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Comprehensive analysis on investigating water-saving potentials of irrigated cotton in semi-arid area in China

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ABSTRACT

Deficit irrigation is a common strategy to reduce water use and improve the sustainability of cotton production. However, the effects of water deficits on crop productivity and quality are subject to genotype by management by environmental interactions. This study investigated effects of water deficits and frequency of irrigation on cotton performance grown in semi-arid region, Xinjiang, the main cotton-growing area in China. Two field trials (2020 and 2021) with split experimental design, including main factors of three irrigation levels (moderate-deficit, mild-deficit and full-irrigation) and split factors of three irrigation frequencies (4, 8 and 12 days) were conducted. Results from two trials both showed little negative influence of irrigation levels on yield, and higher irrigation frequency improved yield under same irrigation level. Significant effects of irrigation levels on yield components were found in 2021, with a 22 % increase in boll number and an 18 % reduction in boll weight under moderate-deficit irrigation compared with those under full-irrigation. Interactions between irrigation levels and frequencies significantly affected harvest index (HI), showing that reduced irrigation might be beneficial for improving HI. However, decreased fibre length while increased fibre micronaire were found under deficit irrigation. A strong association between radiation use efficiency (RUE) and boll growth rate was observed, suggesting that RUE might be the driving force of yield formation. A tight correlation between both biomass and transpiration efficiency versus delta temperature between air and canopy (ΔTair-canopy) was observed, suggesting ΔTair-canopy could be used as an efficient tool to assess plant production under deficit irrigation. This study provided an improved understanding of the physiological basis of cotton yield formation and further identified a high-throughput and instantaneous method to monitor effects of deficit irrigation on crop productivity.

1. Introduction

Water shortage which steadily reduces water allocation to agriculture, is limiting crop production particularly in the semi-arid and arid areas in the world (Datta et al., 2019; Tsakmakis et al., 2017). At the same time, an approximately 70 % improvement in agricultural production will be required to meet the world's need for basic food and fibre by 2050 (Webb, 2005). Water scarcity, in addition to erratic precipitation and drought, has become one of the major challenges to global food security and sustainable agricultural production. To face the increasing challenges of insufficient water supply for agriculture and food security, deficit irrigation has been adopted in dry areas (Grimes et al., 1969; Fereres and Soriano, 2007; Geerts and Raes, 2009). Deficit irrigation is defined as the deliberate under-irrigation of a crop such that it receives

Abbreviations: ΔTair-canopy, Delta air and canopy temperature; DAS, days after sowing; EAT, effective accumulated temperature; HI, harvest index; NumFB, number of fruiting branches; PAR, photosynthetically available radiation; RUE, radiation use efficiency; TE, transpiration efficiency; WUE, water use efficiency.

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less water than the crop evaporation needed to achieve maximum yield (Zhang et al., 2016).

Numerous studies have explored relationships between water application and crop productivity (Doorenbos and Kassam, 1979; Ertek and Kanber, 2003; Du et al., 2006; DeTar, 2008; Ermanis et al., 2021; Cheng et al., 2021). It has been reported that deficit irrigation could save up to 50 % water and enhance water use efficiency (WUE) by 20–30 % with little penalty on crop production (Bramley et al., 2013). A 12-year drip irrigation experiment with a wide range of water application rates showed an only 2.6 % averaged yield loss by reducing water applications by 20 % compared with the water used to achieve maximum yields (Wanjura et al., 2002). Researchers also found no significant variation in yield among different irrigation levels and frequencies, however, in a low-yielding season, a significant reduction in yield was found under low irrigation levels (Ertek and Kanber, 2003). This means the impact of different deficit irrigation treatments on crop production varies from year to year. Therefore, a better understanding of the underlying physiological determinants that limit yield under different irrigation strategies is needed. Crop yield is the product of cumulative photosynthetically active radiation (PAR) intercepted by the crop canopy during the growing season (Evans, 2013), the efficiency with which a crop converts PAR into biomass (radiation use efficiency, RUE), and the percent of total biomass allocated to economical yield (harvest index, HI). Crop yield is further determined by water consumption, transpiration efficiency (TE) and HI, under water-limiting conditions (Passioura, 1996). Studying the effects of deficit irrigation with regard to these individual yield determinants will therefore provide us with a better understanding of the physiological mechanism underpinning the response on yield and may provide us with a way to monitor crop performance under different irrigation regimes.

Cotton (*Gossypium hirsutum* L.), as an important industrial crop for fibre, plays an important role in the economy of many countries (Khan et al., 2020). Cotton is relatively drought-tolerant (DeTar, 2008), however, deficit irrigation could substantially limit potential seed cotton yield, which is usually associated with a decline in boll number per land area (Hu et al., 2018). Fibre quality has also been reported to be reduced by water stress due to increased fibre micronaire and decreased length (Hu et al., 2018). Different amounts of water are required at different growth stages, varying from 2.5 mm per day at the seedling stage to the peak of 6.2–10 mm per day during flowering, when about 40 % of total seasonal water is consumed (Datta et al., 2019). Water stress during the most critical growth stages of flowering and boll opening is most detrimental and can result in about 50–80 % yield loss in cotton (Datta et al., 2019). Exploiting various water-efficient techniques is therefore of great importance to maintain high yield and quality of cotton in China, particularly since water resources are extremely scarce in Xinjiang, the primary cotton growing area in China.

Therefore, the objectives of this study were to explore sustainable irrigation strategies to improve cotton performance in semi-arid areas, by using deficit irrigation methods. A two-year field trial was conducted in Xinjiang to investigate the effects of irrigating at three different levels (deficit irrigation: 3200 and 3700 m^3 ha^{-1}, and full irrigation: 4200 m^3 ha^{-1}) and three irrigation frequencies (every 4, 8 and 12 days) on seed cotton yield, HI, fibre quality, critical physiological traits and canopy thermal response.

2. Materials and methods

2.1. Experimental site and design

A two-year field trial was conducted in 2020 and 2021 at the Alar Station (40, 36'N, 81, 19'E) of the Institute of Cotton Research of the Chinese Academy of Agricultural Sciences. A split plot design with three replications was used, including main plot factors of irrigation levels (3200, 3700, 4200 m^3 ha^{-1}) and split plot factors of irrigation frequencies (every 4, 8, 12 days), resulting in nine treatments in total

Table 1
Details of treatments in two field trials.

Main plot Irrigation level (m^3 ha^{-1})	Split plot Frequency (days)	Abbreviation of treatment
3200 (moderate-deficit irrigation)	4	3200–4
	8	3200–8
	12	3200–12
3700 (mild-deficit irrigation)	4	3700–4
	8	3700–8
	12	3700–12
4200 (full-irrigation)	4	4200–4
	8	4200–8
	12	4200–12

(Table 1). According to local planting practices and previous studies (Chai et al., 2015; Yang et al., 2015; Zhang et al., 2016), 4200 m^3 ha^{-1} is the conventional amount of drip irrigation for cotton in this area (well-watered), and the other two levels are mild deficit (3700 m^3 ha^{-1}) and moderate deficit (3200 m^3 ha^{-1}). Drip irrigation was implemented using a customized irrigation system, featuring 16 mm tape with drip emitter spaced 30 cm apart, and a flow rate of 2.6 L h^{-1}. The two field trials were sown on 20 April 2020 and 19 April 2021. A commonly used cotton variety, SCRC619, was planted at a density of 90,000 plants ha^{-1} and in both trials each plot consisted of four rows (Fig. 1A). Meteorological conditions (average monthly temperature and precipitation, Fig. 2) were recorded by a weather station near the site during the two seasons. The site has a warm-arid desert climate and mainly sandy loam soil. Prior to planting, the top 20 cm of soil contained 10.58 g kg^{-1} organic matter, 84.87 mg kg^{-1} alkalihydrolyzable nitrogen, 0.64 g kg^{-1} total nitrogen, 25.38 mg kg^{-1} available phosphorus, and 190.5 mg kg^{-1} available potassium with a pH of 7.7. For medium-term management, mechanical cultivation methods were used, including weeding, along with spraying pesticides and plant growth regulators. Additionally, chemical control methods were employed to manage pests and diseases. In both trials, all plots had good establishment and no nutrient stress was observed. And all the plots were hand-harvested after reaching physical maturity on 6th October in 2020 and 8th October in 2021.

2.2. Data collection

2.2.1. Plant growth associated traits

To investigate the effects of different irrigation levels and frequencies on plant growth and development, leaf gas exchange, biomass, and number of fruiting branches (NumFB) were determined. Gas exchange measurements were performed on the third last leaf of one randomly selected plant in each plot by using a LI-6800 (LI-COR, inc., Lincoln, Nebraska USA) with the 6800–01 A light source which has a chamber size of 6 cm^2, at 87 days after sowing (DAS), flowering stage, as which is the most critical growth stage for cotton yield formation. For biomass harvesting, two plants with even stands and selected randomly were dug out in the middle two rows of each plot every 15 days from 57 DAS in 2020 and 58 DAS in 2021 (seedling stage). The plants were then separated into roots, stems, leaves and bolls, and then dried in an oven (80 °C) until constant weight. The NumFB as a good indicator of yield potential was determined on two plants selected randomly in each plot at 160 DAS in 2020 and 153 DAS in 2021 (boll-opening stage).

2.2.2. Canopy light interception, soil moisture content and canopy temperature

A spatial grid method was used to investigate variations in canopy light interception and soil moisture content among different treatments as sampling points in vertical and horizontal directions shown in *Fig. 1* . A customized rack, equipped with 30 photosynthetically available radiation (PAR) sensors (LI-190R, Licor, inc., Lincoln, Nebraska USA) at an interval of 20 cm in both vertical and horizontal directions was used to determine canopy light interception in one plot of each treatment.

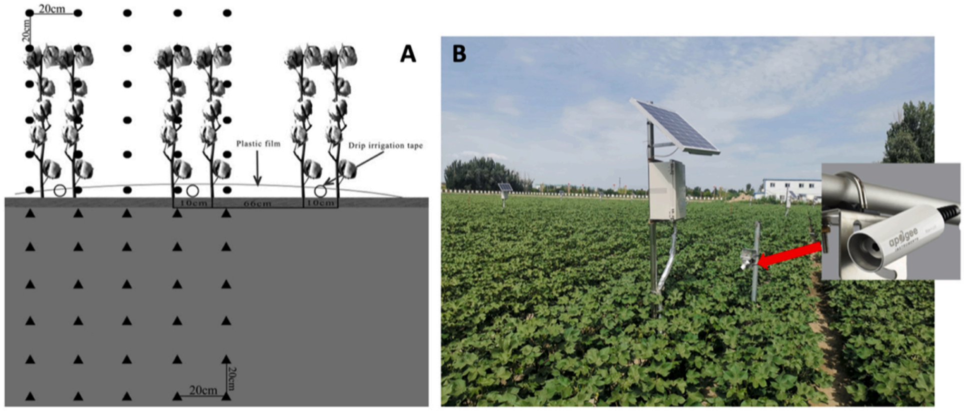

Fig. 1. Layout of four rows in each plot of both trials with diagram of sampling points for canopy light interception and soil moisture content (A), and image showing sensor setup for canopy temperature measurements (B). Note: Row spacing (10 and 66 cm) and intervals (20 cm in both vertical and horizontal directions) of sampling points above- (solid circles) and under-ground (solid triangles) (A); circles between two narrow rows show drip irrigation tapes (A). A solar panel powered system for continuously recording canopy temperature is shown (B).

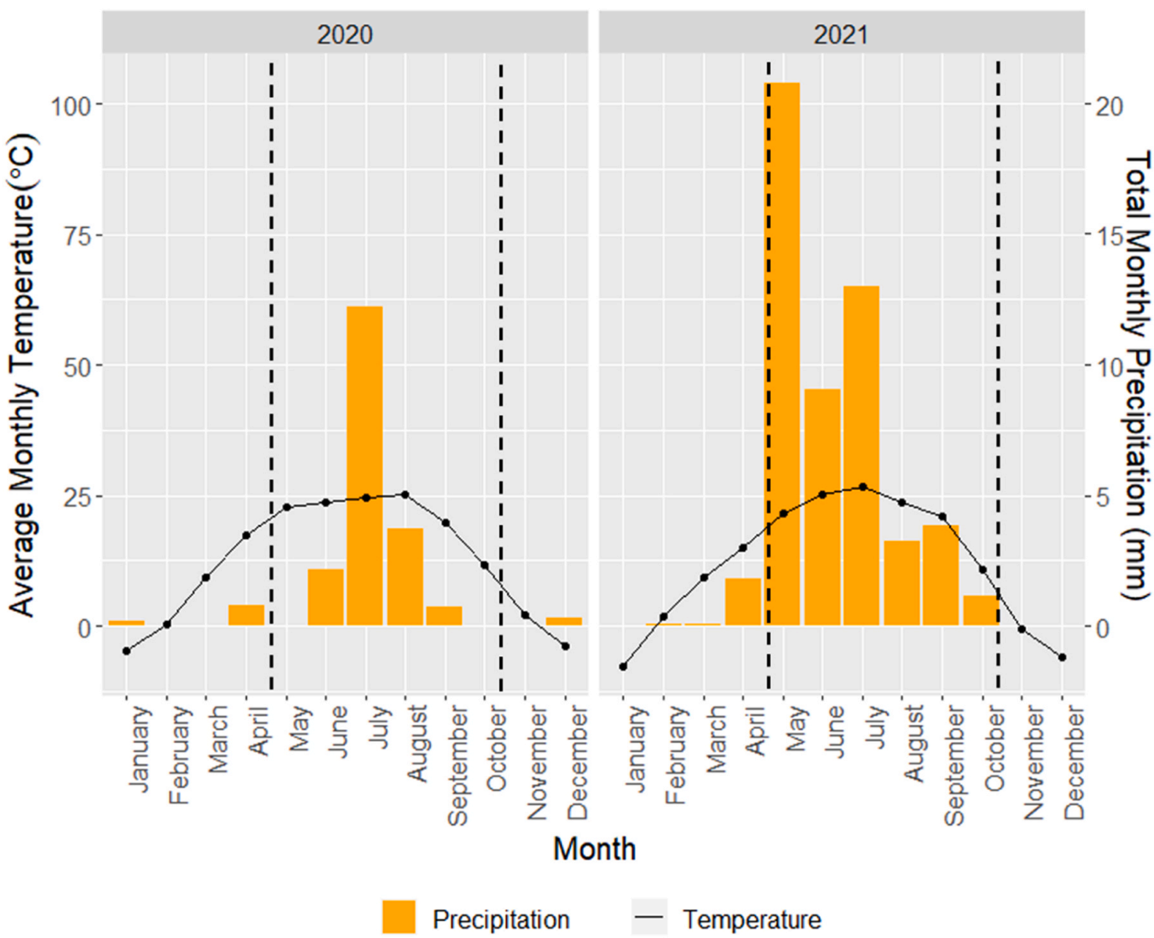

Fig. 2. Monthly average temperature and total precipitation during cotton growth duration in 2020 and 2021. Note: The dash lines indicate the growing season from 20th April to 6th October in 2020 and 19th April to 8th October in 2021.

Incident PAR at each sampling point throughout the canopy was recorded by a customized data logger to calculate light interception of the whole canopy (Zhi et al., 2014, 2019).

Soil moisture content (m^3 m^{-3}) was recorded continually at an interval of one hour over the growth seasons in two trials, using 30 water content sensors (5TE, Decagon Devices Inc., Pullman, WA) distributed aligned to the under-ground sampling points (solid triangle points in *Fig. 1*) following the method reported previously (Wu et al., 2022). Throughout the two seasons, the soil moisture content in the top layer (0–20 cm), averaged across the main factors (irrigation levels), split factors (irrigation frequencies) and their interactions were shown in Figure S1.

Canopy temperature of each plot was determined during the cotton critical growth stage, by averaging two values from two infrared radiometers (SI-411, Apogee Instruments, USA). This sensor is only sensitive from 8 to 14 μm (atmospheric window), which is beneficial for minimizing the influence of water vapor and CO_2 on the measurements. It is therefore typically used to monitor plant canopy temperature to estimate plant water status (Drew et al., 2019; Huang et al., 2022; Mira-García et al., 2022). The sensor has a single 22° half-angle field of view option and a response time of 0.1 seconds, with a measurement uncertainty of ± 0.5 °C from 0 to 50 °C. Sensors as shown in *Fig. 1* were mounted to customized solar panel platforms which were used to power the dataloggers for continuous output. Two digital values including target temperature (canopy) and detector temperature were output by each sensor. The detector temperature was defined as air temperature to evaluate differences between air and canopy temperature (ΔTair-canopy), given detector temperature is reported to be very near to air temperature.

2.2.3. Yield, yield components and fibre quality

After physiological maturity, each plot was hand-harvested twice within one week to avoid underestimation in both trials to determine seed cotton yield. To determine yield components, 100 randomly collected, fully opened bolls were used to determine lint percent and individual boll weight. In addition, boll number per area was estimated by seed cotton yield per plot and individual boll weight. A hundred bolls from different parts of plants (bottom, middle and top) were taken at random to determine fibre quality by using a High Volume Instrument (HVI) from the Testing Center of Cotton Quality (Ministry of Agriculture, Anyang, Henan).

2.3. Statistical analysis

2.3.1. Effects of irrigation treatments on yield, yield components, fibre quality, harvest index, partitioning of dry matter allocation and physiological traits

Variations in gas exchange measurements, yield, yield components, HI and fibre quality among different treatments were analysed separately for each trial by performing ANOVA using R open source language (R Core Team, 2021). To analyse changes in biomass allocation, ratios of root, stem, leaf and boll to total dry matter were analysed. For both trials, the treatment factors were irrigation levels (3200, 3700, 4200 m^3 ha^{-1}), irrigation frequencies (every 4, 8, 12 days) and their interactions (irrigation level × frequency), while replications were set as random factors. The HI was defined as the ratio of seed cotton (kg ha^{-1}) to total biomass (kg ha^{-1}).

2.3.2. Relationships among boll growth associated traits, radiation use efficiency and water use efficiency

Correlation analysis was performed for RUE, WUE, boll growth rate and NumFB by using 'performance' package in R software (Lüdecke et al., 2021). Log- or square-root transformation were used for variables with a left or right skew, respectively, to make the data a better approximation of the normal distribution. The RUE was calculated by fitting the linear relationship between cumulative radiation received (MJ m^{-2}) and cumulative above-ground biomass (g m^{-2}) from sowing to 136 DAS in 2020 and 133 DAS in 2021 (George-Jaeggli et al., 2013; Saleh Ravan et al., 2022). Accumulated biomass was calculated as the difference in biomass between the first biomass sample taken at seedling stage and another sample taken at different growth stages. For the same period, cumulative PAR intercepted (MJ m^{-2}) was calculated by the sum of daily radiation obtained from the weather station nearby the site and the fraction of incident PAR intercepted up to the time of each biomass harvest date in both trials. The WUE (kg ha^{-1} mm^{-1}) was calculated by ratio of seed cotton yield (kg ha^{-1}) to total water evapotranspiration (mm) of each plot which was determined by using a water-balance equation over the seasons at the profile intervals (Fig. 1A). Boll growth rate was defined as the initial slope of the linear relationship between boll dry matter (g m^{-2}) and effective accumulated temperature (EAT, ℃ d) from sowing to each sample taken (at 57, 72, 87, 131 and 149 Dai in 2020 and 58, 77, 102, 133 and 148 Dai in 2021). The EAT was calculated by using temperature data accessed from the weather station near the site. After taking the average of daily temperature, the base temperature for cotton growth (15 ℃) was subtracted, resulting in the heat units received that day. The EAT was then taken as total of the heat units from sowing to a specific biomass sample taken.

2.3.3. Regressions of transpiration efficiency and biomass versus delta temperature between air and canopy

To further evaluate the effects of different irrigation treatments on water productivity, ΔTair-canopy were calculated throughout the cotton critical growth stage, given it is a good indicator of plant water status. Over the same time period, TE was calculated as the ratio of accumulated biomass (kg ha^{-1}) to water evaporation (mm) in 2021. Subsequently, relationships of biomass (kg ha^{-1}) and TE (kg ha^{-1} mm^{-1}) versus ΔTair-canopy were investigated during the cotton critical growth stage (from 60 to 90 DAS in 2021).

3. Results

3.1. Effects of irrigation treatments on yield, yield components and harvest index

3.1.1. Changes in seed cotton yield under different irrigation treatments

Seed cotton yield was significantly affected by irrigation frequency, however, there was no significant impact of irrigation levels on seed cotton yield in both trials (Table 2). When averaged across the three irrigation levels in 2020, a 19 % enhancement in seed cotton yield was observed under irrigation frequency of 4 days compared with that under irrigation frequency of 8 days (Table 2). Consistently, plants under irrigation frequency of 4 days produced the highest seed cotton yield, increased by 9 % in comparison with the lowest yield under irrigation frequency of 12 days in 2021. In both trials, comparable seed cotton yields were observed under irrigation frequencies of 8 days and 12 days when averaged across irrigation levels (Table 2). Briefly, more frequent irrigation yielded higher seed cotton for the same amount of irrigation, but no significant negative impact of deficit irrigation (moderate-deficit irrigation of 3200 m^3 ha^{-1} and mild-deficit irrigation of 3700 m^3 ha^{-1}) on plant production was observed.

3.1.2. Changes in yield components under different irrigation treatments

No significant effects of interactions between the three irrigation levels and irrigation frequencies were found on yield components in both trials (Table 2). For yield components in 2020, significant variation was only found in boll number across different irrigation treatments, suggesting 21 % increase under irrigation frequency of 4 days compared with that under frequency of 8 days. For yield components in 2021, boll number, boll weight and lint percent were significantly affected by irrigation levels, while no significant differences were observed under the three irrigation frequencies (Table 2). In 2021, there were 22 % and 8 % more bolls per area under moderate-deficit irrigation (3200 m^3 ha^{-1}) than those under full-irrigation (4200 m^3 ha^{-1}) and mild-deficit irrigation (3700 m^3 ha^{-1}), respectively. However, boll weight increased by 18 % under full-irrigation, compared with that under moderate-deficit irrigation in 2021. Similar boll weights were found under mild- and moderate-deficit irrigation in 2021. However, about 17 % enhancement of lint percent was found under full-irrigation, compared with that under mild-deficit irrigation in 2021. In summary, increased boll number was associated with frequent irrigation (4 days) in 2020 and deficit irrigation (3200 and 3700 m^3 ha^{-1}) in 2021, however, reduced boll weight and lint percent were observed under the two deficit irrigation treatments in 2021.

3.1.3. Changes in harvest index under different irrigation treatments

There were significant interactions between irrigation levels and

Table 2
Effects of main and sub-plot factors on yield and yield components in 2020 and 2021.

Effects		Seed Cotton (kg ha^{-1})		Boll Number (m^{-2})		Boll Weight (g)		Lint Percent (%)	
		2020	2021	2020	2021	2020	2021	2020	2021
Main plot	3200 m^3 ha^{-1}	4436	6097	88	101a	5.07	6.09b	47.63	49.27b
	3700 m^3 ha^{-1}	4582	5999	90	93a	5.06	6.49b	47.10	48.07b
	4200 m^3 ha^{-1}	4289	5901	85	79b	5.07	7.45a	47.56	58.07a
Split plot	4 days	4984a	6342a	100a	92	5.00	6.75	47.40	53.30
	8 days	4038b	5888b	79b	90	5.14	6.63	47.39	53.10
	12 days	4286b	5788b	84b	87	5.05	6.88	47.50	51.01
Source of variation	main	ns	ns	ns	< 0.001	ns	< 0.001	ns	0.007
	split	< 0.001	0.011	< 0.001	ns	ns	ns	ns	ns
	main * split	ns	ns	ns	ns	ns	ns	ns	ns

Note: Values followed by the same letters are not significantly different at $p < 0.05$.

frequencies for HI (fraction of harvestable biomass) (Table 2), suggesting that reduced irrigation was potentially associated with increased HI except in combinations with irrigation frequencies of 4 days in 2020 and 8 days in 2021 (Fig. 3). This might be attributed to changes in responses of plants to irrigation at different growth stages, however, further studies are needed.

3.2. Effects of different irrigation treatments on fibre quality

Significant effects of irrigation levels were observed on length, strength and micronaire, and irrigation frequency significantly affected fibre uniformity in 2020 (Table 3). In comparison with fibre length under moderate-deficit irrigation of 3200 m^3 ha^{-1}, a 2.8 % improvement in fibre length was found under full-irrigation of 4200 m^3 ha^{-1} in 2020 (Table 3). For fibre strength, no significant differences were observed between full-irrigation and two deficit irrigation levels (Table 3). Additionally, fibre micronaire increased by 6.3 % and 3.0 % under moderate-deficit irrigation of 3200 m^3 ha^{-1} compared with those under full-irrigation of 4200 m^3 ha^{-1} in 2020 and 2021, respectively. Moreover, fibre uniformity increased by 1.3 % under irrigation frequency of 4 days when compared with the lowest uniformity (82.43) from irrigation frequency of 12 days. Briefly, increased fibre micronaire and reduced length were associated with both deficit irrigation levels, and fibre uniformity was decreased with increase in irrigation frequency.

3.3. Response of biomass allocation to different irrigation treatments

Variations in biomass allocation to root, stem, leaf and boll over different growth stages are shown in Figure S2 and S3. There were significant effects from interaction between irrigation levels and frequencies on dry matter partitioning to bolls in 2020. However, significant differences in ratio of dry matter to boll was found only across different irrigation frequencies in 2021, with the highest ratio of dry matter to boll occurring under an irrigation frequency of 12 days (*Table 4*). In addition, for ratios of dry matter to root at squaring stage, significant differences were found across irrigation levels in 2021, indicating 24 % more dry matter partitioned to root under irrigation level of 3200 m^3 ha^{-1} than under 4200 m^3 ha^{-1} (*Table 4*). While there were no significant effects of irrigation levels and frequencies on ratio of dry matter to root in 2020 (*Table 4*). In summary, deficit irrigation was associated with higher ratio of dry matter to root at early stage and potentially higher ratio of dry matter to boll at flowering stage, and effects of interactions between irrigation levels and frequencies on dry matter partitioning might confound other factors.

3.4. Variations in photosynthesis and transpiration among different irrigation treatments

Significant differences in Ci were observed among the three irrigation levels (main factor), suggesting 17 % increase under irrigation level of 4200 m^3 ha^{-1} compared with that under 3200 m^3 ha^{-1}. Photosynthetic rate was significantly affected by three irrigation frequencies (split factor), however, there were no significant differences in photosynthetic rate between irrigation levels (*Table 5*). Additionally, photosynthetic rate was slightly, but significantly greater in cotton plants irrigated at the lower frequencies (particularly 8 days), compared with that from the frequency of 4 days (*Table 5*). On another hand, there was a significant interaction between effects of irrigation levels and irrigation frequencies on transpiration rate (*Fig. 4*), with the lowest

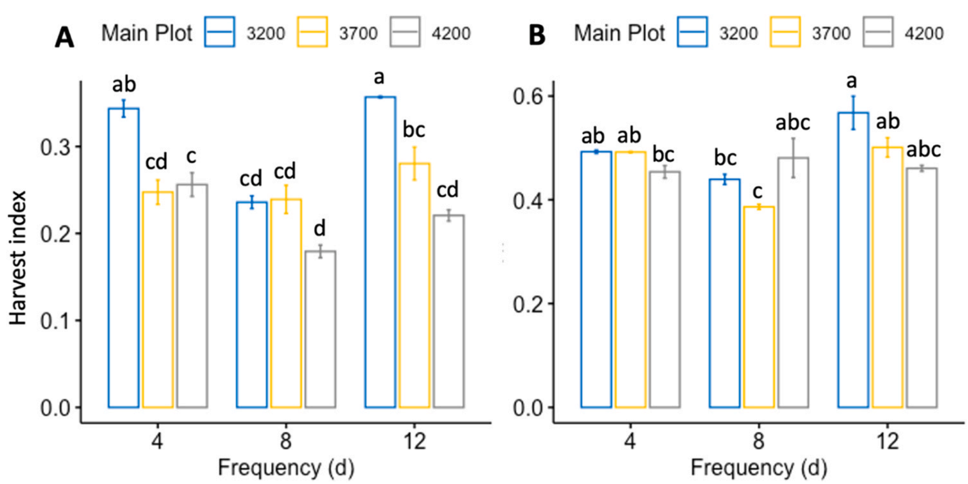

Fig. 3. Variation in harvest index among different irrigation treatments in 2020 (A) and 2021 (B). Note: Values followed by the same letters are not significantly different at $p < 0.05$.

Table 3
Variation in fibre quality among different irrigation levels and frequencies in 2020 and 2021.

Effects		Length (mm)		Uniformity (%)		Strength (kN m kg^{-1})		Micronaire (Units)	
		2020	2021	2020	2021	2020	2021	2020	2021
Main plot	3200 m^3 ha^{-1}	27.63b	28.99	82.80	84.78	28.14	28.50a	5.09a	4.92a
	3700 m^3 ha^{-1}	28.36a	29.41	82.83	84.81	28.43	27.76b	4.80b	4.78b
	4200 m^3 ha^{-1}	28.44a	29.52	83.22	85.17	27.82	28.38ab	4.77b	4.77b
Split plot	4 days	27.94	29.12	83.49a	85.12	28.53	28.14	4.80	4.83
	8 days	28.17	29.43	82.92b	84.78	27.94	27.95	4.88	4.82
	12 days	28.32	29.36	82.43b	84.85	27.91	28.56	4.97	4.82
Source of variation	main	0.005	ns	ns	ns	ns	0.046	< 0.001	0.036
	split	ns	ns	0.001	ns	ns	ns	ns	ns
	main * split	ns	ns	ns	ns	ns	ns	ns	ns

Note: Values followed by the same letters are not significantly different at $p < 0.05$.

Table 4
Partitioning of dry matter to root at square stage and to boll at flowering and boll stage in 2020 and 2021.

Effects		Partitioning of dry matter to root		Partitioning of dry matter to boll	
		2020	2021	2020	2021
Main plot	3200 m^3 ha^{-1}	0.17	0.17a	0.11	0.09
	3700 m^3 ha^{-1}	0.16	0.14b	0.09	0.09
	4200 m^3 ha^{-1}	0.16	0.13b	0.08	0.10
Split plot	4 days	0.16	0.15	0.11	0.08b
	8 days	0.16	0.16	0.10	0.09ab
	12 days	0.17	0.17	0.08	0.11a
Source of variation	main	ns	0.007	< 0.001	ns
	split	ns	ns	< 0.001	< 0.001
	main * split	ns	ns	0.003	ns

Note: Data of dry matter allocation to root shown is from 58 and 57 DAS in 2020 and 2021, respectively; and data of dry matter allocation to boll is from 72 and 77 DAS in 2020 and 2021, respectively; values followed by the same letters are not significantly different at $p < 0.05$.

Table 5
Gas exchange measurements including inter-cellular CO_2 concentration (Ci, μmol CO_2 mol^{-1}), transpiration rate (mmol H_2O m^{-2} s^{-1}), and photosynthetic rate (μmol CO_2 m^{-2} s^{-1}) of different treatments in 2020.

Effect		Ci	Transpiration Rate	Photosynthetic Rate
Main plot	3200 m^3 ha^{-1}	226b	5.11	34.03
	3700 m^3 ha^{-1}	243b	5.14	34.60
	4200 m^3 ha^{-1}	272a	6.01	35.60
Split plot	4 days	249	5.47	33.51b
	8 days	253	5.65	36.59a
	12 days	247	5.19	34.04ab
Source of variation	main	0.001	0.003	ns
	split	ns	ns	0.019
	main * split	ns	0.012	ns

Note: Values followed by the same letters are not significantly different at $p < 0.05$

transpiration rate (4.3 mmol H_2O m^{-2} s^{-1}) observed under the treatment of 3700–8. This treatment was associated with a 36 % reduction in transpiration rate compared with the highest transpiration rate (6.7 mmol H_2O m^{-2} s^{-1}) which occurred under 3200–8 (*Fig. 4*).

3.5. Relationships between RUE, WUE, boll growth rate and NumFB

Relationships between RUE, WUE, boll growth rate and NumFB were analysed for both trials (*Fig. 5*), showing significantly strong correlations between RUE and boll growth rate ($r = 0.68$ and $r = 0.75$ in 2020 and 2021, respectively). There was a significant correlation between RUE and WUE in 2020 ($r = 0.62$), however, this was not observed in 2021. This might be affected by differences in rainfall between 2021 and 2020 (*Fig. 1*). In addition, a significant and tight relationship was found between RUE and NumFB in 2021 ($r = 0.66$), suggesting that RUE might be associated with coordination between source and sink organs. Moreover, NumFB was significantly correlated with boll growth rate ($r = 0.79$) in 2020. In summary, RUE played an important role in boll growth and development under different irrigation treatments in cotton.

3.6. Regressions of biomass and transpiration efficiency versus delta air to canopy temperature (ΔTair-canopy)

3.6.1. Relationship between ΔTair-canopy and biomass under different irrigation treatments

As a good indicator of plant water status, the relationship between ΔTair-canopy and total biomass was investigated under different irrigation treatments in 2021 (Fig. 6). There were significant- and tight-negative relationships between ΔTair-canopy and biomass across different treatments ($p < 0.01$ and $r > 0.6$), suggesting ΔTair-canopy might be able to be used as a surrogate of dry matter productivity in a high-throughput manner. Based on Pearson correlation coefficients, stronger correlation tended to be associated with less irrigation (moderate-deficit and mild-deficit irrigation) except for the treatment of 3700–4 (Fig. 6). For example, under irrigation frequency of 8 days, the correlation coefficients between ΔTair-canopy and biomass were −0.80, −0.75 and −0.67 across irrigation levels of 3200, 3700 and 4200 m^3 ha^{-1}, respectively (Fig. 6). In summary, significantly negative associations between biomass and ΔTair-canopy were observed during the critical cotton growth stage in 2020, suggesting its potential to be a surrogate for dry matter production in cotton in a high-throughput way.

3.6.2. Relationship between ΔTair-canopy and transpiration efficiency (TE) under different irrigation treatments

To further investigate whether ΔTair-canopy could be a quick and accurate indicator for water productivity in cotton, regressions of ΔTair-canopy versus canopy TE were analysed across different irrigation treatments (Fig. 7). Significantly and strongly negative associations were observed between ΔTair-canopy and TE among irrigation treatments with correlation coefficients ranging from −0.67 to −0.38 ($p < 0.01$). This suggested that ΔTair-canopy might be used as a surrogate for the complex trait TE, however, their relationships varied across different irrigation treatments. This might be attributed to the range of TE (from 0.8 to 3.3 kg ha^{-1} mm^{-1}) and the greatest TE occurred in the treatment of 3700–8 (Fig. 7) which also showed lowest leaf transpiration rate.

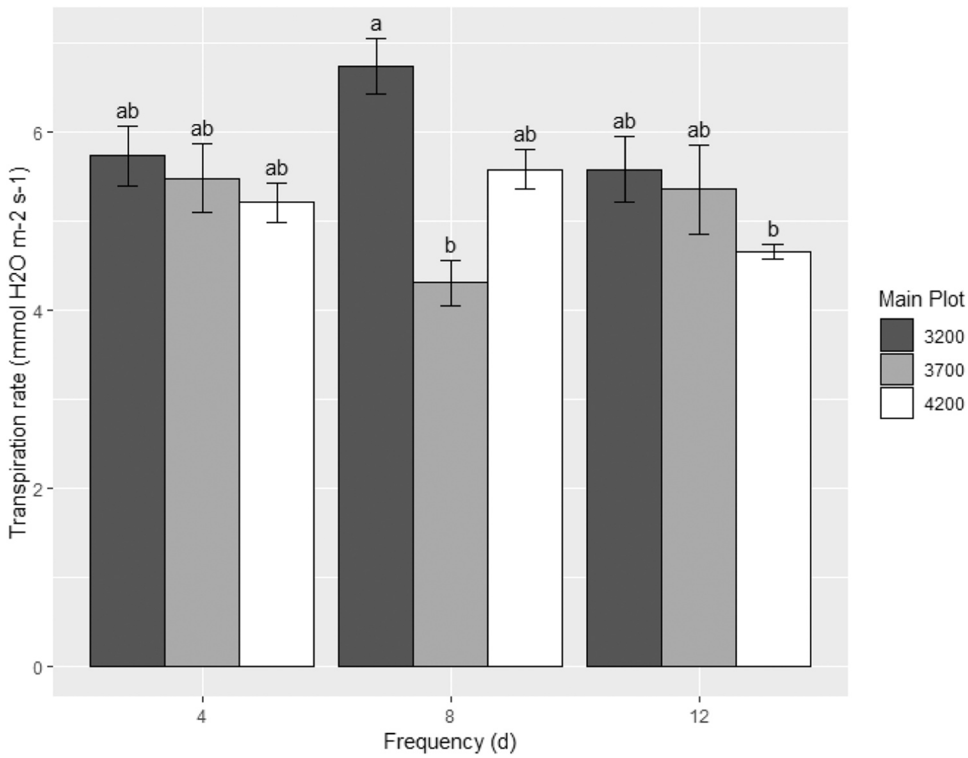

Fig. 4. Effects of the interaction between main factor (irrigation levels: 3200, 3700 and 4200 m^3 ha^{-1}) and split plot factor (irrigation frequencies: 4, 8 and 12 days) on transpiration rate in 2020. Note: Values followed by the same letters are not significantly different at $p < 0.05$.

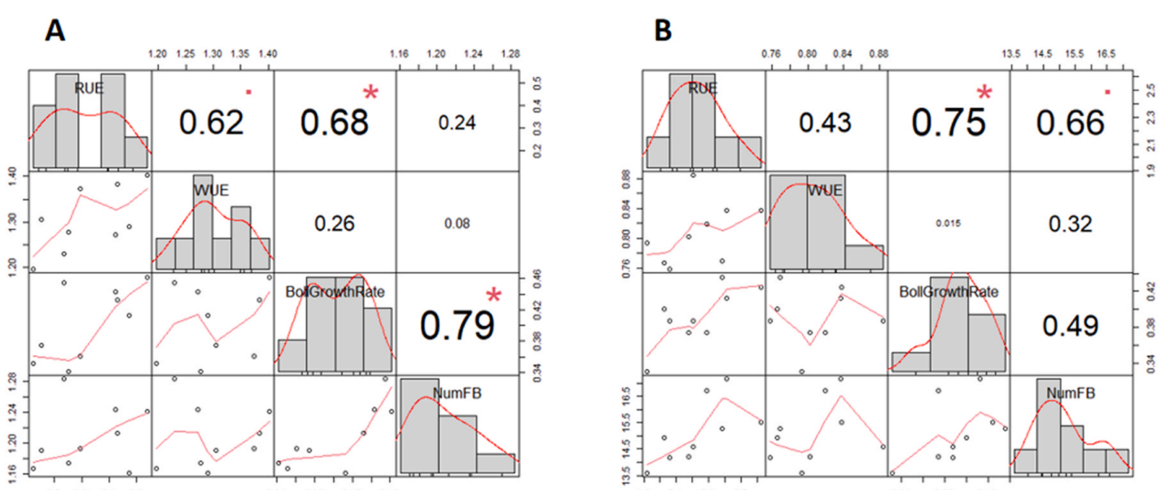

Fig. 5. Correlation among radiation use efficiency (RUE), water use efficiency (WUE), boll growth rate (BollGrowthRate) and number of fruit branching (NumFB) in 2020 (A) and 2021 (B). Note: To make data conform to normality, log-transformed RUE and NumFB were used in 2020, and square-root transformed WUE and BollGrowthRate were used in both 2020 and 2021. The boxes in the upper right corner display the Pearson correlation coefficient between each variable plus significance levels as stars (***, **, * correspond to $p < 0.001$, 0.01, 0.05, respectively).

4. Discussion

4.1. Higher irrigation frequency was associated with higher yield potential while deficit irrigation had negative influence on fibre quality

Enhancing yield and quality in cotton are needed with optimized irrigation, especially in arid or semi-arid areas. It has been reported that deficit irrigation could lead to decrease in fibre length and increase in fibre micronaire (Zhang et al., 2016). In the present study, reduced water application was associated with decreased fibre length and increased fibre micronaire, while there was no significant effect of irrigation frequency on these two parameters (Table 3). However, little negative impact of two deficit irrigation levels on seed cotton yield was observed in both trials, and more frequent irrigation yielded about 9–19 % higher seed cotton for the same amount of irrigation (Table 2). Consistently, small amount but frequent irrigation have shown higher productivity benefits in cotton than fewer large applications in sandy soils (DeTar, 2008). In addition, seed cotton yield has been shown linearly correlated with boll number per area that is also linearly associated with plant water application (Ertek and Kanber, 2003). In the current study, the increased boll number coordinated high yield was indicated across different irrigation frequencies, suggesting around 20 % more

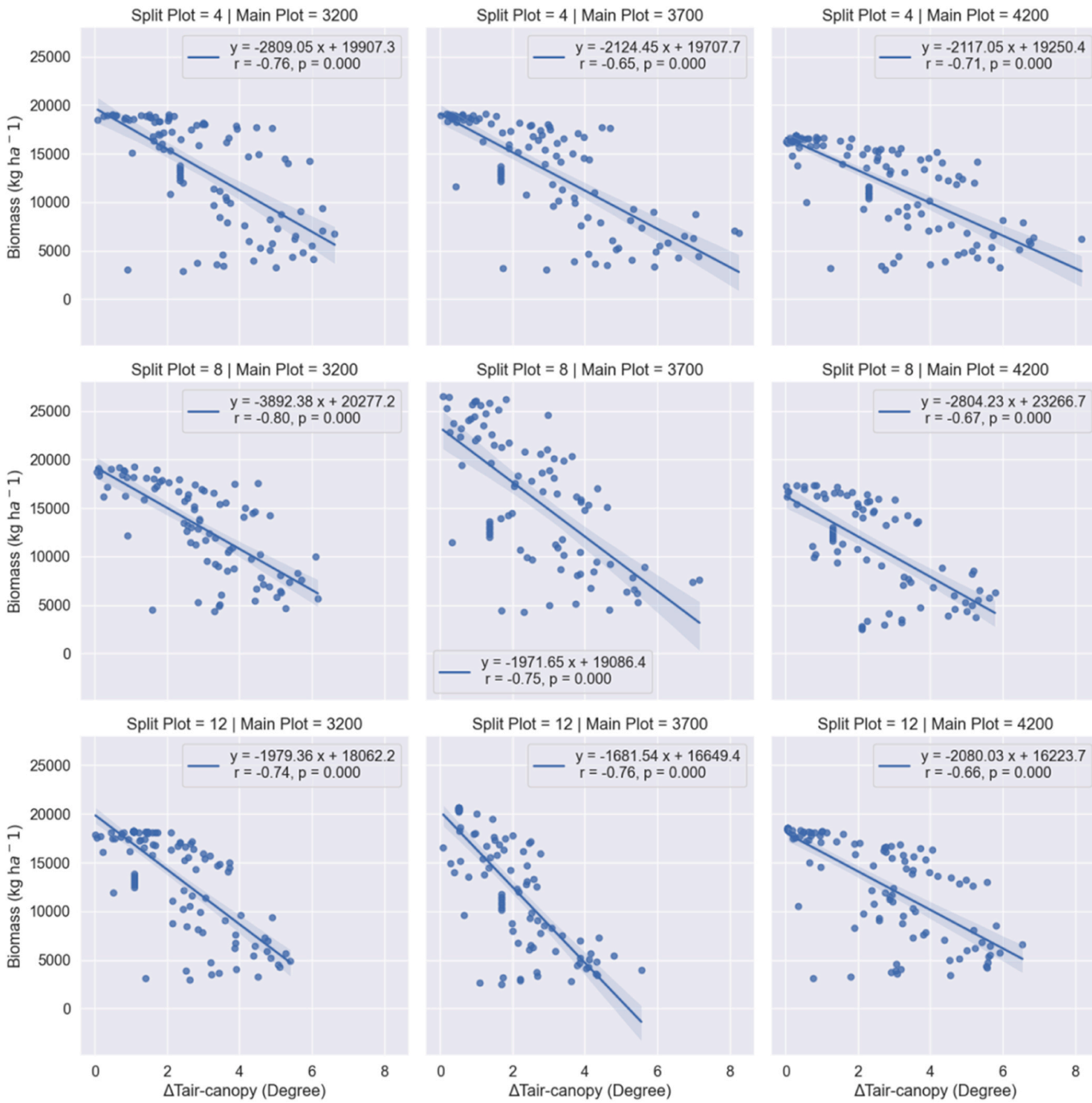

Fig. 6. Regression between biomass versus delta temperature between air and canopy temperature (ΔTair-canopy) in 2021. Note: Data shown is from critical cotton growth stages (60–90 DAS); equations show the linear relationships between biomass and ΔTair-canopy of different treatments; values of r and p show Pearson correlation coefficient and significance level.

boll number per area under more frequent irrigation (Table 2). On the other hand, increased seed cotton yield under reduced irrigation was also associated with enhanced HI in both trials (Table 2). This is supported by previous studies showing that deficit irrigation is beneficial for improving HI, which could be because of increased sinks (bolls) resulting from deficit irrigation (Heuer and Nadler, 2000; Zhang et al., 2016). However, the positive response of HI to deficit irrigation was less obvious in combination with more frequent irrigation in the present study (Table 2 and Fig. 3). Altogether, small amount and frequent irrigation, for example, treatments of 3700–8 or 3700–4, could be applied in cotton farming in semi-arid areas, with benefits primarily attributed to increased boll number per area and HI.

Physiologically, the increased yield under more frequent irrigation was also associated with more assimilates partitioned to reproductive organs (bolls) during the flowering stage, indicated in the current study (Table 4) and previous studies (Dai and Dong, 2014; Zhang et al., 2016). Another important physiological response to reduced water application is related with stomatal opening or size, which affect uptake of CO_2 for photosynthesis and water loss through transpiration (Schroeder et al., 2001). The lowest transpiration rate was obtained under the treatment of 3700–8, suggesting that both irrigation amount and frequency could affect it. In summary, frequent irrigation associated with high yield potential was related to increased allocation of dry matter to bolls during the critical growth stage and reduced transpiration rate.

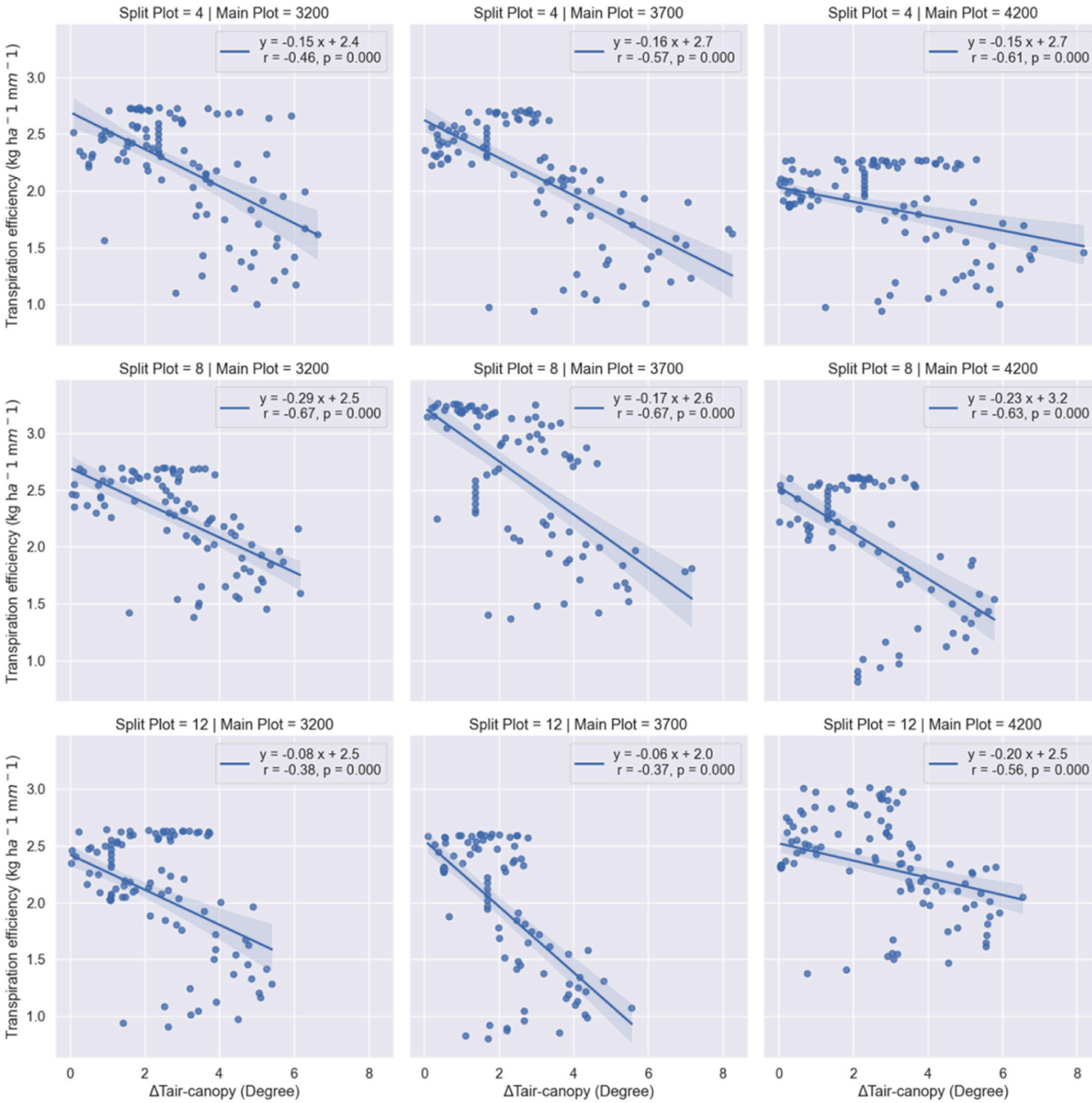

Fig. 7. Regression between transpiration efficiency versus delta temperature between air and canopy temperature (ΔTair-canopy) in 2021. Note: Equations show the linear relationships between TE and ΔTair-canopy; values of r and p show Pearson correlation coefficient and significance level.

4.2. Radiation use efficiency had strong influence on yield formation

The RUE, an important indicator of crop production, has been defined as the relationship between accumulated biomass per amount of light intercepted by the crop (Sadras et al., 2016). A strong relationship between RUE and boll growth rate indicated that RUE might be the determinant of seed cotton yield under different irrigation treatments in the current study (*Fig. 5*). This is supported by the linear correlation between crop growth rate and RUE shown previously (Monteith, 1972). Additionally, significant correlation between RUE and WUE ($r = 0.62$) was observed in 2020, suggesting RUE could be a good indicator of water productivity under various irrigation treatments in cotton. Therefore, enhancing RUE is of great value to improve plant growth and development under deficit irrigation in cotton.

4.3. Delta temperature between air and canopy was related to water productivity under varying irrigation conditions

The temperature of a water-stressed canopy is significantly higher than that of an unstressed canopy (DeTar and Penner, 2007). In the present study, we found a significant linear relationship between ΔTair-canopy and TE, suggesting that the thermal response of canopies could be used to assess cotton yield under deficit irrigation. The Crop Water Stress Index derived from the relationship between canopy temperature and transpiration has previously been used to estimate crop production (Egea et al., 2017; Gonzalez-Dugo et al., 2014, 2019). For comparative purposes, ΔTair-canopy rather than canopy temperature *per se* was used to regress with TE and biomass in the current study, however, the relationship between the two varied across different irrigation treatments (Fig. 7). This might be because of water stress related stomatal closure and reduced cooling effect from transpiration and thus increased temperature (Hsiao, 1973). Taking advantage of the strong correlation between ΔTair-canopy and TE would provide a non-destructive and high-throughput approach to estimate cotton yield potential with low labour requirements. However, further studies are needed to explore the benefits under different agricultural contexts, as the correlation might vary depending on the crop type, its growth stage, and the environmental conditions. In summary, results from the present study have laid a solid basis for using canopy temperature and recent remote sensing technologies to assess yield potential in cotton for water- and labour-saving.

5. Conclusions

Deficit irrigation aims to maximize TE and stabilize rather than maximize crop production and quality. The outcomes of this study suggested that mild-deficit irrigation (3700 m^3 ha^{-1}) under irrigation frequency of 8 days was relatively favourable comparing with the other treatments. A deficit irrigation-induced response is influenced by many factors, such as the stages of crop growth when the deficit is applied, the intensity and severity of the imposed deficit. This study has developed an intelligent and sustainable irrigation management strategy with insignificant negative effects on seed cotton yield and fiber quality. Additionally, the underlying physiological responses indicated that RUE played an important role in yield formation. Furthermore, this study confirmed that difference between air and canopy temperature could be beneficial for yield assessment at large scales in cotton, which thus would significantly reduce labor consumption.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

Data availability

Data will be made available on request.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agwat.2024.108960.

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