Crop photosynthetic productivity enhancement through uniform row-spacing with optimal plant density in Xinjiang, China

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Abstract
Xinjiang is currently the most dominant cotton (Gossypium hirsutum L.)-growing region in China and possesses abundant radiation resource. The cultivation techniques such as wide and narrow row-spacing and high density are widely adopted to obtain high cotton yield in the region. However, the region is facing some problems including poor light transmittance in the field and low exploitation for light resources under the current planting pattern which impedes further growth in cotton yields. Therefore, it is essential to develop some cultivation practices to increase radiation use efficiency (RUE) and cotton yields in Xinjiang. Here we conducted a field experiment to quantify the effects of row spacing pattern and plant density on RUE, intercepted photosynthetically active radiation from May to August (IPAR 5–8), and lint yield during 2017 and 2018. In this study, we designed two row-spacing configurations (R1, wide and narrow configuration, 66 cm + 10 cm; R2, uniform row-spacing configuration, 76 cm) and six plant densities (4.5, 9.0, 13.5, 18.0, 22.5, and 27.0 plants m⁻²). The RUE, lint yield, and number of bolls were higher in R2 than R1 by 4.1–5.9, 2.5–4.8, and 9.1–14.2%, respectively. The RUE significantly increased with plant density, but lint yield stabilized at 18.0 plants m⁻². Moreover, RUE had more significant positive effects on boll number and lint yield. Overall, we found that R2 combined with optimal plant densities (13.5–18.0 plants m⁻²) would be an effective strategy to achieve higher RUE and yields in the Xinjiang cotton system.

Abbreviations: D1–D6, 4.5, 9.0, 13.5, 18.0, 22.5 and 27.0 plants m⁻²; DAS, days after sowing; FB1–3N, the boll numbers on Fruiting Branches 1–3; FB4–6N, the boll numbers on Fruiting Branches 4–6; FB7+N, the boll numbers on branches above Fruiting Branch 7; IPAR 5–8, intercepted photosynthetically active radiation from May to August; LAI, Leaf area index; LI, daily fraction of intercepted photosynthetically active radiation; R1, 66+10-cm wide-narrow row-spacing; R2, 76-cm uniform row-spacing; RUE, radiation use efficiency; TBN, number of total bolls; VBN, boll numbers on vegetative branches.
1 | INTRODUCTION

Cotton (Gossypium hirsutum L.) is a vital natural fiber crop (Dai & Dong, 2014), and its yield and fiber quality are important to world economy. Xinjiang is the largest production area of high-quality cotton in China, accounting for more than 75% of cotton planting area and more than 80% of total cotton production in the nation in 2019 (Wang et al., 2019). Therefore, it is of great significance for the development of agricultural economy to increase and maintain the cotton yield in this region. Xinjiang has a typical continental arid climate with abundant heat units and solar radiation but scarce precipitation. Recent studies showed that high plant density, using dwarf cultivars, application of plastic film mulching, and drip irrigation under mulching significantly contributed to the high yields in Xinjiang (Li & Zhu, 2014; Qiao & Tao, 2001; Yu et al., 2015). However, the current management practices have been based on better use of water and heat resources but less exploration of light resources (Chen, Yu et al., 2014).

Plant canopy structure is directly related to the radiation utilization. Thus, it is important for the full use of light energy to optimize crop canopy structure and light distribution (Maddonni & Otegui, 1996). Canopy structure, related to plant density (Khan et al., 2017; Yao et al., 2016), row spacing pattern (Balkcom et al., 2010; Nichols et al., 2003), and fertilizer application (Dong et al., 2010; Dong et al., 2012), can affect the light distribution, interception, and radiation use efficiency (RUE), and ultimately affect the yield in the field. Plant density and row spacing pattern have always been important factors affecting canopy structure (Bednarz et al., 2000; Dong et al., 2006; Feng et al., 2017).

Leaf area index and photosynthetic rate may increase with plant population (Gwathmey & Clement, 2010; Zhang et al., 2004). Growing crops in dense populations resulted in more plant–plant competition for light and nutrients (Chen, Yu et al., 2014). As such, the dense canopy that developed early in the growing season can cause poor light distribution, lead to boll shedding, and reduce boll size (Bednarz et al., 2006; Yang et al., 2014). Although lint yield increased with increasing populations, it remained relatively stable across a wide range of planting densities (Bednarz et al., 2000; Siebert & Stewart, 2006). Currently, it is recommended that plant density should be 16.5–19.5 plants m$^{-2}$ in southern Xinjiang, and 18.0–22.5 plants m$^{-2}$ in northern Xinjiang (Bai et al., 2017).

High density alone is not enough to establish a high-RUE population for high cotton yield (Chen, Yu et al., 2014; Feng et al., 2017). Appropriate row spacing pattern can also improve radiation, heat, and water utilization efficiency. Research has shown that more equidistant planting pattern with high density could obtain more light interception and higher light utilization efficiency (Warner et al., 2002). In the United States and Australia, equidistant row-spacing planting pattern has long been adopted in the cotton fields (Brodrick et al., 2010; Nichols et al., 2003). In Xinjiang, cotton has been typically planted in wide-narrow row-spacing configurations of 66 + 10, 64 + 12, or 72 + 4 cm, and high population (Bai et al., 2017). It is difficult to explore the potential of cotton productions under wide-narrow row-spacing configurations and high density in Xinjiang because of serious interstitial closure, underdevelopment of individual plants, and low boll rate in middle and lower canopy. In recent years, studies have qualitatively shown that cotton cultivation mode of equidistant row-spacing configuration of 76 + 76 cm could be beneficial to further promote the integration of agronomic techniques and mechanization, make better use of light resources, easy application of chemical defoliation, and have better yield potential than that of the traditional wide-narrow row-spacing configuration (Chen, Yang et al., 2014; Cheng et al., 2017).

However, few studies have quantitatively explained the differences of photosynthetic characteristics and cotton yields, and the relationships between them under the uniform row-spacing configuration and traditional wide-narrow row spacing configuration with different densities in Xinjiang.

The objectives of this study were to (a) quantify the effects of row spacing patterns (wide-narrow vs uniform row-spacing configuration) and plant densities on light interception and radiation use efficiency; (b) analyze the variations of yield and its components under different management practices in terms of light use; and (c) determine the optimal combination of row spacing pattern and plant density in terms of light interception, radiation use efficiency, and cotton production.

2 | MATERIALS AND METHODS

2.1 | Experimental design and field management

The field experiment was conducted in 2017 and 2018 at an experiment station near Huyanghe city, the seventh agricultural corps, Xinjiang, China (44°73’ N, 84°81’ E).
The region is a typical temperate continental climate. The annual active growing degree days of ≥15 °C, annual average sunshine hours and annual average rainfall are 3,291.2 °C d, 1,988 h, and 127 mm during the growing season of cotton from 1961 to 2015, respectively. The total solar radiation during the cotton growing season in 2018 was 2.0% higher than in 2017, but rainfall in 2018 was 25.0% less than in 2017 (Figure 1). The experimental field has a fine clay loam soil. Technology of drip irrigation of integral control of water and fertilization was typical in the region. Plastic film mulch and drip irrigation were used in the experiment. Before sowing, the experiment plots were covered with 2.28-m-wide sheets of transparent plastic film. Drip irrigation lines were installed beneath the plastic film. The cultivar, one of the main varieties in the production in north Xinjiang, was ‘CCRI 92’, which was sown through holes on the plastic film mulch on 22 Apr. 2017 and 20 Apr. 2018.

A split-plot experimental design was employed with two row spacing patterns (R₁, wide-narrow row-spacing configuration, 66 + 10 cm; R₂, uniform row-spacing configuration, 76 cm) in the main plots and six planting densities (D₁–D₆, 4.5, 9.0, 13.5, 18.0, 22.5, and 27.0 plants m⁻²) in the subplots. The split-plot arrangement with three independent replicates was used to improve the accuracy of comparisons. Each subplot consisted of 12 (R₁) or six (R₂) 8-m rows of cotton plants with two 2.28-m-wide sheets of transparent plastic film. Six (three) rows from the same sheet of plastic film were used for plant sampling and the others for measuring leaf area index, light interception, yield components, and yield. Plant distances was adjusted according to the corresponding plant density. Plant distances in D₁–D₆ with R₁ system were 58.5, 29.2, 19.5, 14.6, 11.7 and 9.7 cm, respectively, and plant distances in D₁–D₆ with R₂ system were 29.2, 14.6, 9.7, 7.3, 5.8 and 4.9 cm, respectively (Figure 2). One to two seeds were planted in each hole. And seedlings were thinned at 2 wk after emergence to the required plant density.

The plots were fertilized before sowing each year with 300 kg ha⁻¹ [([NH₄]₂HPO₄], 75 kg ha⁻¹ K and 60 kg ha⁻¹ humic acid fertilizer. Plant topping was conducted at peak flowering (75–80 d after sowing, DAS). The same amount of growth regulator mepiquat chloride was applied to all plots to regulate cotton growth, and other field managements were conducted according to local agronomic practices.

### 2.2 Data collection and analysis

#### 2.2.1 Weather data

Daily maximum temperature, daily minimum temperature, daily mean air temperature, sunshine duration, and rainfall...
The active growing degree days (°C d) was calculated as Σ (mean temperature ≥15 °C).

The solar radiation (MJ m⁻²) was calculated using the Angstrom equation (Angstrom, 1924; He et al., 2020):

\[ H = H_L \left( a + b \frac{S}{S_L} \right) \]  \hspace{1cm} (1)

\[ S_L = \frac{24}{\pi} \omega_0 \]  \hspace{1cm} (2)

Where \( H \) is the actual daily total solar radiation (MJ m⁻²); \( H_L \) is the total daily radiation under sunny conditions (MJ m⁻²); \( S \) is the actual sunshine hours (h); \( S_L \) is the possible sunshine hours (h); and \( a \) and \( b \) are 0.25 and 0.50, respectively.

\[ H_L = I_0 d_m^2 \frac{24 (60)}{\pi} (\omega_0 \sin \varphi \sin \delta + \cos \varphi \cos \delta \sin \omega_0) \]  \hspace{1cm} (3)

Where \( I_0 \) is a solar constant (0.0820 MJ m⁻² min⁻¹); \( d_m^2 \) is the inverse relative distance Earth–Sun; \( \omega_0 \) is the sunset hour angle (rad); \( \varphi \) is latitude (rad); and \( \delta \) is the solar declination (rad).

\[ d_m^2 = 1 + 0.033 \cos \left( \frac{2\pi J}{365} \right) \]  \hspace{1cm} (4)

\[ \delta = 0.409 \sin \left( \frac{2\pi J}{365} - 1.39 \right) \]  \hspace{1cm} (5)

\[ \omega_0 = \arccos \left( -\tan \varphi \tan \delta \right) \]  \hspace{1cm} (6)

where \( J \) is the ordinal number of the day in the year, from 1 (1 Jan.) to 365 or 366 (31 Dec.).

2.2.2 Aboveground dry matter

Three plants were randomly sampled from the inner row of each plot approximately every 20 d, starting at squaring stage (between 45 and 55 DAS). In each sampling, the aboveground parts of plants which were divided into cotton stems (including branches and petioles), leaves, and reproductive organs were dried in an oven at 105 °C for 2 h first and then 80 °C for at least 48 h to constant weight to determine dry matter.

2.2.3 Yield and its components

Yield components, and distribution of harvestable bolls were determined by the cotton plants randomly selected and tagged in each plot: five cotton plants under \( D_1 \) treatment (more than 100 bolls) and 10 cotton plants under \( D_2- D_6 \) treatments. The tagged cotton plants per plot were hand-harvested at harvest time, and they were divided into four parts: the first part
included vegetative branch (VB), the second one included fruiting branches 1–3 (FB_{1–3}), the third one included fruiting branches 4–6 (FB_{4–6}), and the last one included fruiting branches above Number 7 (FB_{7+}). The yield components which consisted of total number of bolls per unit area, single boll weight, lint percentage (lint/seed cotton, w/w), were also observed according to the four parts of the cotton plants. Cotton was hand-harvested from the whole plot of each treatment at harvest time and afterwards dried, ginned, and weighted with respect to plots to obtain lint yield. Final yield (kg ha\(^{-1}\)) was determined by the total yield of each plot (include the tagged plants for yield components) and plot areas.

### 2.2.4 Leaf area index and light interception

Leaf area index (LAI) were measured by LAI-2000 plant canopy analyzer (LI-COR). Intercepted photosynthetically active radiation (IPAR) was calculated periodically (every 5 d before blooming stage, and every 15 d after blooming stage) above and below the canopy using a linear quantum of light (LI-191, LI-COR) to measure incident photosynthetically active radiation (PAR\(_i\)) and transmitted photosynthetically active radiation (PAR\(_t\)). Measurements were done on sunny days between 11:00 a.m. and 1:00 p.m. The PAR\(_i\) was recorded above canopy in each plot averaging three readings. The PAR\(_t\) was recorded averaging readings by positioning linear quantum of light at ground level in three random areas in each plot from the center of the furrow to the center of the bed.

The fraction of PAR intercepted by the crop at midday (LI\(_m\)) was calculated using the equation:

\[
LI_m = \frac{\text{PAR}_i - \text{PAR}_t}{\text{PAR}_i} \quad (7)
\]

The daily proportion of PAR intercepted (LI) was calculated by adjusting LI\(_m\) using the relationship (Charles-Edwards & Lawn Csiro, 1984):

\[
LI = \frac{2LI_m}{1 + LI_m} \quad (8)
\]

Where daily LI between measurements was estimated by a linear interpolation between measured LI and DAS.

### 2.2.5 Radiation use efficiency

Radiation use efficiency for each treatment was calculated as the slope of linear relationship between dry matter accumulation and the accumulation of intercepted photosynthetically active radiation (IPAR). Daily IPAR was obtained by multiplication of the daily solar radiation, a coefficient of 0.50 and daily LI (Szeicz, 1974).

### 2.2.6 Data analysis

All the statistical analyses were performed by using SPSS 21 (SPSS). Analysis of variance (ANOVA) was performed to determine the treatment differences for the effects of row spacing pattern, plant density, and year. In our analysis, row spacing pattern, plant density, and year were entered as fixed effects, whereas the replicate was entered as random factors and the replicate was nested within the year. Means within different treatments were compared by using Duncan’s Multiple Range Tests at a significance level of 5%. The regression models between each variable and plant density were chose by the tests results. We analyzed the quadratic relationships between IPAR and lint yield and plant density, and linear regression models were applied to assess the relationships between RUE and plant density. Pearson correlation analysis was used to determine the relationships among all the variables.

### 3 RESULTS

#### 3.1 Leaf area index

Early leaf area index was significantly influenced by both row spacing pattern and plant density, and LAI in R\(_1\) was significantly higher than that in R\(_2\) at the budding stage (prior to 70 DAS; Figure 3a, 3d). Except for the minimum density (D\(_1\)), there was no significant effect on the maximum LAI among the densities or between two row spacing patterns at the flowering and boll period (Figure 3b, 3c). The LAI in R\(_2\) was higher than that in R\(_1\), and LAI in D\(_1\) was lowest at the early boll opening period than that in other densities (Figure 3c, 3f).

#### 3.2 Light interception

The LI in the R\(_1\) treatment was higher than that in R\(_2\) before the maximum LI was reached, and the canopy in R\(_1\) reached the maximum LI earlier than in R\(_2\) (Figure 4). There was a significant effect on LI among densities prior to 60 DAS (Figure 4).

The effect of year or the effect of row spacing pattern or the effect of plant density on the IPAR\(_{5–8}\) was significant, but there was no interaction effect of row spacing pattern with plant density (Table 1). The IPAR\(_{5–8}\) in R\(_1\) was 1.3–4.9% slightly higher than that in R\(_2\) during the 2 yr (Figure 5; \(P < .05\)). The IPAR\(_{5–8}\) first increased but then decreased with increasing plant density in both 2017 and 2018. The IPAR\(_{5–8}\) in D\(_1\) was much lower than that in other densities regardless of the row spacing pattern, and IPAR\(_{5–8}\) in D\(_3\)–D\(_6\) was 3.3–4.4% significantly higher than that in D\(_1\) (\(P < .05\)). The significant quadratic relationships were found between IPAR\(_{5–8}\)
and plant density in $R_1$ ($R^2 = .663; P < .01$) and $R_2$ ($R^2 = .561; P < .01$) in 2017 (Figure 5a). However, there was no significant correlation between IPAR$_{5-8}$ and plant density in 2018 ($R_1, P = .243; R_2, P = .495$; Figure 5b).

### 3.3 Radiation use efficiency

Row spacing pattern, plant density, and year all significantly affected RUE (Table 1). The row spacing pattern × plant density interaction and three-way interaction of year × row spacing pattern × plant density also had significant effects on RUE. The RUE in $R_2$ was 4.1–5.9% significantly higher than that in $R_1$ during both years. The RUE increased with plant density, and the significant increase of RUE in higher plant densities were due to a higher growth rate per unit area (Figure 6). There was no significant difference in RUE between row spacing patterns in low densities ($D_1$–$D_2$) during both years, but significant difference in RUE between row spacing patterns was shown in middle densities ($D_3$–$D_4$; Figure 6). There were significant positive linear correlations between RUE and plant density in two row spacing patterns in both 2017 and 2018 (Figure 7). The slope of the linear regression between RUE and plant density in $R_2$ was higher than that in $R_1$ by approximately 20.6% during both years (Figure 7).

### 3.4 Lint yield and yield components

Lint yield and total boll number (TBN) were significantly affected by plant density (Table 2). Cotton planted in minimum plant density ($D_1$) produced the least TBN, and the number of bolls in different canopy layers varied with plant densities (Table 2). The number of bolls in the vegetative
### TABLE 2  Summary of significant differences from plant density, row spacing, and year for lint yield and yield components

| Treatment | Boll numbers | Boll weight | Lint | Lint yield |
|-----------|--------------|-------------|------|-----------|
|          | VB | FB<sub>1–3</sub> | FB<sub>4–6</sub> | FB<sub>7+</sub> | Total | VB | FB<sub>1–3</sub> | FB<sub>4–6</sub> | FB<sub>7+</sub> | Total |
|          | bolls m<sup>-2</sup> | g | % | kg ha<sup>-1</sup> |%
| 2017     |                |             |      |                |      |      |      |      |
| R<sub>1</sub> | 13.4b | 60.1a | 58.3a | 56.8a | 188.6b | 2.4a | 3.9a | 4.8a | 5.4a | 4.7a | 44.0a | 2,898.1b |
| R<sub>2</sub> | 20.2a | 61.6a | 63.1a | 61.5a | 206.4a | 2.3a | 3.9a | 4.8a | 5.2a | 4.6a | 44.2a | 3,037.6a |
| D<sub>1</sub> | 49.5a | 31.2a | 27.2e | 41.3c | 149.1c | 4.5a | 4.0a | 4.9a | 5.3a | 4.7a | 44.4a | 2,667.1b |
| D<sub>2</sub> | 26.1b | 47.4c | 46.8d | 51bc | 171.3b | 4.0ab | 4.1a | 4.6a | 5.5a | 4.6a | 44.1a | 2,960a |
| D<sub>3</sub> | 18.9c | 61.2b | 63.5c | 66a | 210.2a | 2.4bc | 3.8a | 4.8a | 5.3a | 4.5a | 44.2a | 3,045.4a |
| D<sub>4</sub> | 4.2d | 75.6a | 71.4bc | 67.2a | 218.4a | 2.5bc | 3.7a | 4.8a | 5.3a | 4.6a | 44.2a | 3,024.8a |
| D<sub>5</sub> | 2d | 73.1a | 73.8ab | 68.6a | 217.5a | 0.8cd | 3.7a | 4.6a | 5.2a | 4.5a | 43.8a | 3,093.2a |
| D<sub>6</sub> | 0d | 76.6a | 81.6a | 60.2ab | 218.5a | 0d | 4.0a | 5.0a | 5.4a | 4.7a | 43.8a | 3,016.5a |
| Mean     |                |             |      |                |      |      |      |      |
| R<sub>1</sub> | 12.7b | 59.6b | 54.3b | 43.3b | 153.2b | 2.6a | 4.5a | 4.9a | 4.6a | 4.6a | 46.7a | 3,203.5b |
| R<sub>2</sub> | 15.8a | 65.1a | 55.1a | 39.5a | 175.6a | 2.4a | 4.1a | 4.7a | 4.5a | 4.4b | 46.9a | 3,284.9a |
| D<sub>1</sub> | 49.7a | 32d | 28.7d | 34.2a | 144.5b | 4.6a | 4.5a | 4.9a | 4.8a | 4.7a | 46.4a | 2,939.1d |
| D<sub>2</sub> | 20.7b | 48c | 39.3c | 34.5a | 142.5b | 3.9a | 4.4a | 4.9a | 4.7ab | 4.5ab | 47.0a | 3,189.2c |
| D<sub>3</sub> | 6.7c | 63.9b | 50.9b | 38.8a | 160.3ab | 3.5a | 4.1a | 4.9a | 4.6abc | 4.5ab | 47.0a | 3,484.5a |
| D<sub>4</sub> | 4.2c | 67.8b | 63a | 37.2a | 172.2ab | 1.5b | 4.5a | 4.8a | 4.5abc | 4.6ab | 47.6a | 3,373.3ab |
| D<sub>5</sub> | 1.4c | 80.2a | 63.2a | 34.9a | 185.2a | 1.1b | 4.3a | 4.9a | 4.2c | 4.5ab | 47.0a | 3,182.5c |
| D<sub>6</sub> | 0.8c | 80.6a | 71.3a | 34.2a | 186.9a | 0.6b | 4.1a | 4.5a | 4.3bc | 4.3b | 47.2a | 3,296.6bc |

Source of variance

| Y | .102 | .515 | ** | ** | ** | .635 | ** | ** | ** | .711 | ** | .070 | ** | ** |
| R | ** | * | ** | ** | ** | .747 | .103 | .314 | .104 | * | .636 | ** | ** | ** |
| D | ** | ** | ** | ** | ** | ** | .533 | .767 | .107 | .460 | .700 | ** | ** | ** |
| Y × R | .388 | .212 | .990 | .474 | .628 | .896 | .194 | .247 | .505 | .525 | .504 | .341 | ** | ** |
| Y × D | .220 | .308 | .313 | ** | .096 | .653 | .764 | .072 | .361 | .300 | .498 | * | ** | ** |
| R × D | ** | .138 | .344 | * | .201 | .258 | .396 | .546 | .792 | .578 | .261 | .683 | ** | ** |
| Y × R × D | .103 | ** | .206 | ** | ** | .892 | .241 | .096 | .433 | .280 | .427 | .982 | ** | ** |

Note: Within the same cultivation measure treatment of a column, means not sharing a common letter are significantly different at P < .05 according to Duncan’s multiple range test.

*<sup>a</sup>R<sub>1</sub>, 66 + 10-cm-width row spacing; R<sub>2</sub>, 76-cm uniform row spacing; D<sub>1–6</sub>, 4.5, 9.0, 13.5, 18.0, 22.5, and 27.0 plants m<sup>-2</sup> planting density.

<sup>b</sup>VB, vegetative branches; FB<sub>1–3</sub>, Fruiting Branches 1–3; FB<sub>4–6</sub>, Fruiting Branches 4–6; FB<sub>7+</sub>, branches above Fruiting Branch 7.

*Significant at the .05 probability level;

**Significant at the .01 probability level.
FIGURE 4 Proportion of intercepted photosynthetically active radiation (LI) under different plant densities and row spacing configurations in 2017 (a, b) and 2018 (c, d) growing seasons. Error bars are least significant difference among plant densities. R1, wide-narrow row-spacing configuration (66 cm + 10 cm); R2, uniform row-spacing configuration (76 cm). D1–6, 4.5, 9.0, 13.5, 18.0, 22.5, and 27.0 plants m⁻² planting densities. Bars indicate least significant difference among plant densities. *Significant at the .05 probability level; **Significant at the .01 probability level.

FIGURE 5 Relationship between intercepted photosynthetically active radiation from May to August (IPAR₅–₈) and plant density in 2017 (a) and 2018 (b) under two different row-spacing treatments. R1, wide-narrow row-spacing configuration (66 cm + 10 cm); R2, uniform row-spacing configuration (76 cm).

branches (VBN) decreased significantly with increasing plant density in both years. However, the number of bolls on the Fruiting Branches 1–3 (FB₁–₃N), the number of bolls on the Fruiting Branches 4–6 (FB₄–₆N), and TBN increased significantly with plant density. The difference of FB₁–₃N between high densities (D₅ and D₆) was not significant, and difference of FB₇₄N, TBN or lint yield among the middle and high densities (D₃–D₆) was also not significant. In addition, the density also had no significant effect on lint percentage and boll weight (Table 2). There were significant correlations between lint yield and plant density in two row spacing patterns in both years (quadratic polynomial models; P < .01), and the yield increased firstly but then decreased gently with increasing plant density, which showed that highest lint yield (2,900–3,400 kg ha⁻¹) was in middle density (13.5–18.0 plants m⁻²; Figure 8).
Row spacing pattern had significant effects on VBN, FB\textsubscript{1–3}N, FB\textsubscript{4–6}N, FB\textsubscript{7+}N, TBN, boll weight, and lint yield during both years. Lint yield in R\textsubscript{2} was 2.5–4.8% higher than that in R\textsubscript{1}. Cotton planted in R\textsubscript{2} produced 9.1–14.2% more total bolls than that planted in R\textsubscript{1}. The VBN, FB\textsubscript{1–3}N, FB\textsubscript{4–6}N, and FB\textsubscript{7+}N in R\textsubscript{2} were higher by 31.3–50.2, 1.7–11.2, 7.8–9.4, and 8.9–20.9% than those in R\textsubscript{1}, respectively. There were significant interaction effects between row spacing pattern and plant density on both VBN and FB\textsubscript{7+}N in both years (Table 2).

### 3.5 Correlation analysis

The TBN, FB\textsubscript{1–3}N, FB\textsubscript{4–6}N, and FB\textsubscript{7+}N were positively correlated to IPAR\textsubscript{5–8}, respectively (R\textsubscript{IPAR\textsubscript{5–8}/TBN} = .326, R\textsubscript{IPAR\textsubscript{5–8}/FB\textsubscript{1–3}N} = .401, R\textsubscript{IPAR\textsubscript{5–8}/FB\textsubscript{4–6}N} = .446, R\textsubscript{IPAR\textsubscript{5–8}/FB\textsubscript{7+}N} = .232; \( P < .01 \)). However, VBN was negatively correlated with IPAR\textsubscript{5–8} (R\textsubscript{IPAR\textsubscript{5–8}/VBN} = −.454; \( P < .01 \); Table 3).

TBN, FB\textsubscript{1–3}N, FB\textsubscript{4–6}N, FB\textsubscript{7+}N, and lint yield were positively correlated to RUE, respectively (R\textsubscript{RUE/TBN} = .693, R\textsubscript{RUE/FB\textsubscript{1–3}N} = .797, R\textsubscript{RUE/FB\textsubscript{4–6}N} = .795, R\textsubscript{RUE/FB\textsubscript{7+}N} = .358, R\textsubscript{RUE/yield} = .422, respectively; \( P < .05 \); Table 3). However, VBN was negatively correlated to RUE (R\textsubscript{RUE/VBN} = −.695; \( P < .01 \); Table 3). There was no significant correlation between boll weight or lint percentage and RUE (Table 3). The TBN was negatively correlated to VBN (R\textsubscript{TBN/VBN} = −.473; \( P < .01 \)), and it had positively correlations to FB\textsubscript{1–3}N, FB\textsubscript{4–6}N, FB\textsubscript{7+}N and lint yield (R\textsubscript{TBN/FB\textsubscript{1–3}N} = .807, R\textsubscript{TBN/FB\textsubscript{4–6}N} = .843, R\textsubscript{TBN/FB\textsubscript{7+}N} = .690, R\textsubscript{TBN/yield} = .430, respectively; \( P < .05 \); Table 3). VBN was negatively correlated with lint yield (R\textsubscript{VBN/yield} = −.635; \( P < .01 \)). The correlation between FB\textsubscript{1–3}N and lint yield was similar to that between FB\textsubscript{4–6}N and the yield. FB\textsubscript{1–3}N and FB\textsubscript{4–6}N were both positively

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**Figure 6** Radiation use efficiency under different plant densities and row spacing configurations in 2017 (a) and 2018 (b). R\textsubscript{1}, wide-narrow row-spacing configuration (66 cm + 10 cm); R\textsubscript{2}, uniform row-spacing configuration (76 cm). D\textsubscript{1–6}, 4.5, 9.0, 13.5, 18.0, 22.5, and 27.0 plants m\textsuperscript{−2}. Bars are means ± standard deviation. Bars within the same row spacing configuration not sharing a common letter are significantly different at \( P < .05 \) according to Duncan’s multiple range test.

**Figure 7** Relationship between radiation use efficiency and plant density in 2017 (a) and 2018 (b) under two different row-spacing treatments. R\textsubscript{1}, wide-narrow row-spacing configuration (66 cm + 10 cm); R\textsubscript{2}, uniform row-spacing configuration (76 cm).
FIGURE 8 Relationship between lint yield and plant density in 2017 (a) and 2018 (b) under two different row-spacing treatments. $R_1$, wide-narrow row-spacing configuration (66 cm + 10 cm); $R_2$, uniform row-spacing configuration (76 cm).

TABLE 3 Correlations between intercepted photosynthetically active radiation from May to August (IPAR$_{5-8}$), radiation use efficiency (RUE), boll weight, total boll number (TBN), number of bolls on vegetative branches (VBN), number of bolls on Fruiting Branches 1–3 (FB$_{1-3}$N), number of bolls on Fruiting Branches 4–6 (FB$_{4-6}$N), number of bolls on branches above Fruiting Branch 7 (FB$_{7+N}$), lint percentage, and lint yield.

| IPAR$_{5-8}$ | RUE | Boll weight | TBN | VBN | FB$_{1-3}$N | FB$_{4-6}$N | FB$_{7+N}$ | Lint percentage | Lint yield |
|------------|-----|-------------|-----|-----|------------|------------|------------|-----------------|-----------|
| IPAR$_{5-8}$ | 1   |             |     |     |            |            |            |                 |           |
| RUE        | .248| 1           |     |     |            |            |            |                 |           |
| Boll weight | −.083| −.265 | 1    |     |            |            |            |                 |           |
| TBN        | .326***| .693*** | −.378 | 1   |            |            |            |                 |           |
| VBN        | −.454**| −.695** | .166 | −.473**| 1          |            |            |                 |           |
| FB$_{1-3}$N | .401***| .797*** | −.341 | .807** | −.770** | 1          |            |                 |           |
| FB$_{4-6}$N | .446***| .795*** | −.287 | .843** | −.806** | .874** | 1          |                 |           |
| FB$_{7+N}$ | .232**| .358** | −.227 | .690** | −.310* | .327* | .471** | 1              |           |
| Lint percentage | −.037| −.066 | −.329** | .038 | .017 | .023 | −.009 | .037 | 1 |
| Lint yield | .366 | .422* | −.259 | .430* | −.635** | .545** | .550*** | .372* | .166 | 1 |

*Significant at the .05 probability level; **Significant at the .01 probability level.

Correlated with lint yield ($R_{FB1-3N/yield} = .545$, $R_{FB4-6N/yield} = .550$; $P < .01$; Table 3).

4 | DISCUSSION

This study showed that plant density and row spacing pattern affected canopy structure, light interception, and RUE, thereby influencing the number of bolls and cotton yields.

The IPAR$_{5-8}$ in low density was significantly lower than that in other plant densities, but there was no significant effect on IPAR$_{5-8}$ among other densities, similar to results by Zhang et al. (2014) and Yao et al. (2016). This is because LI significantly increased with plant density in association with an increase of LAI in crops (Zhang et al., 2014). The canopy in $D_1$ had smaller LAI prior to canopy closure at flowering and boll period (70 DAS in 2017, 80 DAS in 2018), and had smaller LI prior to 55 DAS than that in other densities, but there was no significant effect on LAI and LI among other densities (Figures 3, 4).

The main reason of poor canopy photosynthetic capacity is that the canopy has less IPAR in low densities (Yao et al., 2016). According to our results, IPAR$_{5-8}$ and RUE in low densities were lower than those in other densities. The IPAR$_{5-8}$ was highest in the middle plant densities (13.5–18.0 plants m$^{-2}$) rather than higher densities (Figure 9). We considered that the canopy had high light extinction coefficient at higher plant density so that the canopy cover ratio did not increase with plant density (Mao et al., 2014; Zhang et al., 2008). Therefore, the IPAR$_{5-8}$ did not correspondingly increase with increasing plant density at higher density (>18.0 plants m$^{-2}$). However, the variation of RUE
in higher densities was inconsistent with that of IPAR, and RUE increased with plant density which was consistent with previous studies (Mao et al., 2014). An explanation may be that there were more green leaves at the late growth stage due to leaf senescence delayed in the dense cotton canopy in higher plant density (Dong et al., 2012). However, Siebert and Stewart (2006) found the opposite result, that the increase of density in association with taller plants can result in more shading within the cotton canopy and adversely affect the photosynthetic capacity of leaves. However, in our research, cotton plants were shorter in higher plant populations, and this may be due to main stem topping early and chemical regulation with the application of mepiquat chloride that can reduce plant height in the cotton field in Xinjiang.

The relative change in the yield between row spacing patterns was inconsistent with the change in IPAR. In the experiment, LI and IPAR in R were higher than those in R before maximum LI was reached. In addition, we also found LAI in R was higher than that in R at early growth stage which indicated that the low-canopy layer received less light in R and resulted poor light distribution from squaring to early bloom in R. Some studies found that low light intensity in the lower canopy can reduce photosynthetic rates of those leaves (Feng et al., 2016), negatively affect boll development (Zhao & Oosterhuis, 2000), cause more boll shedding, and result in lower fruit retention and smaller boll size (Bednarz et al., 2006). Light that leaves in the canopy could receive has a direct effect on nitrogen content of leaves that determines photosynthetic capacity (Yao et al., 2015). The RUE in R was higher than that in R, similar to results that RUE diminishes as the row spacing narrows (Maddonni et al., 2006; Mattera et al., 2013), and RUE in R increased at a faster rate than that in R as plant density increased; that is to say, cotton plants in R can make better use of light energy to assimilate into the dry matter. The TBN was significantly and positively correlated with RUE (R = .693, P < .01). Therefore, there was more bolls in R than R by 9.1% in 2017 and 14.2% in 2018.

Row spacing pattern and plant density considerably altered the yield and yield components during the study. The VBN, FB, FB, FB, and lint yield were all significantly higher in R than those in R during both years. The number of bolls was obviously influenced by plant density which was similar to previous reports (Bednarz et al., 2000; Zhi et al., 2016). Only VBN decreased, and FB, FB, FB, and TBN increased with plant population (Table 2). There was no effect on boll weight or lint percentage among plant densities in this study, inconsistent with Bednarz et al. (2006). Thus, it can be seen that the yield gap among plant densities or row spacing patterns was likely a consequence of the number of bolls rather than boll size and lint percentage. The rise in the density significantly increased the number of bolls but may not contribute significantly to the yield (Dong et al., 2010; Mao et al., 2015). It was worth noting that there were significant positive correlations among RUE, TBN, and yield. Also, RUE had a more significant positive effect on TBN than IPAR, especially FB and FB. Thus, higher RUE was conducive to achieve higher lint yield. However, we
found that cotton at moderate plant density (13.5–18.0 plants m\(^{-2}\)) achieved the highest yield, and lint yield was relatively stable within a certain range of high plant densities which could be a consequence of compensation between IPAR\(_{5-8}\) and RUE. The RUE increased because more leaf surface was intercepting light in higher populations, resulting that total dry matter accumulation increased with plant density (Dong et al., 2010; Khan et al., 2017). However, IPAR\(_{5-8}\) was not significantly different among the medium and high densities (D\(_3\)–D\(_6\)), so that the lower canopy may had less light penetrating, reproductive organ biomass accumulation decreased in the dense canopy, and reproductive organ biomass was high at moderate density (Brodrick et al., 2013; Khan et al., 2017; Mao et al., 2015). The insufficient light in high densities could reduce canopy temperature, improve humidity, and have more fruit shedding in the low canopy layer which would lead to a decrease in reproductive organ formation (Khan et al., 2017).

Cotton fields in R\(_2\) combined with moderate plant densities (13.5–18.0 plants m\(^{-2}\)) could achieved higher yields and light use efficiency in terms of economic benefits (Figure 9).

There were more days of extreme high temperature (>35 °C) and more rainfall in July and August in 2017 than 2018 (Figure 1). The study has shown that the extreme high temperature (>35 °C) during flowering and boll setting stage could stop cotton plants growing and affect fiber development (Zhou et al., 2016). And the warmer temperature during the reproductive stage leaded to lower yields (Chen et al., 2014). Moreover, higher rainfall at the reproductive stage inhibited the translocation of photochemical substances and reduced the yield (Tung et al., 2018). In our study, lint yield and lint percentage were markedly higher in 2018 (more solar radiation) than 2017. Irrespective of climatic variations, lint yield in R\(_2\) was higher than that in R\(_1\).

In equidistant row-spacing configuration, there is more uniform plant distribution which can reduce the competition between individuals for water, nutrition, and light (Li et al., 2015; Sharratt & McWilliams, 2005). The cotton field in uniform row-spacing configuration is beneficial to mechanical harvesting and chemical defoliation (Chen, Yang et al., 2014; Cheng et al., 2017). In the R\(_2\) system, it can be beneficial to establish high RUE populations to further improve yield and promote the fully mechanized cotton production technology.

### 5 | CONCLUSIONS

Optimizing cotton plant density and row spacing pattern can improve the canopy structure, light distribution, and population photosynthetic production. The RUE had more significant positive effect on TBN and lint yield than IPAR\(_{5-8}\). In the R\(_2\) system, cotton plants had better RUE and light distribution which can make plants produce more bolls, especially VB and FB\(_{74}\) N. In addition, cotton plants in R\(_2\) had higher lint yield at the same density than that in R\(_1\) (Figure 9). The increase in yield was mainly attributed to the increase in boll number per unit area rather than boll size or lint percentage. Moderate plant densities (13.5–18.0 plants m\(^{-2}\)) can optimize light resource to achieve high yields in both row spacing patterns (Figure 9). In addition, lint yield improved by a rise of plant density up to 18.0 plants m\(^{-2}\), and the yield could be stable across a range of densities due to the compensating effect of IPAR\(_{5-8}\) and RUE. At present, the management goal of cotton production is to make full use of heat resources in Xinjiang, but the efficient use of light resources is seldom considered. Therefore, in order to achieve higher light utilization efficiency and productivity of the cotton system and promote fully mechanized cotton production technology, uniform row-spacing configuration (R\(_2\)) combined with the optimal plant densities (13.5–18.0 plants m\(^{-2}\)) would be a promising option in Xinjiang.

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### AUTHOR CONTRIBUTIONS

Liting Hu: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Resources; Validation; Visualization; Writing-original draft. Xuebiao Pan: Conceptualization; Funding acquisition; Methodology; Supervision; Writing-review & editing. Xiaochen Wang: Data curation; Investigation. Qi Hu: Conceptualization; Data curation; Investigation. Xiangru Wang: Conceptualization; Data curation; Investigation; Resources. Hengheng Zhang: Data curation; Investigation; Methodology. Qingwu Xue: Writing-review & editing. Meizhen Song: Conceptualization; Data curation; Formal analysis; Funding acquisition; Methodology; Supervision

### CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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