2011 and 2013. In all 3 years, WUE was

significantly greater in the drip irrigation treatments compared with the border irrigation treatments. Considering the full irrigation scheduling, the DT treatment increased the WUE values by 25.4, 35.1 and 14.3 % compared to the BT treatment in 2011, 2012 and 2013, respectively.

Fiber quality

Some quality parameters related to the short-season cotton lint, such as fiber length, fiber uniformity, micronaire, fiber elongation and fiber strength, are presented in Table 7. The

Table 6 Water use efficiency (WUE) of the short-season cotton in different treatments in 2011, 2012 and 2013 seasons

Season	Treatment	ET (mm)	Irrigation (I_r) (mm)	WUE (kg m^{-3})
2011	DT	369 ± 9.0b	145	0.76 ± 0.02a
	DDT	324 ± 11.2c	85	0.78 ± 0.01a
	BT	406 ± 8.4a	213	0.61 ± 0.03b
	DBT	339 ± 9.3c	76.4	0.63 ± 0.04b
2012	DT	395 ± 5.6b	150	0.87 ± 0.04b
	DDT	342 ± 8.3c	90	0.97 ± 0.02a
	BT	463 ± 7.7a	240	0.64 ± 0.03d
	DBT	323 ± 5.5c	73	0.75 ± 0.04c
2013	DT	424 ± 12.5b	120	0.77 ± 0.01a
	DDT	404 ± 9.7c	75	0.74 ± 0.02a
	BT	456 ± 13.6a	171	0.67 ± 0.05b
	DBT	414 ± 8.8bc	77	0.68 ± 0.04b

Letters indicate statistical significance at $P_{0.05}$ level within the same column based on Duncan's multiple range test for each season; the column means followed by the same letter are not significantly different at the $P_{0.05}$ level for each season

Table 7 Cotton quality parameters in different irrigation treatments in 2011, 2012 and 2013 seasons

Season	Treatment	Fiber length (mm)	Fiber uniformity (%)	Micronaire	Fiber elongation (%)	Fiber strength (g tex^{-1})
2011	DT	28.68 ± 0.35a	83.23 ± 0.68a	4.0 ± 0.11b	6.5 ± 0.07a	28.80 ± 0.41a
	DDT	28.24 ± 0.43a	82.40 ± 0.49a	4.4 ± 0.21a	6.4 ± 0.05a	27.77 ± 0.52b
	BT	28.63 ± 0.25a	82.43 ± 0.50a	3.5 ± 0.25c	6.5 ± 0.08a	28.70 ± 0.30a
	DBT	28.23 ± 0.22a	82.60 ± 0.73a	3.5 ± 0.27c	6.5 ± 0.11a	27.75 ± 0.28b
2012	DT	29.25 ± 0.31a	82.78 ± 0.51a	4.2 ± 0.29bc	6.5 ± 0.09a	30.14 ± 0.22a
	DDT	29.04 ± 0.20a	83.02 ± 0.63a	4.7 ± 0.17a	6.4 ± 0.03a	29.43 ± 0.47b
	BT	29.00 ± 0.47a	82.15 ± 0.46a	4.0 ± 0.14c	6.5 ± 0.10a	30.16 ± 0.35a
	DBT	28.97 ± 0.28a	82.78 ± 0.33a	4.4 ± 0.11b	6.4 ± 0.13a	29.63 ± 0.10b
2013	DT	28.06 ± 0.20a	84.70 ± 0.55a	4.6 ± 0.21a	6.5 ± 0.03a	28.72 ± 0.40a
	DDT	27.13 ± 0.28b	84.98 ± 0.91a	4.8 ± 0.15a	6.6 ± 0.07a	28.32 ± 0.49ab
	BT	27.64 ± 0.43ab	85.27 ± 0.64a	4.7 ± 0.17a	6.5 ± 0.08a	28.92 ± 0.51a
	DBT	26.99 ± 0.40b	85.50 ± 0.35a	4.7 ± 0.18a	6.6 ± 0.05a	27.52 ± 0.63b

Letters indicate statistical significance at $P_{0.05}$ level within the same column based on Duncan's multiple range test for each season; the column means followed by the same letter are not significantly different at the $P_{0.05}$ level for each season

study revealed that the fiber elongation of cotton lint was not affected by the water application methods. The fiber length was found to be lengthened in response to the drip irrigation method. The fiber length in the DT treatment was on average 0.9 % longer than that in the BT treatment, but not significantly different. The deficit irrigation treatments produced no significant differences in the fiber length in 2011 and 2012, but significantly decreased the fiber length in 2013. The fiber length in general shortened in response to deficit irrigation scheduling. The DBT treatment was 1.2 % shorter than the BT treatment, and the DDT treatment was 1.8 % shorter than the DT treatment on average for the three growing seasons. Any irrigation effect on fiber uniformity was too inconsistent to be definitively assessed. There were no significant influences on the micronaire values among the irrigation treatments in 2013. However, the irrigation treatments had significant influences on the micronaire in 2011 and 2012. The highest micronaire value was observed in the DDT treatment, and the lowest micronaire value was observed in the BT treatment. Thus, the drip irrigation method and deficit irrigation generally increased the micronaire. Similarly, there were no statistically significant differences in the fiber strength between the two irrigation methods in all years, but the deficit irrigation treatments significantly decreased the fiber strength for all years. On average, the DDT decreased the fiber strength by 2.4 % compared to the DT, and the DBT decreased the fiber strength by 3.3 % in comparison with the BT.

Discussion

Effect of irrigation water management on ET in cotton cultivation

In this study, the largest ET in the short-season cotton cultivation was found in the middle stage, and relatively lower ET values were observed at the early and later stage, which is in accordance with the water requirement for the cotton growth process and was similar to the result of Farahani et al. (2008) in the Mediterranean. The drip irrigation point emitters keep a small fraction of the surface frequently wet, while the rest of the area remains dry (Bonachela et al. 2001), thereby reducing soil evaporation (Kang et al. 2012). Thus, a lower ET was measured in the drip irrigation treatment compared with the border irrigation. Water stress generally inhibits leaf growth (Table 3), which results in decreasing the transpiration area of the leaves. In addition, water stress would reduce the soil moisture content of the topsoil and thereby reduce soil evaporation. Therefore, compared with the full irrigation treatments, the deficit irrigation treatments show lower values of ET in different stages and over the whole season.

An average ET value of 398 mm, which was obtained in the DT, was in accordance with the 396 mm of cotton in Minqin of Gansu Province reported by Du et al. (2008). However, this ET value was not in accordance with those found in other areas where the highest cotton ET values under drip irrigation were found to be between 450 and 800 mm (Cetin and Bilgel 2002; Ertek and Kanber 2003; Ibragimov et al. 2007; Dağdelen et al. 2009; Ünlü et al. 2011; Kang et al. 2012). These differences may have been due to the differences in climate and agricultural practices in the different regions and to the short-season cotton variety cultivated in this study.

Effect of irrigation water management on growth and development of cotton plant

It is well known that drip irrigation can apply frequent and uniform water into the soil in the root zone in accordance with crop water requirements and does not disturb soil structure. Kang et al. (2004) illustrated that in drip irrigation water, the nutrients, gases and heat inside the soil are well maintained and able to adapt for crop growth. However, surface flooding will inhibit soil aeration due to the higher water application, and packed ground produces surface cracks after irrigation. Sometimes, some roots of the cotton seedling are torn by the soil cracks, prolonging seedling recovery and inhibiting root growth, which inevitably inhibits plant vegetative growth. This is the main reason why the average plant height and LAI in the early stage of the short-season cotton with drip irrigation were higher than with border irrigation in this study (Table 3). Then, the differences in plant height and LAI between drip irrigation and border irrigation gradually decreased with vegetative growth because of the lower precipitation in June (seedling stage) and heavier precipitation in July (squaring stage) (Fig. 1). These stages are the main vegetative growth stages for the short-season cotton during these 2 months. As reported by many researchers, deficient irrigation practices can cause a significant decline in cotton vegetative growth parameters, while excessive irrigation can cause an increase in vegetative growth (Dağdelen et al. 2009; Ünlü et al. 2011; Kang et al. 2012). Similar results were also observed in this study.

Effect of irrigation water management on the short-season cotton yield

This study found that drip irrigation produced more cotton yield than the border irrigation in 2011 and 2012 due to three main reasons as follows: Firstly, the point-source emitters keep a small fraction of the surface frequently wet, while the rest of the area remains dry in a drip irrigation system, which will probably improve soil aeration

(Bonachela et al. 2001; Kang et al. 2004). Thus, drip irrigation contributes to the absorption of soil water and nutrients and promotes production. Secondly, a higher boll mass was obtained in the drip irrigation treatments than in the border irrigation treatments (Table 4). Finally, drip irrigation tended to produce a higher lint percentage. This indicated that drip irrigation not only improved the seed cotton yield but also increased the lint yield by increasing the lint percentage in comparison with the border irrigation. In 2013, the drip irrigation could not improve cotton growth and boll setting due to the additional precipitation received during the flowering and boll setting periods (Fig. 1). Thus, drip irrigation did not significantly affect the seed cotton yield.

Because the cotton seeds were immature hollow kernels when water stress occurred during the boll maturing stage (Mao 2013), cotton seed mass would decrease under deficit irrigation conditions, which is in accordance with the results reported by Pettigrew (2004). This study also shows that deficit irrigation significantly increased the lint percentage (Table 4). The reason was the increase in the lint percentage of the drip-irrigated cotton with deficit irrigation (Table 4). Deficit irrigation reduced the loss of lint cotton yield to a certain extent. Therefore, although the DDT treatment significantly decreased seed yield in comparison with the DT treatment in 2011, no significant influence on the lint yield was found between the DT and DDT treatments in all years. Because of differences in meteorological factors and precipitation distribution during the growing seasons, deficit irrigation significantly decreased the number of bolls per plant in 2011 and 2012, which was similar to the results in drip-irrigated cotton measured by Ibragimov et al. (2007) and Kang et al. (2012). Ünlü et al. (2011) also studied the effects of deficit drip irrigation on the number of bolls per plant of cotton. They reported that deficit drip irrigation significantly reduced the number of bolls per plant in two seasons. In this study, no significant differences in the number of bolls per plant, boll mass and seed yield were obtained among DT, DDT and BT in 2013 due to the greater rainfall during the squaring, flowering and boll setting periods (Fig. 1). However, because of the lower precipitation during the boll development period, water stress occurred in the no-irrigation treatment during this period (DBT), so the DBT treatment produced a significant decline in boll mass, which was the main reason why the cotton seed yield decreased in the DBT treatment.

The boll masses below 4.0 g for all of the treatments in 2011 were much lower than those in other years due to the different meteorological factors. Numerous studies have reported that temperature and sunshine hours are the key meteorological factors influencing cotton production (Reddy et al. 2005; Sawan 2009; Sawan et al. 2010; Hatfield et al. 2011). August and September are the key months for short-season cotton growth from boll development to

boll opening. In this study, several continuously cloudy and rainy days happened in August and September in 2011 (Fig. 1). The daily average temperature in August decreased by 0.5 °C compared to the 60-year mean. However, the daily average temperature of 19.2 °C in September decreased by 2.3 °C in comparison with the 60-year mean, which is much lower than the optimal temperature of 20–30 °C for cotton growth (Mao and Dong 2003). Reddy et al. (2005) reported that maximum growth rate per boll occurs at 25–26 °C and then declines at lower or higher temperatures. Hatfield et al. (2011) also found that there was a quadratic equation between cotton yield and temperature and that the maximum yield occurred at 25 °C. Additionally, the daily average sunshine hours of 4.0 h decreased by 2.9 h in August 2011 compared to that of the 60-year mean in this study. A decrease in sunshine hours can prolong the boll growing period and delay maturity (Mao and Dong 2003); thus, boll mass was reduced. Therefore, low temperature and light conditions can prolong the development of bolls. Additionally, because of the increased competition between the leaves and bolls for available assimilates, excessive precipitation can delay the boll growth period and reduce the number of open bolls (Kang et al. 2012) and then decrease the number of bolls, which leads to the generally decreased cotton yield seen in 2011.

Over the three seasons, the seed yield of cotton in the DT treatment varied from 2801 to 3434 kg ha⁻¹ and the lint yield in DT ranged from 1100 to 1361 kg ha⁻¹ (Table 4), which was similar to the results of Ünlü et al. (2011), who reported an average seed cotton yield of 3397 kg ha⁻¹ over 4 years for drip-irrigated cotton in Turkey and is also similar to the findings of Pettigrew (2004), who reported that lint yield ranged from 845 to 1158 kg ha⁻¹ for irrigated cotton in USA. However, the finding of the present study was lower than the 4380 kg ha⁻¹ seed cotton yield reported by Cetin and Bilgel (2002) and the 5760 kg ha⁻¹ seed cotton yield reported by Dağdelen et al. (2009). These differences may have been due to the differences in climate and agricultural practices in the different regions. Additionally, in China, Dong et al. (2006) reported that lint yield was 1185 kg ha⁻¹ for irrigated cotton in the same region, which is similar to the results of this study. However, the results of the present study were lower than the 4500 kg ha⁻¹ seed yield reported by Kang et al. (2012) in Northwest China, but higher than the 2652 kg ha⁻¹ seed yield reported by Du et al. (2008) in Minqing. Differences in climate, soil and cotton varieties were mainly attributed to these differences in cotton yield.

Effect of irrigation water management on water use efficiency for the short-season cotton

Compared to the border irrigation, the drip irrigation significantly increased WUE of the short-season cotton (Table 6),

which was similar to the findings of Cetin and Bilgel (2002) in Turkey and Ibragimov et al. (2007) in Uzbekistan. WUE varied from 0.76 to 0.97 kg m⁻³ under drip irrigation conditions in this study. In general, our results differed from those of previous studies conducted in different regions. Yazar et al. (2002) and Ünlü et al. (2011) found that WUE values for drip-irrigated cotton ranged from 0.48 to 0.74 kg m⁻³, and WUE of 0.49 kg m⁻³ under drip irrigation was reported by Cetin and Bilgel (2002) in Turkey. Although more seed yield was obtained, more water was consumed in those studies. Thus, lower WUE values were obtained compared to the present study. However, Dağdelen et al. (2009) reported that WUE values in Turkey for drip-irrigated cotton ranged from 0.76 to 0.98 kg m⁻³, which were greater than those studies mentioned above in the same region but similar to the results of our study. Ibragimov et al. (2007) found that WUE values for drip irrigation in Uzbekistan varied from 0.63 to 0.88 kg m⁻³, which was similar to our findings. This indicated that higher WUE could be obtained with a short-season cotton variety transplanted after the winter wheat harvest.

As mentioned above, compared with the traditional irrigation method, drip irrigation resulted in water savings, high seed cotton yield and high water use efficiency. Also, drip irrigation has been suggested as a means of supplying most types of crops with frequent and uniform applications of water, adaptable over a wide range of topographic and soil conditions (Cetin and Bilgel 2002; Dagdelen et al. 2009). Moreover, drip irrigation can apply water both precisely and uniformly at a high frequency compared with furrow and sprinkler irrigation (Hanson and May 2006). However, installation of drip irrigation systems may cost approximately US\$ 2500 per hectare (Ma et al. 2004; Hanson et al. 2006). If the automatic control system is applied, the cost could be more than \$ 4500 per hectare (Ma et al. 2004). Therefore, one of the greatest obstacles to the widespread adoption of this method is its relatively high costs of initial installation and operation (Thompson et al. 2009; Guan et al. 2013), that is the main reason the farmers do not like using drip irrigation in the NCP.

Effect of irrigation water management on fiber quality for the short-season cotton

In general, the fiber quality of irrigated cotton varies in response to irrigation depending on genotype, irrigation management and climatic conditions (Ünlü et al. 2011). This research determined that drip irrigation treatment tended to increase fiber length compared to border irrigation treatment under the same irrigation scheduling, but no statistically significant difference was obtained between the different irrigation methods in all years, which is in

accordance with the findings of Constable and Hodgson (1990). Dağdelen et al. (2009) reported that water stress during the early flowering period does not alter the fiber length, which is similar to the findings that deficit irrigation did not significantly affect the fiber length in 2011 and 2012 of this study. However, water stress occurring during the fiber elongation stage can shorten the fiber length due to the direct mechanical and physiological processes of cell expansion (Pettigrew 2004; Dağdelen et al. 2009). So, the deficit irrigation significantly shortened the fiber length in the 2013 growing season. Similar results have also been reported by Ünlü et al. (2011) and Guan et al. (2013).

Constable and Hodgson (1990) found no significant difference in the fiber strengths for different irrigation methods, which agrees with the results of the present study. However, deficit irrigation produced a significant decline in fiber strength in all years in this study due to variations in the growth environment (Dağdelen et al. 2009). This response disagrees with the findings of Pettigrew (2004) and Ünlü et al. (2011). They reported that irrigation levels had no effect on fiber strength. However, Dağdelen et al. (2009) and Guan et al. (2013) reported that deficit irrigation generally reduced the fiber strength, which is similar to the results of this study.

The effect of water deficiency and different irrigation methods on the micronaire was not consistent throughout the 3 years. In general, the deficit irrigation tended to increase the micronaire values for a given irrigation method in this study. This response is contradictory to the results of Pettigrew (2004) and Snowden et al. (2013), who reported that irrigation increased micronaire in some years. However, Dağdelen et al. (2009) and Guan et al. (2013) found that deficit irrigation generally increased the micronaire, which is similar to the finding of this study. Furthermore, the acceptable level of micronaire is considered to be between 3.5 and 4.9, the best level of micronaire is considered to be between 3.7 and 4.2, and the quality generally suffers when the micronaire is greater than 4.9 or less than 3.5 (Chinese Standard 2007). The micronaire values for all treatments in all years were within the acceptable range in this study. The micronaire values for the DT treatment in 2011 and 2012 were within the best range, which indicated that drip irrigation could optimize the micronaire.

The fact that some of the fiber parameters, such as fiber uniformity and fiber elongation, did not respond to irrigation management can probably be explained by genotype differences (Ünlü et al. 2011). Similar results were reported by Pettigrew (2004) and Guan et al. (2013).

The net pricing of lint yield based on fiber parameters in the different treatments in the three seasons is presented in Fig. 4. There were statistically significant differences

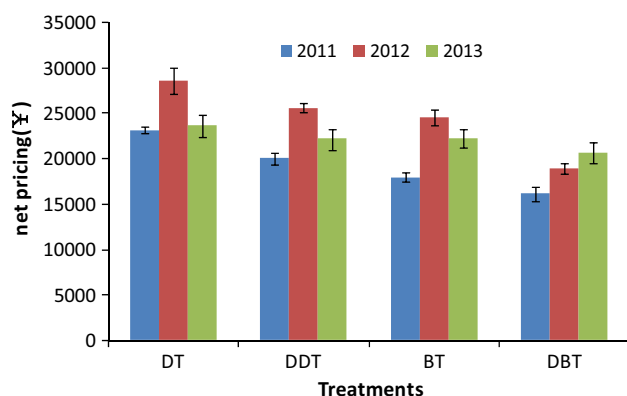


Fig. 4 Net pricing of lint yield based on fiber parameters of the short-season cotton in different treatments

between the treatments in 2011 and 2012, but no significant differences between the treatments in 2013. Drip irrigation significantly increased the net pricing of lint yield in terms of different irrigation methods. On average for the three growing seasons, the DT treatments increased the net pricing by 16.4 % compared to the BT treatments. Under the same irrigation method, the deficit irrigation decreased the net pricing of lint yield. On average for the three growing seasons, the DDT treatments decreased the net pricing by 10.1 % compared with the DT treatments, and the DBT treatments decreased net pricing by 14.0 % compared with the BT treatments.

Conclusion

As a result of this 3-year study, it was concluded that seed cotton yield was significantly affected by irrigation management. The DDT significantly increased the lint percentage, but did not significantly influence the lint yield in comparison with the DT. On average for the three growing seasons, the DT increased the lint yield by 12.9 % compared to the BT. Drip irrigation increased WUE and tended to lengthen the fiber length and optimize the micronaires within the acceptable range. Deficit irrigation significantly reduced the fiber strength and tended to decrease the fiber length under the same irrigation methods. It was concluded that full drip irrigation conditions as described for the DT could be used to produce higher yield for the short-season cotton cultivated continuously after harvesting winter wheat in the North China Plain.

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