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Yields, growth and water use under chemical topping in relations to row configuration and plant density in drip-irrigated cotton

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Abstract

Background Water deficit is an important problem in agricultural production in arid regions. With the advent of wholly mechanized technology for cotton planting in Xinjiang, it is important to determine which planting mode could achieve high yield, fiber quality and water use efficiency (WUE). This study aimed to explore if chemical topping affected cotton yield, quality and water use in relation to row configuration and plant densities.

Results Experiments were carried out in Xinjiang China, in 2020 and 2021 with two topping method, manual topping and chemical topping, two plant densities, low and high, and two row configurations, i.e., 76 cm equal rows and 10+66 cm narrow-wide rows, which were commonly applied in matching harvest machine. Chemical topping increased seed cotton yield, but did not affect cotton fiber quality comparing to traditional manual topping. Under equal row spacing, the WUE in higher density was 62.4% higher than in the lower one. However, under narrow-wide row spacing, the WUE in lower density was 53.3% higher than in higher one (farmers' practice). For machine-harvest cotton in Xinjiang, the optimal row configuration and plant density for chemical topping was narrow-wide rows with 15 plants m^{-2} or equal rows with 18 plants m^{-2}.

Conclusion The plant density recommended in narrow-wide rows was less than farmers' practice and the density in equal rows was moderate with local practice. Our results provide new knowledge on optimizing agronomic managements of machine-harvested cotton for both high yield and water efficient.

Keywords Yield components, Fiber quality, Transpiration, Water use efficiency, Heat ratio method (HRM)

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Introduction

The 89% of cotton in China is growing in Xinjiang, which covers 20% of the world total productions (https://www.stats.gov.cn/sj/zxfb/202302/t20230203_1901689.htmln.d.). However, the development of cotton production in Xinjiang is limited by factors such as insufficient irrigation water, low water use efficiency (Song et al., 2020), and shortage of labors (Meng et al., 2021). Drip irrigation covered with plastic film (Li et al., 2019) and mechanization of cotton production are widely used. The traditional cotton managements in machine-harvested cotton lead to a poor defoliation and ripening percentage, and decrease fiber quality (Zhang et al., 2020).

Optimizing row configuration, plant density, and chemical regulation is considered as the effective approaches to adapte machine-harvest cotton production (Dai et al., 2017). The shift towards machine-harvest has led to changes in row configurations into two typical patterns: 76 cm equal row spacing, or narrow and wide row spacing of 10 cm plus 66 cm (narrow-wide row spacing), which affects cotton growth and development, transpiration, and water use efficiency (Wang et al., 2019; Enciso-Medina et al., 2002). Appropriate row configuration, plant density, and chemical topping are important agronomy practices to improve cotton water use and yield (Luo et al., 2006; dos Santos et al., 2021). However, there is limited information if these agronomic measures and their interactions affect cotton transpiration and yield formation.

Optimizing plant population density and row configuration is essential for regulating canopy structure and transpiration and coordinating high yield and water saving (Wang et al., 2019). The increase of plant density causes a decline in boll weight, but increases boll numbers (Mao et al., 2015). Appropriate plant density shapes a reasonable population structure, coordinate the contradiction between cotton population and individuals, and maximize the utilization efficiency of natural resources (Ren et al., 2013). Comparing with narrow-wide row spacing, equal row spacing has a positive impact on air exchange, light transmittance, soil temperature, and light absorption (Zhang et al., 2020). Row spacing indirectly affects crop water consumption and use efficiency by influencing soil hydrothermal conditions (Zhang et al., 2020).

To accurately quantify crop transpiration, several methods are available for measuring crop transpiration under field conditions, such as weighing lysimeters (Marek et al., 2006; Lascano et al., 2014), the Bowen ratio (Todd et al., 2000; Irmak et al., 2014), Eddy covariance (Baldocchi, 2003; Zhang et al., 2014a, b; Wilson et al., 2001), and stem flow gauges (Dugas et al., 1994; Lascano et al., 2016; Alarcon et al., 2000). Sap flow directly measures crop transpiration that can be used to determine plant water uptake continuously (Grime et al., 1995). Various thermometric methods, such as heat pulse (Cohen et al., 1993; Bleby et al., 2004), heat balance (Lascano et al., 2016), heat dissipation (Flo et al., 2019), and heat ratio method (HRM) (Burgess et al., 2001), are used to measure sap flow. The HRM stem flow instrument is ideal in field crops while plant stem is small (Chen et al., 2022). The field measurements of transpiration in relations to row configuration, plant density, and chemical topping would provide insight understanding to explore the physiological and agronomic effects of new cotton cultivation technologies. We hypothesized that cotton yield and water use could be further improved by chemical topping due to the increase of plant transpiration and canopy growth, and it would be affected by the interaction with row configuration and plant density.

The objectives of this study were (1) to quantify crop transpiration, growth, yield components, and fiber quality under chemical topping with varying row spacing and population densities, and (2) to optimize agronomic managements in drip-irrigated and plastic film-covered cotton designed for machine harvest.

Materials and methods

Experimental site

Field experiments were conducted in 2020 and 2021 at the Wulanwusu Agrometeorological Experiment Station in Shihezi city, Xinjiang Uygur Autonomous Region, China, located at 44º17′ N and 85º49′ E. The average above 10 °C cumulative temperature of study site is 3 581 °C from 1964 to 2021. During experimental years, the yearly mean air temperature was 23.4 °C, the total precipitation was 64.1 mm from sowing to harvest (Fig. 1). The soil texture was sandy loam, with 17 $g·kg^{-1}$ of organic matter, 0.91 $g·kg^{-1}$of total N, 91.5 $mg·kg^{-1}$of available P and 315 $mg·kg^{-1}$ of available K within 0–40 cm soil layer.

Layout of experiments

Field experiments comprised eight treatments, including two row configurations (equal row spacing and narrow-wide row spacing), two plant densities (low, L and high, H), and two topping methods (manual topping and chemical topping). The treatments were tested for optimizing the managements of machine harvest cotton. The equal row spacing consisted of 3 rows of cotton with 76 cm row spacing in one piece of plastic film (2.05 m wide), while the narrow-wide row spacing consisted of 6 rows of cotton with a 10 cm narrow row spacing and a 66 cm wide row spacing (Fig. 2a, b). The plant densities were 18 (H) and 10 (L) $plants·m^{-2}$ in equal rows, 25 (H) and 15 (L) $plants·m^{-2}$ in narrow-wide rows, respectively. The high plant density treatments in both row configurations were the common practices applied by farmers. Manual topping was cuting out buds of main stem by hand to terminate further growth, and chemical topping was conducted by appling a high concentration mepiquat chloride (225 $g·ha^{-1}$) to restrict the growth. Topping treatments were conducted on 10 July 2020 and 11 July 2021, respetively. For the chemical topping treatments, additional mepiquat chloride of 150 $g·ha^{-1}$ was applied after 10 days to guarantee the topping effect.

The field experiments were arranged in a completely randomized block design, which was repeated three times. Plot area was 31.5 m^2 (7 m×4.5 m). Cotton (*Gossypium hirsutum*) cultivar was Xinluzao 78 in two years.

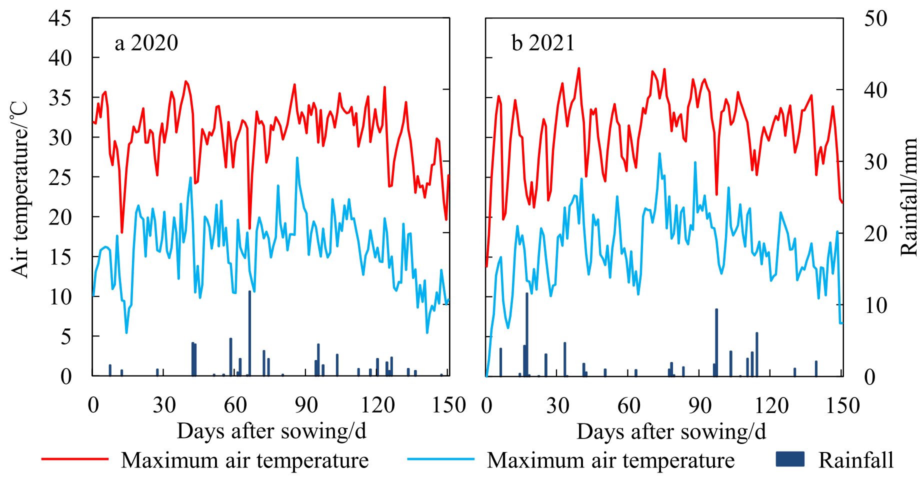

Fig. 1 Weather data during the cotton growing seasons in 2020 and 2021 in Wulanwusu, Shihezi, China

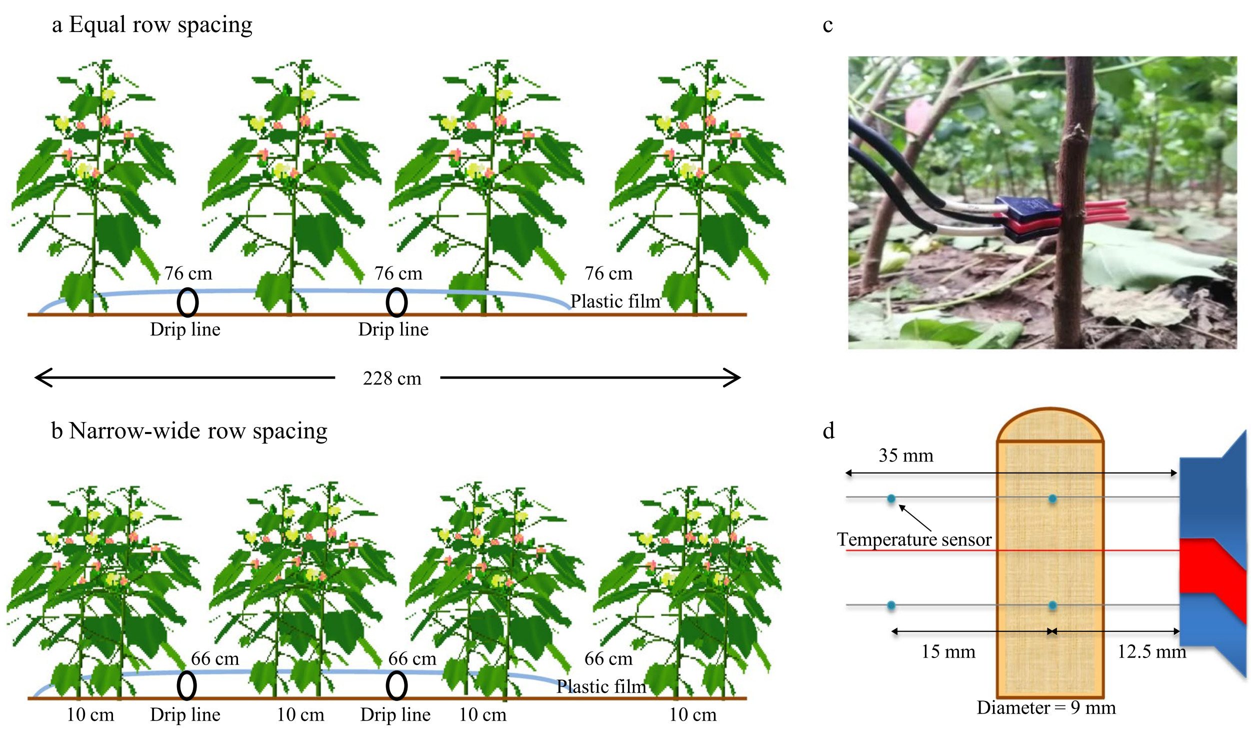

Fig. 2 Row configurations of the field experiment (**a**, **b**) and the installation of sap flow meter (**c**, **d**)

The sowing date was April 24 in 2020 and April 26 in 2021, respetively. The drip tube was covered by plastic film. All practices, e.g., sowing, applying drip tube, and covering film were conducted by machine at one operation. The open bolls were harvested three times by hand, on 20 September, 1 October, 10 October in 2020 and 25 September, 5 October, 20 October in 2021, respetively. Six times irrigation in 2020 and seven times irrigation in 2021 were given during cotton growing seasons with 480 mm in both years. Fertilizer was applied along drip irrigation with a total amount of 680 kg·ha^{-1}, 270 kg·ha^{-1} P and 80 kg·ha^{-1} K in two years according to local agronomic practices.

Measurements

For measuring aboveground dry matter, three plants were randomly sampled for each plot in five times in 2020 and six times in 2021 during cotton growing seasons. Leaves, stems, and fruits were separately dried in the oven at 80 °C for two days until reaching a constant weight.

For determining the maximum values of stem diameter to calculate transpiration of one plant, the first internode of the main stem of three plants for each plot were measured on August 20 in 2020 and August 23 in 2021, respetively.

For measuring seed cotton yield, all plants in an 4 m^2 sub-sampling area of each plot were harvested three times. The boll numbers of plants in the sub-sampling area were counted to calculate boll density (bolls·m^{-2}). The number of open bolls was used to determine yield. Thirty open bolls were randomly sampled per plot to measure boll weight.

Cotton fiber was separated by a roller ginning machine. Fiber quality of the samples of all plots were evaluated using a High Volume Instrument (HVI-900) according to ICC standard (United States Department of Agriculture, Agricultural Marketing Service (USDA-ARS), 2001).

Sap flow measurements

To quantify the cotton transpiration from flowering stage to boll opening stage, sap flow meter SFM1 (ICT International, Armidale, Australia) was used to measure the sap velocity from July 8 to August 30 in 2020 and July13 to August 30 in 2021, respetively. One plant was randomly selected from each treatment to install a SFM1. The installation position of SFM1 was shown in Fig. 2 (c, d). The sap flow was continuously measured in a time interval of 30 minutes from cotton flowering to harvesting times. Due to limited instruments, just two treatments (equal row spacing with high plant density, narrow-wide row spacing with low plant density) were measured in 2021.

The instrument SFM1 measured the sap velocity using heat ratio method (Schoppach et al., 2021), which measures temperature change ratio of two thermistors (Burgess et al., 2001). The thermal diffusivity of cotton stem for calculating the sap velocity of plant stem (V_h, cm·h^{-1}) was 0.002 5 cm^2·s^{-1} (Marshall, 1958; Chen et al., 2022).

Plant transpiration (cm^3·h^{-1}) was the production of sap area of one plant (cm^2) and sap velocity (cm·h^{-1}). The sap velocity was the output of the instrument measurements and the sap area of cotton plant was measured at field condition. Cotton hourly transpiration (mm·h^{-1}) per unit ground area was the production of transpiration of one plant and plant density (plants·m^{-2}) (Again et al., 2012). The sap area was computed by measuring diameter (cm) of stem where SFM1 was installed (first internode). Daily transpiration (mm·d^{-1}) was calculated by the plant transpiration within 24 hours, and the total transpiration during a cotton growing period (mm) was the sum of all daily transpirations (Chen et al., 2022).

Data analysis

To determine cotton growth under different agronomic practices, we used an expolinear equation (Goudriaan and Monteith, 1990; Zhang et al., 2007) to fit growth dynamics at a daily base.

$$W_t = \frac{c_m}{r_m} ln[1 + exp[r_m(t - t_b)]] \quad (1)$$

where W_t was the dry mass (g·m^{-2}), r_m (d^{-1}) was the relative growth rate at the initial stage. The t_b (d) was the time when reaching the half of maximum absolute growth rate c_m (g·m^{-2}·d^{-1}). The time t was days after sowing (DAS).

The water use efficiency (WUE) was obtained from a linear regression, the slope (g·m^{-2}·mm^{-1}) between dry matter and total transpiration was calcualted from field observations in two years.

The normalized root means square error (NRMSE, %) was used to evaluate the accuracy of fitted biomass growth with observed dry matter measurements.

$$NRMSE = \frac{\sqrt{\frac{1}{n}\sum_{1}^{n}(X_i - Y_i)^2}}{\overline{X_i}} \times 100\% \quad (2)$$

where X_i was the observed aboveground dry matter, Y_i was the curve fitted value, The $\overline{X_i}$ is mean value of X_i. The i was each measurement and n was the number of measurements.

The growth equation for aboveground dry matter were fitted by exponential regressions in SPSS 26 (IBM, USA). Treatment effects on growth traits, yield, quality, WUE, and fitting parameters (c_m, r_m, t_b) in two years were analyzed by using the General Linear Model in SPSS 26 (IBM, USA). Row configuration, plant density, topping method, and year were set as fixed factors, including all interactions, while replicate was set as a random factor, nested with year (replicate(year)) (Zhang et al., 2014a, b; Zhang et al., 2019). The treatment means were compared using least significant difference method.

Results

Yields and yield components

Seed cotton yield was not significantly (P>0.05) affected by row spacing and plant density treatments (Table 1). Except for the treatment of manual topping under equal row spacing, the seed cotton yield under the lower plant density was slightly higher than that in the higher density (Table 2). The seed cotton yield in narrow-wide row spacing was slightly higher than that in equal rows in 2020, but opposite in 2021 (Table 2). Topping method and year extremely significantly (P<0.01) affected seed cotton yield (Table 1). Across all years and row

Table 1 The ANOVA analysis for the effects of year, replicate, row spacing, plant density, topping method, on yield components, fiber quality parameters, growth traits, and water use efficiency (WUE) in 2020-2021

Effect	df	Boll weight	Boll density	seed cotton yield	Fiber length	Fiber strength	micronaire	Plant height	Stem diameter	LAI	WUE
Year (Y)	1	142**	14.0*	51.3**	1.77	0.77	46.8**	81.7**	83.3**	114**	6.32*
Replicate(Y)	4	2.04	0.26	0.73	3.10*	5.93**	1.10	1.53	0.36	0.22	3.04*
Row spacing (RS)	1	12.0**	9.20**	0.77	0.00	0.63	15.8*	0.01	0.15	39.8**	2.20
Plant density (PD)	3	0.76	10.2**	1.65	0.46	0.03	1.05	8.44**	9.04**	109**	0.18
Topping (TOP)	1	1.83	4.31*	8.45**	7.73**	1.57	0.00	37.5**	5.81*	1.27	6.50*
RS×PD	3	0.01	0.20	0.49	0.31	4.69*	7.09*	1.10	1.42	9.00**	68.6**
RS×TOP	1	0.05	5.28*	0.85	0.46	0.30	1.05	1.57	0.89	0.00	0.78
TOP×PD	3	0.49	0.52	2.02	0.36	1.25	0.61	0.48	0.15	0.00	5.17*
RS×TOP×PD	3	1.23	0.92	0.00	0.10	0.13	1.41	0.25	1.24	1.51	4.64*
RS×Y	1	6.40*	12.6**	12.2**	0.63	8.37**	5.46*	5.51*	0.09	1.01	
PD×Y	3	2.29	11.0**	0.01	0.06	3.20	0.29	5.09*	0.32	6.01*	
TOP×Y	1	2.29	3.80	0.15	0.13	0.11	0.29	0.00	1.69	0.06	0.56

The value given in the table is *F* value. **indicates $P<0.01$ and * for $P<0.05$

Table 2 Yield components and quality parameters of cotton under different row configuration, plant density, and topping treatments in Shihezi, Xinjiang, China in 2020 and 2021

Year	Row spacing	Plant density Plants·m^{-2}	Topping	Boll weight	Boll density	seed cotton yield	Fiber length	Fiber strength	Micronaire
				g	Bolls·m^{-2}	kg·ha^{-1}	mm	cN·tex^{-1}	
2020	Equal row spacing	18	Manual topping	3.72±0.20 a	126±24.2 a	4417±363 a	28.6±0.81 a	28.3±1.24 a	5.23±0.07 a
			Chemical topping	3.28±0.11 a	146±26.0 a	4958±561 a	29.1±0.18 a	28.1±0.15 a	5.17±0.03 a
		10	Manual topping	3.78±0.06 a	92.2±6.76 a	4291±273 b	28.3±0.27 a	28.0±0.53 a	4.93±0.27 a
			Chemical topping	3.23±0.10 b	106±2.94 a	5708±341 a	29.4±0.46 a	29.6±0.50 a	4.87±0.07 a
	Narrow-wide row spacing	25	Manual topping	3.56±0.38 a	175±25.5 a	5333±583 a	29.0±0.40 a	30.1±0.90 a	4.00±0.15 a
			Chemical topping	3.38±0.40 a	228±24.2 a	5333±601 a	29.5±0.47 a	29.8±1.14 a	4.20±0.35 a
		15	Manual topping	3.35±0.28 a	117±13.0 b	5375±573 a	28.9±0.58 a	28.3±1.13 a	4.63±0.33 a
			Chemical topping	3.33±0.11 a	157±4.41 a	5750±382 a	28.9±0.64 a	28.4±0.68 a	4.80±0.32 a
2021	Equal row spacing	18	Manual topping	5.37±0.23 a	158±12.5 a	6792±253 a	29.3±0.68 a	29.5±0.88 a	4.37±0.18 a
			Chemical topping	5.60±0.20 a	108±14.2 b	7375±505 a	29.8±0.18 a	29.8±0.42 a	3.83±0.03 b
		10	Manual topping	5.57±0.12 a	123±2.64 a	6542±292 b	29.1±0.48 a	30.3±0.59 a	3.93±0.09 a
			Chemical topping	5.73±0.03 a	132±1.98 b	7542±150 a	29.9±0.31 a	30.7±1.04 a	4.20±0.27 a
	Narrow-wide row spacing	25	Manual topping	5.00±0.29 a	113±9.06 a	5583±588 a	29.3±0.35 a	28.6±0.41 a	3.80±0.23 a
			Chemical topping	4.53±0.29 a	132±7.62 a	5833±273 a	29.6±0.21 a	28.9±0.36 a	3.90±0.00 a
		15	Manual topping	5.03±0.22 a	118±7.36 a	5792±647 a	28.8±0.51 a	28.7±0.82 a	4.00±0.25 a
			Chemical topping	5.17±0.15 a	143±16.0 a	7000±473 a	29.8±0.46 a	29.5±0.79 a	3.97±0.03 a

Same lower cases in each column indicate no significant difference between topping treatments within same year, row configurations, and plant density

configuration treatments, the seed cotton yield under chemical topping was 12.2% higher than that under manual topping (P>0.05) (Table 2). There were no interactions between row spacing, plant density and topping treatment on seed cotton yield (P>0.05), but extreme significant effect between row spacing and year on seed cotton yield (P<0.01).

Row configuration, density, and topping treatments significantly affected (P<0.05) boll density (Table 1). Boll density was higher under chemical topping than that under manual topping (Table 2).

Boll weight was extremely significantly affected (P<0.01) by row spacing and year, not by plant density and topping method. The interactions among row configuration, density, and topping method was not significant (Table 1). Average boll weight across different treatments in equal row spacing was 4.6 g, 9.5% higher than in narrow-wide row spacing. In 2021, boll weight was 5.3 g, 51% higher than that in 2020 (Table 2).

Fiber quality

Regarding fiber length, the topping treatments had a significant effect (P<0.05), while other treatments had no effects (Table 1). The average fiber length in chemical topping was 29.5 mm, which was 2.1% higher than that in manual topping. In 2021, average fiber length was 29.5 mm, 1.7 % higher than that in 2020 (Table 2).

Fiber strength was not significantly affected by main effects of topping method, row spacing, or plant density, however, the interactions of row spacing–plant density and row spacing–year were significant (P<0.05). The average strength across all treatments was 29.2 mm (Table 2).

Micronaire was significantly affected by row configuration (P<0.05) and extremely significantly by year (P<0.01). Plant density and row configuration interaction significantly affected (P<0.05) fiber micronaire. Micronaire in equal rows treatment was 4.57, which was 9.6% higher than that in the narrow-wide rows treatment (Table 2).

Plant traits

Stem diameter of first internode was extremely significantly affected by plant density (P<0.01) and significantly by chemical topping (P<0.05) (Table 1; Fig. 3). Chemical topping had a larger stem diameter of 8.92±0.22 mm, which was 2.3% larger than that of manual topping (8.72±0.20 mm). The stem diameter of low plant density was 8.91±0.21 mm, which was 2.2% larger than that of high plant density (8.72±0.19 mm). In 2021, the stem diameter was 9.45±0.21 mm, which was 14.5% larger than that in 2020 (8.25±0.12 mm).

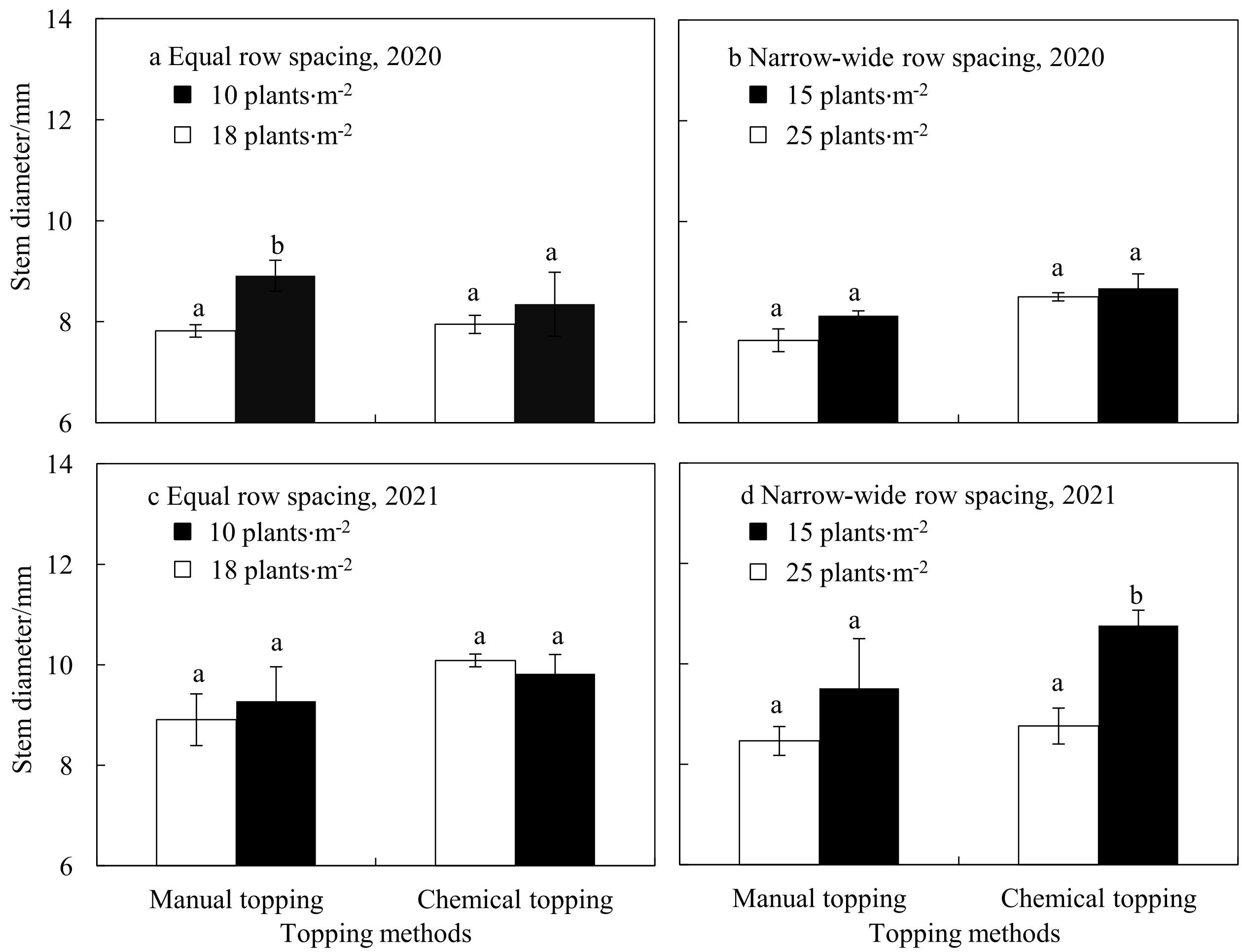

Fig. 3 Stem diameter at the first internode of cotton in different row configuration, plant density, and topping treatments in 2020 and 2021

Row spacing and plant density extremely significantly affected the maximal leaf area index (LAI), and there was extremely significant interaction effect between them on the maximal leaf area index (Table 1). Narrow-wide row spacing had a maximal LAI of 3.90±0.24, which was 35.4% higher than that of equal row spacing (2.88±0.19). High plant density had a maximal LAI of 4.23±0.26, which was 65.9% higher than that of low plant density (2.55±0.26). Chemical topping significantly increased plant height by 13.2% comparing with manual topping. Plant height was lower in 2020 (65.7±1.6 cm) comparing with that in 2021 (82.5±1.5 cm).

Growth dynamics

The growth course of cotton was fitted using an expo-linear equation in 2020 and 2021. The R^2 of fitted equations across all treatments and years was above 0.95, indicating that the model could describe the growth of cotton well (Table 3).

The fitted parameter r_m showed extremely significant difference in years (Table 4). The t_b was extremely significantly differed (P<0.01) between 2020 and 2021 (Table 4), with a growth delay of 4 d in 2020 (t_b=64.4±0.4) comparing with that in 2021 (t_b= 60.5±0.1). The c_m was extremely significantly affected by density and year (P<0.01). The c_m was 47.1% and 32.8% higher at high plant density comparing with that at low plant density in equal rows and narrow-wide rows, respectively (Table 3; Fig. 4).

Diurnal course of sap velocity

Chemical topping increased plant sap velocity by 8.7% comparing with the manual topping (Fig. 5). The sap velocity was 14.6 cm·h^{-1} in low plant density and 12.5 cm·h^{-1} in high plant density under narrow-wide rows, and was 16.1 cm·h^{-1} in low plant density and 14.3 cm·h^{-1} in high plant density in equal row spacing.

Table 3 Parameters of growth equation for aboveground dry matter in cotton under different row configuration, plant density, and topping treatments in 2020 and 2021

Year	Row configuration	Topping	Plant density plants·m^{-2}	c_m g·m^{-2}·d^{-1}	r_m d^{-1}	t_b d	NRMSE (%)	R^2
2020	Equal row spacing	Manual topping	18	21.3±1.63 a	0.06±0.00 a	62.6±0.22 b	13.7	0.99
			10	13.7±1.16 b	0.04±0.00 b	65.8±0.76 a	10.7	0.97
		Chemical topping	18	22.1±1.33 a	0.05±0.01 a	63.5±0.58 a	5.90	0.97
			10	15.8±1.14 b	0.05±0.01 a	63.7±1.02 a	12.4	0.98
	Narrow-wide row spacing	Manual topping	25	25.4±3.35 a	0.05±0.01 a	65.1±2.17 a	12.4	0.97
			15	19.3±2.73 a	0.06±0.01 a	63.7±1.39 a	10.0	0.98
		Chemical topping	25	21.6±1.37 a	0.04±0.00 a	66.3±0.84 a	15.2	0.96
			15	18.9±1.67 a	0.05±0.01 a	64.2±1.23 a	21.0	0.96
2021	Equal row spacing	Manual topping	18	28.2±1.25 a	0.06±0.00 a	60.6±0.17 a	10.5	0.98
			10	20.4±1.17 b	0.08±0.01 a	60.2±0.54 a	9.14	0.97
		Chemical topping	18	31.0±1.57 a	0.06±0.00 b	60.6±0.21 a	12.6	0.98
			10	19.8±0.56 b	0.08±0.00 a	60.1±0.12 a	16.0	0.95
	Narrow-wide row spacing	Manual topping	25	29.0±0.84 a	0.06±0.01 a	60.7±0.31 a	9.88	0.98
			15	20.0±0.85 b	0.07±0.01 a	60.8±0.57 a	11.1	0.98
		Chemical topping	25	29.4±1.72 a	0.08±0.01 a	60.9±0.82 a	5.43	0.98
			15	21.1±1.90 b	0.08±0.01 a	60.1±0.27 a	17.2	0.96

Lowe cases indicate no significant difference between plant density within same row configurations and topping treatments

Table 4 The ANOVA analysis for the effects of row spacing, plant density, topping method on parameters of growth equation for aboveground dry matter.

Effect	df	c_m	r_m	t_b
Year (Y)	1	46.8**	74.7**	221**
Replicate(Y)	4	0.84	0.58	0.32
Row spacing (RS)	1	3.63	0.05	1.60
Plant density (PD)	3	82.1**	1.83	0.22
Topping (TOP)	1	0.14	0.24	0.00
RS×PD	3	1.12	0.15	3.30
RS×TOP	1	1.46	0.00	0.50
TOP×PD	3	0.10	0.02	1.35
RS×TOP×PD×Y	3	0.69	1.99	1.39

The *F* value of each factors on parameter of the equation is given in the table. **indicates $P<0.01$ and *for $P<0.05$

Transpiration and water use efficiency

The daily transpiration at flowering, flower and boll-setting stage, and boll opening stages varied significantly among treatments (Table 5). Across two years, daily cotton transpiration was 4.04 mm at flowering stage, 3.64 mm at flower and boll-setting stage and 3.40 mm at boll opening stage in equal row spacing, while that was 5.33, 4.88, and 2.95 mm at three stages respectively in narrow-wide row. The daily transpiration in narrow-wide row spaces with high plant density and chemical topping was the highest (Table 5), and which was higher in 2021 comparing with that in 2020. The total transpiration from flowering to harvest in equal row spacing with high density was much higher in 2021 comparing with that in 2020 (Fig. 6).

In equal row spacing, WUE was 5.36±0.41 kg·m^{-3} in 18 plants·m^{-2}, 62.4% higher than that in 10 plants·m^{-2} (3.30±0.56 kg·m^{-3}). However, WUE was 4.92±0.54 kg·m^{-3} in narrow-wide row spacing with low plant density (15 plants·m^{-2}), which was 53.2% higher than that in 25 plants·m^{-2} (3.21±0.46 kg·m^{-3}) (Fig. 7).

Discussion

Chemical topping increased seed cotton yield, but did not affect cotton fiber quality. In equal rows, water use efficiency was 62.4% higher in high plant density comparing with that in low plant density. While in narrow-wide row spacing, water use efficiency was 53.3% higher in low plant density comparing with that in high plant density. The water use efficiency was slightly higher in equal row spacing with high plant density comparing with that in narrow-wide row spacing with low plant density ($P>0.05$). Boll densities were significantly higher with narrow-wide row spacing under high plant density and chemical topping than with equal row spacing under low plant density and manual topping. Boll weight was 9.5% higher in equal row spacing comparing with that in the narrow-wide row spacing.

Plant density increased WUE in equal row spacing by enhancing the aboveground biomass but did not affect

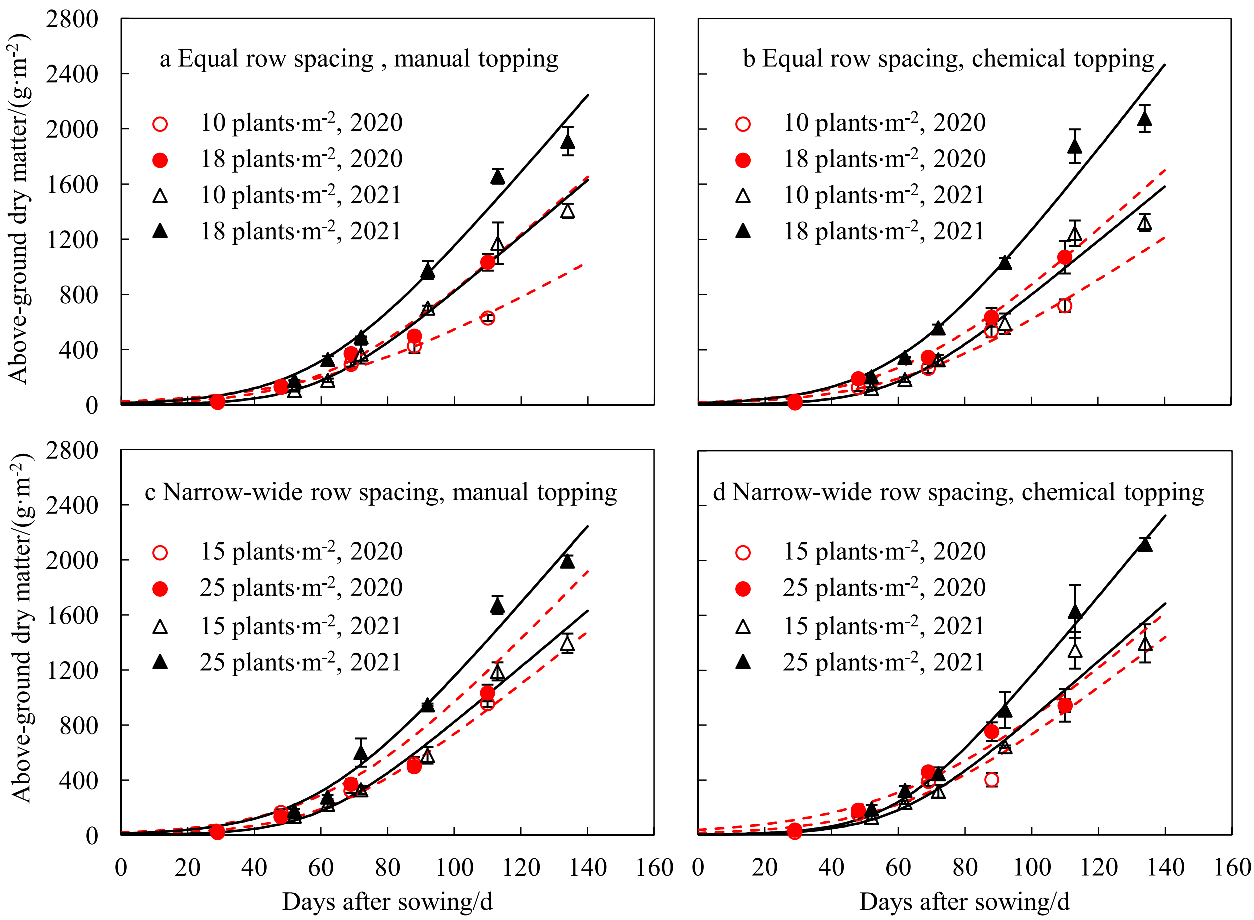

Fig. 4 Fitted (lines) and observed (points) of aboveground dry matter in cotton under different row configuration, plant density, and topping treatments in 2020 and 2021

transpiration in cotton. Plant density determines light interception (Gwathmey et al., 2010; Kaggwa-Asiimwe et al., 2013) by changing leaf area index and plant morphylogical traits (Hussain et al., 2000). Since radiation interception by leaves is the main determinant of the rate of transpiration, altering plant density may modify the demand of leaves for water.

Cotton has strong self-regulation ability, which allows it to adjust dry matter production and distribution in responding to environmental factors (Mao et al., 2018). Row spacing and plant distance can affect cotton dry matter production and sap flow by influencing competition among plants for natural resources and space (Dauzat et al., 2008; Zhu et al., 2014). High plant density results in smaller stem diameter, lower biomass, and less sap flow because of high intraspecific competition for natural resources (Ren et al., 2013). However, the cotton transpiration per unit ground area was calculated by transpiration per plant and plant density (Again et al., 2012), which may explain why there was no significant difference between transpiration of high plant density and low plant density.

Chemical topping increases plant height, boll densities, and fiber length. This topping method leads to a compact plant architecture, which improves air exchange and light transmission in the cotton canopy, thereby reducing the fruit abscission and the number of rotten bolls, and increasing the distribution of assimilates to reproductive tissues (Dai et al., 2022). Besides, compared with manual topping, the chemical topping increased the net returns due to the reduction of labors (Dai et al., 2022). Daily and total transpiration are higher in chemical topping may due to the higher LAI (Chen et al., 2022). However, traditional field measurements, e.g., lysimeter, for determining water uptake have inherent uncertainties and systematic errors because of the difficulty in determining transpiration and evaporation separately (Again et al., 2012; Colaizzi et al., 2014; Zhang et al., 2014a, b). The method used in this study measured sap flow directly for the cotton plant and showed great advantage. The

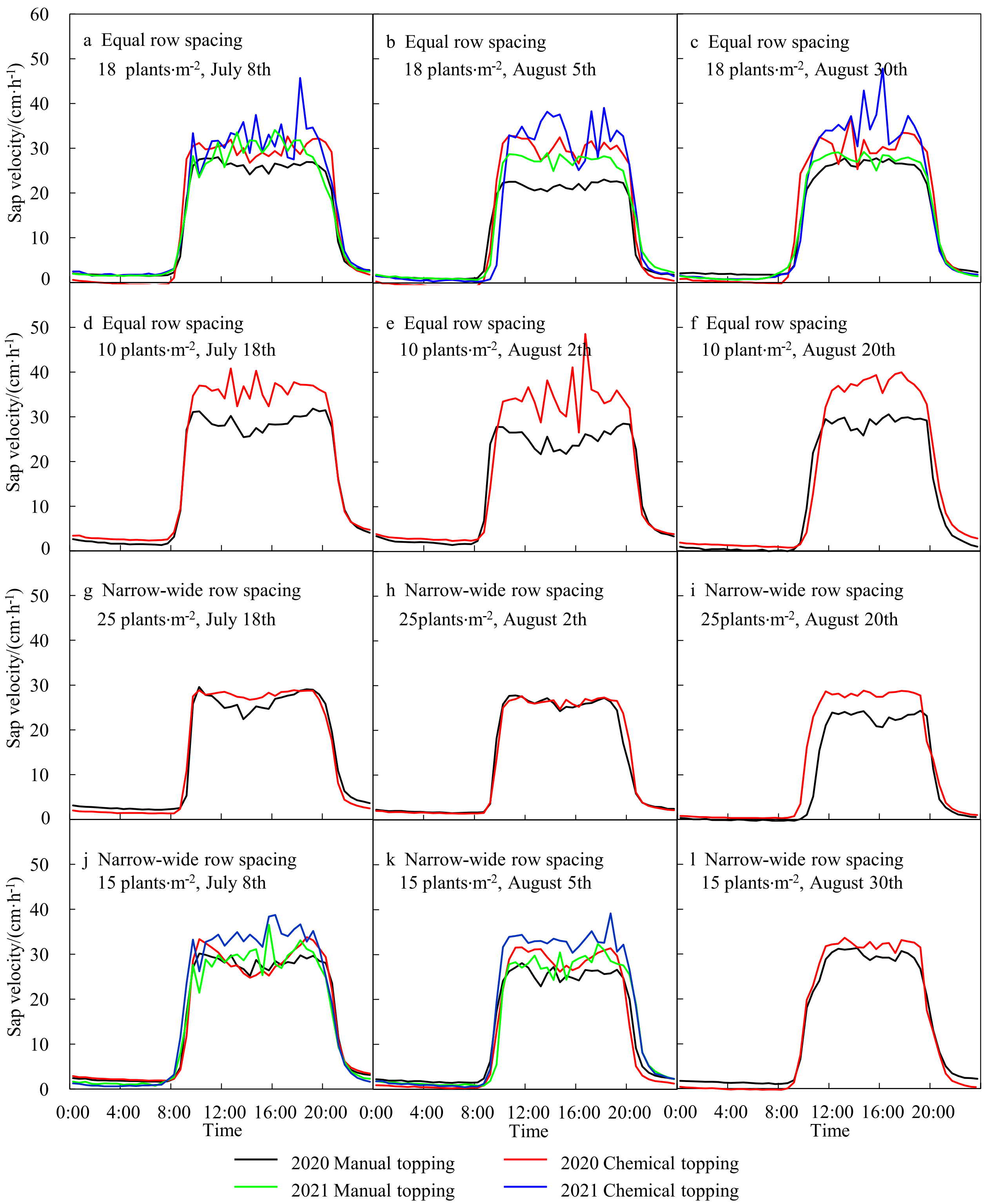

Fig. 5 Diurnal courses of sap velocity in three sunny days at different development stages under different row configurations (equal row spacing, narrow-wide row spacing), plant densities and topping treatments in 2020 and 2021

Table 5 Daily transpiration during flowering to boll opening stage in cotton under different row configurations, plant density, and topping treatments in 2020 and 2021

Year	Row configuration	Plant density Plants·m^{-2}	Topping	Daily transpiration/mm		
				Flowering	Flower and boll setting	Boll opening
2020	Equal row spacing	18	Manual topping	2.98±0.06 b	2.48±0.04 b	2.53±0.10 a
			Chemical topping	3.83±0.11 a	3.34±0.07 a	2.33±0.31 a
		10	Manual topping	2.54±0.09 b	2.17±0.04 b	1.81±0.09 b
			Chemical topping	3.26±0.08 a	2.98±0.05 a	2.36±0.12 a
	Narrow-wide row spacing	25	Manual topping	3.98±0.14 b	3.43±0.07 b	2.39±0.11 b
			Chemical topping	5.41±0.13 a	4.67±0.08 a	4.11±0.20 a
		15	Manual topping	3.12±0.09 b	2.73±0.04 b	2.41±0.12 b
			Chemical topping	3.62±0.13 a	3.20±0.06 a	2.89±0.13 a
2021	Equal row spacing	18	Manual topping	5.74±0.30 a	5.36±0.17 a	5.86±0.22 a
			Chemical topping	5.91±0.34 a	5.52±0.15 a	5.49±0.14 a
	Narrow-wide row spacing	15	Manual topping	7.3±0.36 b	6.88±0.41 b	
			Chemical topping	8.54±0.43 a	8.38±0.51 a	

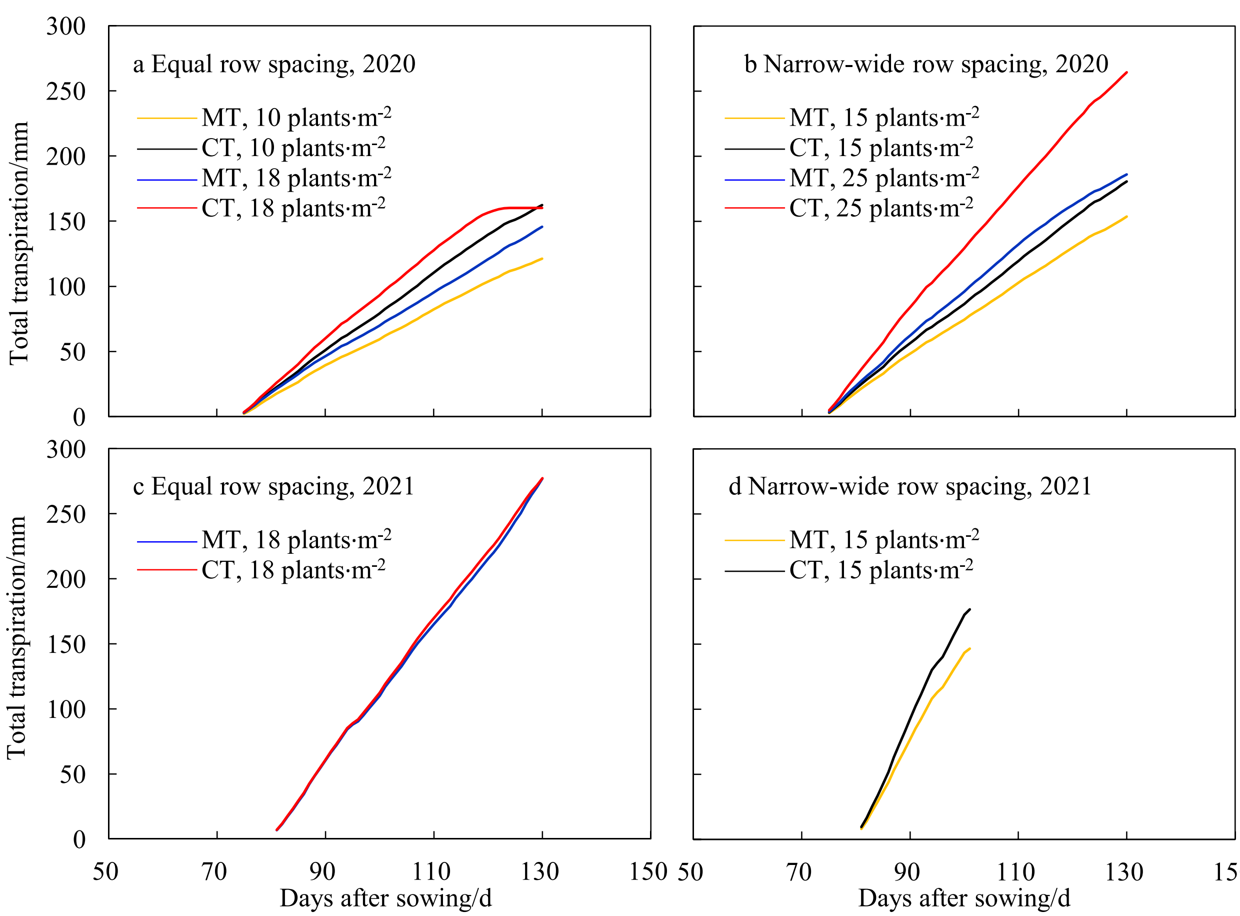

Fig. 6 Total transpiration during flower and boll-setting stage in cotton under different row configurations, plant density, and topping treatments in 2020 and 2021

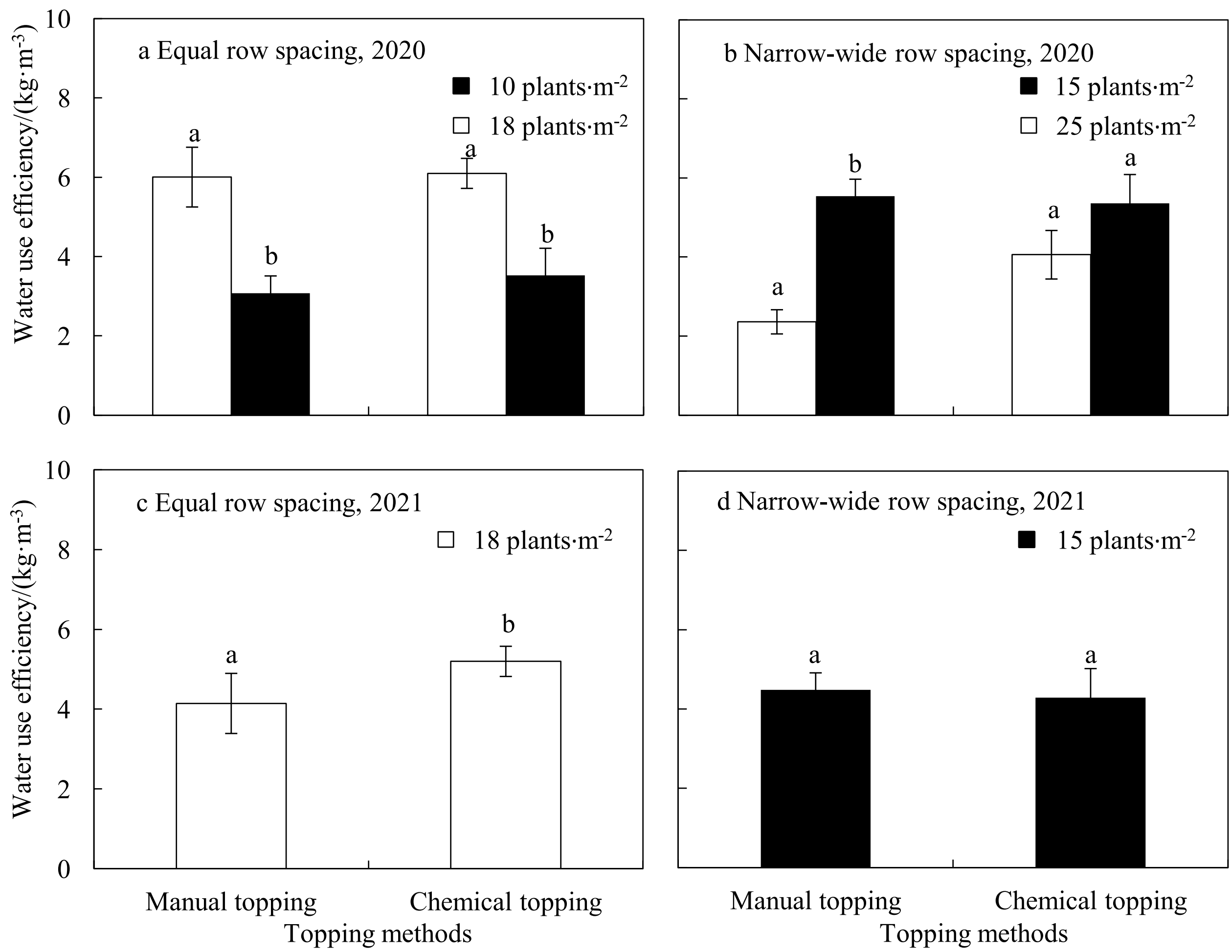

Fig. 7 Water use efficiency of drip-irrigated cotton under different row configurations, plant densities, and topping treatments in 2020 and 2021. Error bars indicate standard error for three replicates. The same lower case indicates no significant difference among topping methods within same density and year at 0.05 level

accuracy of crop transpiration in this study is depended on the representativeness of plant individuals and the limitations of measuring plant numbers due to the cost. In this study, only one cotton plant per treatment was measured by HRM. To minimize the limitations in sap flow measurements, three plants per plot were measured for the stem diameter and the aboveground dry matter, which are used for calculating the transpiration per plant and per unit ground area (Chen et al., 2022). Besides, crop transpiration might be affected by other factors, such as variety and meteorological factors, which require further analysis of the mechanisms of plant transpiration.

Conclusions

For machine-harvest cotton in Xinjiang, the optimal planting mode could be narrow-wide rows spacing with lower plant density (15 plants·m^{-2}), or equal rows with high plant density (18 plant m^{-2}) and applying chemical topping. Both modes achieved the highest seed cotton yield, water use efficiency, and saved labors by applying chemical topping. Our results suggest that the plant density in narrow-wide row spacing mode of farmers' practice, which often grows under a high density (e.g., 25 plants·m^{-2}), could be largely reduced when the chemical topping is applied instead of the manual topping. Our results provide a useful information for optimizing machine-harvest cotton managements and saving water by precisely knowing crop transpiration, growth, and yield formation in water deficient regions.

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Authors' contributions

Wang XJ: Data curation, formal analysis, writing—original draft preparation, funding acquisition and writing—review and editing; Hu YP: field experiment, data curation, review and editing; Ji CR: review and funding acquisition; Chen YF, Zhang ZS, Zhang YT, and Ji F: field experiment, data curation, formal analysis and investigation; Sun S and Wang S: methodology, investigation, and writing—review and editing; Yang MF and Guo YY: data curation and investigation; Zhang LZ: conceptualization and supervision. All authors read and approved the final manuscript.

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Availability of data and materials
All data generated or analyzed during this study are included in this published article.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
Authors declare no conflict of interest. Author Zhang LZ is a member of the Editorial Board of Journal of Cotton Research, he was not involved in the journal's review of, or decision related to this manuscript.

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