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Early Relay Intercropping of Short-Season Cotton Increases Lint Yield and Earliness by Improving the Yield Components and Boll Distribution under Wheat-Cotton Double Cropping

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Abstract: Wheat-cotton double cropping has improved crop productivity and economic benefits per unit land area in many countries, including China. However, relay intercropping of full-season cotton and wheat, the most commonly adopted mode, is labor-intensive and unconducive to mechanization. The direct sowing of short-season cotton after wheat (CAW) has been successful, but cotton yields and economic benefits are greatly reduced. Whether the relay intercropping of short-season cotton before the wheat harvest increases cotton yields remains unclear, as does the earliness and fiber quality relative to those for CAW. Therefore, we directly planted short-season cotton after wheat harvest on 15 June (CAW) as the control and interplanted short-season cotton in wheat on 15 May (S1), 25 May (S2) and 5 June (S3), which were 30, 20 and 10 days prior to wheat harvest, respectively, from 2016 to 2018. The crop growth, yield, yield components, boll distribution, and earliness of the cotton were evaluated. The yields and earliness of short-season cotton under relay intercropping were 26.7–30.6% and 20.4–42.9% higher than those under CAW, respectively. Compared with CAW, relay intercropping treatments increased the boll density, boll weight and lint percentage by 5.6–13.1%, 12.5–24.5% and 5.8–12.7%, respectively. The dry matter accumulation and harvest index under the relay intercropping treatments were also greater than those under CAW, which might be attributed to the greater partitioning of dry matter to the seed cotton than to the boll shells. Among the relay intercropping treatments (S1, S2 and S3), the lint yield did not differ, but S1 and S2 were considerably better than S3 based on earliness and fiber quality. The analysis of the within-plant spatial boll distribution showed that more bolls were formed on the lower to middle fruiting branches and at the first fruiting sites for S1 and S2 than for S3 and CAW. Therefore, the increased earliness and fiber quality induced through early relay intercropping (S1 and S2) could be attributed to an improved spatial boll distribution compared to late relay intercropping (S3) or CAW. Conclusively, compared to late relay intercropping and CAW, early relay intercropping considerably increased the lint yield, fiber quality, and earliness by improving the yield components, boll distribution, and dry matter accumulation and partitioning. The relay intercropping of short-season cotton 20 to 30 days before wheat harvest represents a promising alternative to CAW in wheat-cotton double-cropping systems in the Yellow River Basin of China and other regions with similar conditions.

Keywords: double cropping; short-season cotton; sowing date; relay intercropping; yield formation

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1. Introduction

Improving annual productivity and cropping indices in global crop production is critical considering the increasing population and limited arable land [1]. Many countries, including China, have adopted wheat-cotton double-cropping systems to increase the gross production of both grains and fiber in agricultural areas with abundant heat and water resources [2–6]. In these systems, full-season cotton is sown or transplanted through interplanting in reserved spaces between wheat stands, and this cropping pattern has been reported to produce approximately 70–90% of the cotton and 60–80% of the wheat produced in monocultures [1,7–11]. However, this approach is labor- and material-intensive because of a long intergrowth period and growth season, in which a decreased wheat yield could be caused by incomplete full area planting [1,2,10]. In recent years, labor-saving technologies and mechanized management have been commonly used, considering the labor shortage in the agriculture industry due to rural residents surging into cities [11–13]. Since 2007, winter wheat in China has been successfully mechanically harvested [14]. Farmers are often inclined to produce more grains in wheat-cotton cropping systems, and wheat could occupy a greater relative area in the relay intercropping strip. Thus, the wheat-cotton double-cropping pattern requires a novel approach to increase wheat yields and save time in cotton production in China.

One planting pattern that recently gained interest involves planting wheat in regular rows, harvesting it mechanically and then sowing short-season cotton at a high plant density following the wheat harvest in the south cotton belt of China [1,15–17]. Moreover, a new wheat-cotton cropping pattern adopting the short-season cotton and narrow crop planting strip width increased the grain yield by 15–30% [2,3]. However, in the middle cotton belt of China, which includes the Yellow River Basin, the cotton yields, fiber quality and economic benefits resulting from the pattern are relatively lower than those obtained from relay-intercropped full-season cotton because short-season cotton sown after wheat harvest (CAW) results in an approximately 50 day reduction in the growth period and many late-season bolls [17–19]. Therefore, in the Yellow River Basin, the relay intercropping of short-season cotton before the wheat harvest increases the growth period of cotton and may increase cotton yields and benefits relative to those for CAW. However, the plant growth, yield formation and benefits associated with the relay intercropping of short-season cotton in wheat have rarely been studied.

In the relay intercropping of full-season cotton in wheat, the intergrowth period is usually 40 to 50 days [10]. The adjustment of the intergrowth period length is dependent on the sowing date of the cotton. The earlier the cotton sowing date is, the more sufficient the growth and development periods of the cotton are. However, a longer intergrowth period can lead to wheat having diverse impacts on cotton growth and development [1]. It was previously shown that the adjustment of the sowing dates of intercropped cotton resulted in varied heat and radiation accumulations, not only during the intergrowth period, but also during other cotton growth stages, leading to different growth and development trends and cotton yields [20–23]. Early sowing of cotton has been reported to not necessarily increase the cotton yield due to the reduced boll-setting rate, although early planted cotton had more fruit branches and earlier flowers and bolls [13,22], while late-planted cotton misses the optimal temperature conditions during the reproductive growth period, resulting in insufficient dry matter accumulation, more immature bolls, and poor fiber quality [20,24]. Therefore, optimizing the sowing date of cotton is important in wheat and cotton double-cropping systems [1,2,17]. However, scarce information is available regarding the effects of the sowing date on the yield, boll distribution or crop growth performance of relay intercropping systems with short-season cotton in wheat.

Therefore, the relay intercropping of short-season cotton can improve cotton yields compared with the direct planting of short-season cotton after wheat harvest. The objectives of this study were to determine (1) the differences in cotton yields, yield components and cotton earliness between relay-intercropped cotton and CAW; (2) whether the yield and fiber quality of cotton are associated with the sowing date under relay intercropping;

and (3) how relay intercropping and the sowing date affect cotton yield and earliness based on the spatial distribution of bolls, dry matter accumulation and the partitioning of cotton plants.

2. Materials and Methods

2.1. Experimental Site

A 3-year (2016–2018) field experiment was conducted at the research station (36°07′ N, 116°22′ E) of the Institute of Cotton Research, Chinese Academy of Agricultural Sciences, Anyang, Henan, China. The area has a semihumid and subtropical monsoon climate. It has fluvo-aquic soil (alluvial soil). The soil fertility information prior to wheat sowing is presented in Table 1. Weather data were acquired from a weather station located near the experimental field (Campbell Scientific, Logan, UT, USA). The weather information is provided in Figure 1.

Table 1. Soil fertility metrics for the experimental sites in 2016, 2017 and 2018.

Year	Soil Depth (cm)	PH	Organic Matter (g kg^{-1})	Total Nitrogen (g kg^{-1})	Available Phosphorus (mg kg^{-1})	Available Potassium (mg kg^{-1})
2016	0–20	7.82	14.5	1.05	64.5	235.6
	20–40	7.98	11.2	0.71	46.5	99.6
2017	0–20	7.93	13.9	1.18	37.5	266.8
	20–40	8.01	8.9	1.09	25.6	122.7
2018	0–20	7.92	13.8	1.28	52.7	243.1
	20–40	8.02	8.6	0.89	24.9	111.3

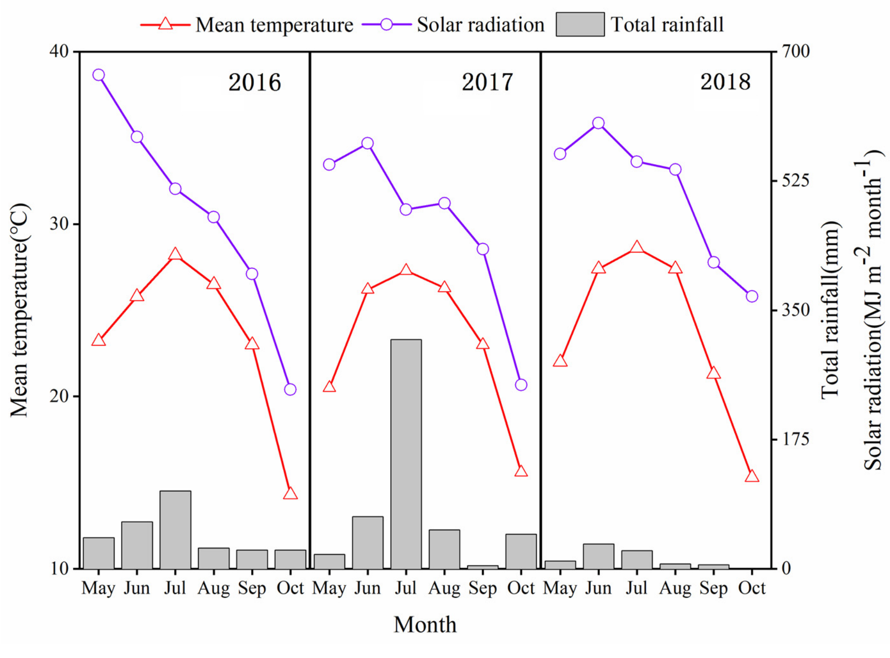


Figure 1. Weather information by month during the cotton growing seasons in 2016, 2017 and 2018.

2.2. Experimental Design and Field Management

The short-season cotton (*Gossypium hirsutum* L.) cultivar ZM50 and the wheat (*Triticum aestivum* L.) cultivar ZY1123, provided by Zhongmian Seed Technologies Co., Ltd., Anyang, Henan, China, were used as the experimental materials in this study. Wheat was sown by a planter on 26 October 2015, 25 October 2016, and 26 October 2017 and was harvested by a combine harvester on 12 June 2016, 7 June 2017, and 12 June 2018. The cotton was sown using a semiautomatic single-row seeder on 15 May (S1), 25 May (S2), 5 June (S3) and 15 June (CAW), with an intergrowth period in the wheat of approximately 30 days, 20 days, 10 days, and 0 days, respectively. The layout of the cropping system is presented in Figure 2. In the relay intercropping system, wheat was sown in strips with bare soil left for cotton. A total of 3 rows of wheat (15 cm row width for wheat) were alternated with 1 row of cotton (76 cm row width for cotton). All treatments were arranged in a randomized complete block design in triplicate. Each plot had an area of 33.6 m^2 (6.84 m wide × 9.0 m long) with 27 rows of wheat and 9 rows of cotton. The cotton seedlings were thinned to 7.5 plants·m^{-2} at the 3-true-leaf stage.

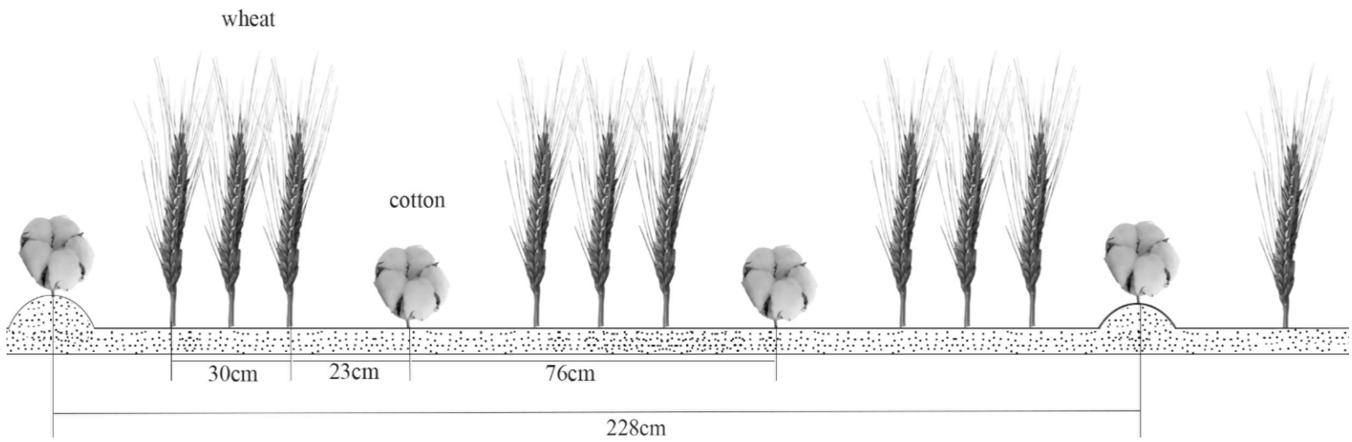


Figure 2. Schematic diagram of the crop arrangement in the field.

Field management was consistent across the treatments. During the wheat growing period, 750 kg·ha^{-1} of compound fertilizer (127.5 kg·ha^{-1} N, 127.5 kg·ha^{-1} P_2O_5, and 127.5 kg·ha^{-1} K_2O) was applied as base fertilizer, 225 kg·ha^{-1} of urea (103.5 kg·ha^{-1} N) was applied as a jointing fertilizer, and 150 kg·ha^{-1} of urea plus 90 kg·ha^{-1} of compound fertilizer (84.3 kg·ha^{-1} N, 15.3 kg·ha^{-1} P_5, 15.3 kg·ha^{-1} K_2O) was applied as an earing fertilizer. For the cotton, 112.5 kg·$ha^{-1}$of urea (N51.75 kg·ha^{-1}) and 150 kg·ha^{-1} of urea together with 150 kg·ha^{-1} of compound fertilizer (94.5 kg·ha^{-1} N, 25.5 kg·ha^{-1} P_2O_5, 25.5 kg·ha^{-1} K_2O) were applied in the squaring and peak-flowering stages, respectively. Weeds and insects were controlled according to local practices. The cotton was hand-harvested.

2.3. Data Collection

2.3.1. Agronomic Traits

Ten cotton plants were randomly selected in each plot to measure the plant height and the number of fruiting branches at 14–15 day intervals from 15 June to 13 October 2016; from 14 June to 12 October 2017; and from 19 June to 17 October 2018.

2.3.2. Dry Matter Accumulation and Leaf Area

A total of 3 cotton plants were randomly sampled from the central rows of each plot for the determination of dry weight and leaf area at 14–15 day intervals from 15 June to 13 October 2016; from 14 June to 12 October 2017; and from 19 June to 17 October 2018. The aboveground plants were separated into three parts (stem and branches, leaves, and reproductive organs). The leaves were imaged using a scanner (Phantom 9800xl, MicroTek, Shanghai, China), and the leaf area (LA) was then determined by using Image-Pro Plus (Media Cybernetics, Inc., Rockville, MD, USA) [3]. Then, each part was heated at 105 °C in an oven for 30 min and then dried at 85 °C to a constant weight to measure the dry weight. On the last sampling date, the boll shell was separated from the boll, and the boll shell proportion was calculated.

The productive organ biomass measured in terms of days after emergence (DAE) was fitted with a nonlinear sigmoidal logistic function model with the following equation:

$$W = \frac{W_{max}}{1 + ae^{-bt}} \quad (1)$$

where W (g plant^{-1}) represents the dry matter weight; t (days) represents the days after emergence; W_{max} (g plant^{-1}) represents the theoretical maximum value of W; and a and b are constants. According to the logistic function, the eigenvalues of t_1, t_2, and V_M can be calculated according to Formulas (2)–(4). The terms t_1 and t_2 represent the initiation and termination times of the fast accumulation period, respectively; V_M represents the maximum biomass growth rate; and Δt (=$t_2 - t_1$) represents the duration of rapid growth (in days) [3].

$$t_1 = -\frac{1}{b}\ln\frac{2+\sqrt{3}}{a} \quad (2)$$

$$t_2 = -\frac{1}{b}\ln\frac{2-\sqrt{3}}{a} \quad (3)$$

$$V_M = \frac{b \times W_{max}}{4} \quad (4)$$

2.3.3. Plant Mapping

Successions of 10 cotton plants were randomly selected from the central 2 rows of each plot for plant mapping every 10 days. Plant mapping was conducted using the software "prplus.apk" (http://202.110.101.4/cecri/prpjj.php, accessed on 15 April 2017) run on a cellular telephone [25,26]. The numbers of bolls at each cotton node and fruiting site were recorded. All cotton bolls were divided into 3 classes according to the flowering date to evaluate the temporal distribution of bolls: early-season bolls (flowering before 25 July), middle-season bolls (flowering between 25 July and 15 August) and late-season bolls (flowering after 15 August).

The boll retention rate at each position was calculated by dividing the number of plants with a boll at that position by the total number of plants. The average boll weight at each fruiting position was also recorded.

2.3.4. Yield and Yield Components and Land Equivalent Ratio (LER)

An area of 2.28 m^2 (3 m × 0.76 m) of wheat was harvested from each plot for yield determination. The grain yields were determined assuming a water content of 12% in the sun-dried grains. In October, the numbers of cotton plants and bolls over 3 m in the central four rows of each plot, covering an area of 9.12 m^2 (0.76 m × 3 m × 4 rows), were recorded before the cotton harvest in October. In 2016, cotton bolls were hand harvested, seed cotton was weighed after drying, and the seed cotton yield and boll weight were calculated.

The lint yield was determined after ginning. In 2017 and 2018, for each cotton plant, the cotton bolls were individually hand-harvested from nodes and fruiting positions, placed into a nylon mesh bag, and then dried to a stable weight in the sunlight to determine the seed cotton yield and the average boll weight [3]. Then, all bolls were mixed and ginned, and the lint percentage was calculated. The prefrost boll opening rate was calculated as the proportion of cotton bolls opened before the frost to the total number of open bolls at harvest. The harvest index was calculated as the ratio of the seed cotton yield to the total biomass.

The land equivalent ratio (LER) was calculated according to the equation proposed by Willey [10,23]:

$$LER = Y_{w,i}/Y_{w,s} + Y_{c,i}/Y_{c,s} \quad (5)$$

where $Y_{w,i}$, $Y_{w,s}$, $Y_{c,i}$, and $Y_{c,s}$ are the grain yields of intercropped and sole wheat, and the lint yields of intercropped and sole cotton, respectively. LER is similar in meaning to total relative yield.

2.3.5. Fiber Quality

The lint samples were pooled to determine the fiber length, strength and micronaire value using a High Volume Instrument cotton fiber tester (HVI-900A, Uster, Knoxville, TN, USA) at the Cotton Quality Supervision, Inspection and Testing Center of the Ministry of Agriculture and Rural Affairs, Anyang, Henan, China [24].

2.3.6. Data Analysis and Statistics

The four sowing dates, that is, S1, S2, S3 and CAW, were arranged in a randomized complete block design with 3 replications in 2016, 2017 and 2018. Analysis of variance (ANOVA) was performed using Duncan′s test in SAS9.0 statistical software (Statistical Analysis System, Cary, NC, USA). Contour graphs were plotted using Surfer13 (Origin Lab, Northampton, MA, USA).

3. Results

3.1. Cotton Yield, Yield Components and LER

The lint yield was significantly affected by the sowing date in all three studied years (Table 2). Compared to those in the relay intercropping treatments (S1–S3), the lint yield for CAW was significantly reduced by 54.9%, 5.36% and 46.6%, averaged across the 3 years. However, no significant difference was observed in the lint yield among the relay intercropping treatments.

Table 2. Effects of the sowing date on the short-season cotton yield and its composition.

Treatment	Lint Yield (kg/hm^2)	Boll Density (Bolls/m^2)	Boll Weight (g)	Lint Percentage (%)	Earliness ** (%) *	Biological Yield (kg/hm^2)	Harvest Index	Wheat Yield (kg/hm^2)	LER ***
					2016				
S1 *	1079a	71.2b	3.98a	37.9a	77.6a	7800b	0.365a	7546a	1.560a
S2	1028a	70.2b	3.90a	37.5a	76.0a	7594b	0.361a	7742a	1.555a
S3	1003a	75.6a	3.75b	37.2a	71.1a	8025a	0.336b	7781a	1.545a
CAW	717b	57.7b	3.53c	35.2b	50.6b	6592b	0.309c	7844a	1.387b
					2017				
S1	1103a	68.9b	4.22a	38.0a	84.8a	7539b	0.385a	8574a	1.575a
S2	1138a	70.0b	4.21a	38.5a	83.6a	7738b	0.382a	8742a	1.613a
S3	1095a	72.8a	4.02a	37.3a	68.0b	8177a	0.359b	8786a	1.595a
CAW	700b	57.5b	3.57b	34.1b	45.9c	6935c	0.296c	8821a	1.382b
					2018				
S1	1076a	79.2b	3.86a	35.5a	80.7a	8603b	0.355a	7953a	1.598a
S2	1064a	78.5b	3.83a	35.3a	78.3a	8612b	0.350a	7977a	1.594a
S3	988a	81.9a	3.58b	34.7a	58.5b	9039a	0.315b	8067a	1.560a
CAW	686b	69.5c	3.01c	31.8b	37.8c	7543c	0.286c	8132a	1.390b
					Average				
S1	1086a	73.2ab	4.02a	37.5a	81.1a	7913b	0.366a	8024a	1.578a
S2	1077a	73.1ab	3.98a	37.2a	79.3a	7981b	0.364a	8154a	1.588a
S3	1028a	76.8a	3.78b	36.4b	65.9b	8414a	0.337b	8211a	1.567a
CAW	701b	61.4b	3.37c	33.9c	44.8c	7023c	0.297c	8266a	1.386b
					Source of variance (p-value)				
Year (Y)	0.1675	0.001	<0.001	<0.001	0.0147	<0.001	<0.001	<0.001	0.2076
Sowing date (SD)	<0.001	0.0361	<0.001	<0.001	<0.001	<0.001	<0.001	0.4436	<0.001
Y × SD	0.5457	0.5134	0.0125	0.0127	0.0325	0.6731	<0.001	0.9994	0.7572

* S1, S2 and S3 represent the relay intercropping of short-season cotton 30, 20 and 10 days before wheat harvest, and CAW represents the direct sowing of short-season cotton after the wheat harvest. ** Earliness is indicated by the percentage of the prefrost seed cotton to the total harvest of seed cotton by weight. Values within a year followed by different letters are significantly different at $p = 0.05$. LER *** is the land equivalent ratio. The wheat yields of the monoculture in 2016, 2017 and 2018 were 8100, 8850, and 8250 kg/hm^2, and the lint yields of the monoculture were 1696, 1819, and 1716 kg/hm^2.

The sowing date significantly influenced cotton yield components. The S3 treatment resulted in the greatest boll density, and the CAW treatment resulted in the lowest boll density (Table 2). No significant difference was found in the boll densities between the S1 and S2 treatments in any of the three years. Relative to CAW, the relay intercropping treatments increased the boll weights by 12.5–24.3%. Moreover, the boll weight (y) linearly decreased with the delayed days (days; x) ($y = -0.0234x + 4.386$ ($R^2 = 0.540^{**}$, $n = 12$)), indicating that the boll weight decreased by 0.234 g for each delay of 10 days. The boll weight measured under the S3 treatment was significantly lower than those measured under S1 and S2, except in 2017. No significant difference in the boll weight was observed between S1 and S2. The lint percentage for CAW was significantly lower (by 7.4–10.6%) than for the relay intercropping treatments. No significant differences in the lint percentage were observed among the relay intercropping treatments.

The sowing date also significantly influenced the LER. The LER of the relay intercropping treatments was higher than that for CAW. The highest LER was observed in S2 in all three years, although no significant difference was detected among the relay intercropping treatments.

3.2. Earliness and Fiber Quality

The sowing date was observed to have a significant effect on cotton earliness, as indicated by the prefrost boll opening rate in all three years (Table 2). As the sowing date was delayed, the cotton earliness decreased. Averaged across the 3 years, the earliness of cotton in CAW was 36.3, 34.5 and 21.1% lower than in S1, S2 and S3, respectively.

A significant reduction in fiber quality was observed in CAW (Table 3). Compared to those of the relay intercropping treatments (S1, S2 and S3), the fiber lengths, fiber strengths and micronaire values of CAW were reduced by 2.2–3.0%, 5.4–11.5% and 16.2–46.8%, respectively, averaged across the 3 years. No significant differences in the fiber quality parameters were observed between the early relay intercropping treatments (S1 and S2). Late relay intercropping (S3) also showed a significant reduction in the fiber strength and micronaire values compared to those under the early intercropping treatments.

3.3. Biomass Accumulation and Partitioning

3.3.1. Harvest Index

The harvest index was significantly affected by the sowing date (Table 2). The 2 early relay intercropping treatments (S1 and S2) resulted in the greatest harvest index values (0.366 and 0.364), followed by the late intercropping treatment (0.337) and then CAW (0.297).

3.3.2. Biomass Accumulation and Partitioning

The logistic growth model was used to simulate cotton biomass accumulation with regard to the different sowing dates (Table 4), and the corresponding eigenvalues were calculated. The cotton in the relay intercropping treatments was characterized by lower maximal reproductive organ biomass accumulation rates (V_m values) and longer growth durations (Δt). As a result, the reproductive organ biomass decreased as the sowing date was delayed. The reproductive biomasses measured under the relay intercropping treatments were significantly higher than those measured under CAW by 13.3–29.9%, 6.3–13.9%, and 0.8–1.1%, respectively.

Table 3. The fiber quality of cotton in the four treatments (2016–2018).

Treatment	Fiber Length (mm)	Strength (cNtex^{-1})	Micronaire Value
	2016		
S1	29.6a	30.1a	4.28a
S2	29.8a	29.8a	4.20a
S3	29.2a	28.1ab	3.96b
CAW	28.2a	26.7c	3.73c
	2017		
S1	29.4a	30.7a	4.35a
S2	29.6a	30.1a	4.11a
S3	30.0a	29.7ab	4.00a
CAW	28.7a	28.2b	3.73b
	2018		
S1	30.6a	30.5a	4.27a
S2	29.9a	29.4ab	4.16a
S3	29.7a	29.0ab	3.61b
CAW	29.5a	27.3b	3.19c
	Average		
S1	29.9a	30.4a	4.29a
S2	29.8a	29.8ab	4.16a
S3	29.6a	29.1b	3.85b
CAW	28.8a	27.4c	3.55c
	Source of variance (*p*-value)		
Year (Y)	0.1793	0.0203	0.0289
Sowing date (SD)	0.0971	<0.001	<0.001
Y × SD	0.7647	0.7423	0.2819

Values within a year followed by different letters are significantly different at $p = 0.05$.

Table 4. Values of the regression equation parameters used to calculate the cotton biomass of reproductive organs.

Year	Treatment	T1 ()	T2 (DAE *)	Vm (g·plant^{-1} d^{-1})	ΔT (d)	Wmax (g·plant^{-1})	R^2
2016	S1	91.4a	122.8	12.84	31.4	612.2a	0.9929
	S2	82.1b	112.1	12.59	30.0	573.9ab	0.9939
	S3	78.6c	104.0	14.16	25.3	544.8b	0.9995
	CAW	78.0c	101.7	15.04	23.6	539.8b	0.9998
2017	S1	85.2a	112.2	12.30	33.2	619.8a	0.9931
	S2	78.2ab	111.8	11.47	33.6	592.6a	0.9970
	S3	73.7c	100.1	13.76	26.4	551.6b	0.9993
	CAW	73.0c	98.0	14.95	25.0	547.1b	0.9954
2018	S1	89.0a	123.4	15.10	34.4	794.1a	0.9841
	S2	84.8b	118.2	13.80	33.4	696.7b	0.9846
	S3	82.1b	111.8	14.90	29.6	671.1b	0.9949
	CAW	75.5c	101.2	15.36	25.7	611.5c	0.9897

* DAE is short for days after emergence. Values within a year followed by different letters are significantly different at $p = 0.05$.

3.3.3. Dry Matter Partitioning Coefficient and the Boll Shell Proportion

The partitioning coefficient of reproductive organs increased with time (Figure 3). The relay intercropping treatments had higher reproductive organ partitioning coefficients than CAW across the whole growth period. At the end of the growing season, the reproductive organ partitioning coefficients measured under CAW were 4.3–5.2%, 3.5–4.1%, and 1.9–3.4% lower than those measured under the relay intercropping treatments, respectively.

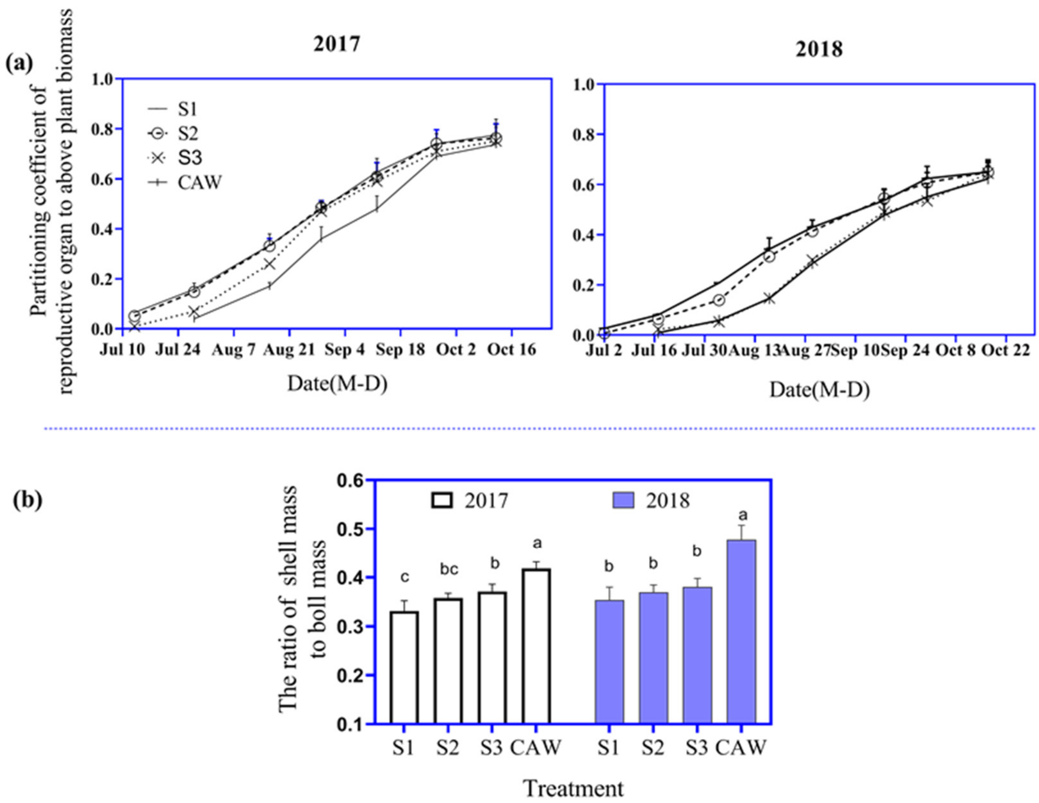


Figure 3. The partitioning coefficient of the reproductive organs after squaring (**a**) and the boll shell proportions (**b**) (Different lowercase letters on the column represent the significant differences at p = 0.05).

An increasing trend was observed in the proportion of the boll shell to the whole boll (PBS) as the sowing date was delayed (Figure 3). Thus, CAW yielded the maximum PBS values (0.418 in 2017 and 0.478 in 2018), and these values were significantly higher than those measured under the relay intercropping treatments by 20.8–26.0%, 14.4–22.7%, and 11.3–20.4%, respectively. These increased PBS values indicated that more dry matter was retained in the boll shell in the late-sown cotton (CAW), which might explain the reduced boll weight measured with the delayed sowing date.

3.4. Agronomic Traits

All agronomic trait parameters were significantly influenced by the sowing date (Table 5). Compared to the relay intercropping treatments, CAW significantly reduced the plant height, number of fruiting branches, number of fruiting sites and maximum leaf area per plant by 13.9–20.9%, 16.7–27.9%, 19.7–24.8% and 6.1–14.1%, respectively. The earliest sowing date resulted in a significantly lower ratio of fruiting sites to fruiting branches (RSB) than the other three sowing dates. As the sowing date was delayed, the RSB first increased and then decreased, and the greatest RSB value was observed under the late relay intercropping treatment (S3).

3.5. Boll Distribution

3.5.1. Temporal Distribution of Bolls

The sowing date significantly influenced the number of bolls formed at different times. The CAW yielded no early-season bolls in either year (Figure 4). As the sowing date was delayed, the number of early-season bolls decreased, while the number of late-season bolls increased in both years. S3 and CAW had the highest and lowest numbers of middle-season bolls, respectively. No significant difference in middle-season bolls was found among the relay intercropping treatments in 2017, while the number of middle-season bolls measured under S3 was significantly higher than the numbers measured under S1 and S2 in 2018.

Table 5. Agronomic characteristics of cotton plants in the four treatments.

Treatment	Plant Height (cm)	Fruiting Branch (No.plant^{-1})	Fruiting Sites (No.plant^{-1})	Ratio of Fruiting Sites to Fruiting Branch	Maximum Leaf Area (cm^2 plant^{-1})
			2016		
S1	57.0a	11.3a	28.8b	2.55a	2898ab
S2	54.1a	10.6ab	30.7a	2.90a	3012a
S3	56.5a	9.5b	27.9b	2.94a	2835a
CAW	51.2b	8.2c	20.9c	2.58a	2692b
			2017		
S1	58.9a	9.7a	29.1a	3.02b	3200a
S2	62.4a	9.5a	31.7a	3.33ab	3263a
S3	62.6a	9.0a	32.0a	3.61a	2967b
CAW	46.8b	6.9b	22.4b	3.23ab	2640c
			2018		
S1	52.4b	12.3a	29.1a	2.38b	3527a
S2	57.7a	11.4a	30.5a	2.69ab	3367a
S3	56.2ab	10.3b	31.2a	3.03a	3039b
CAW	46.7c	8.9c	26.7b	3.01a	2970b
			Mean		
S1	56.1a	11.1a	29.0a	2.65b	3208a
S2	58.1a	10.5b	31.0a	2.97a	3221a
S3	58.4a	9.6c	30.6a	3.19a	2947b
CAW	48.3b	8.0d	23.3b	2.94ab	2767c
			Source of variance (p-value)		
Year (Y)	0.0015	<0.001	0.0397	<0.001	<0.001
SD	<0.001	<0.001	<0.001	0.003	<0.001
Y × SD	0.007	0.3625	0.1297	0.4441	0.0194

Values within a year followed by different letters are significantly different at p = 0.05.

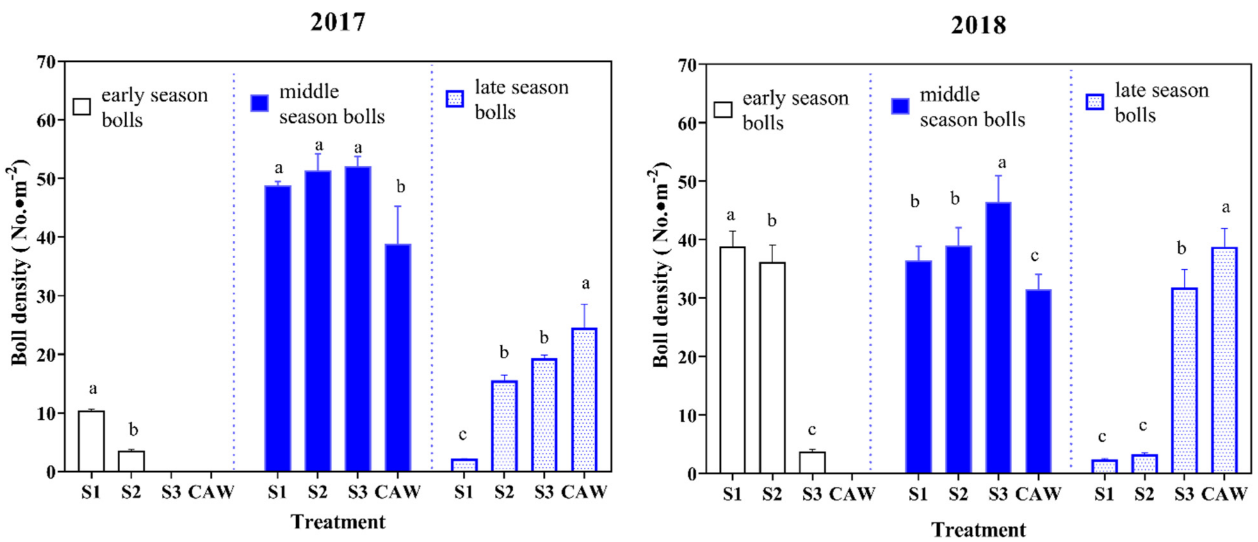


Figure 4. Boll densities measured during the 3 boll-formation seasons in the 4 treatments (the early season, the period from 5 July to 25 July; the middle season, the period from 26 July to 15 August; and the late season, the period from 16 August to the harvest. Different letters on the column represent the significant differences at p = 0.05).

3.5.2. Spatial Distribution of Bolls

The effect of the sowing date on the boll densities at different fruiting positions was significant in both 2017 and 2018 (with the exception of the fourth fruiting position in 2017) (Figure 5). The CAW produced the lowest boll density (28.6 boll·m^{-2} in 2017 and 24.2 boll·m^{-2} in 2018) at the first fruiting position. The early relay intercropping treatments (S1 and S2) resulted in the highest boll densities at the first fruiting position, with no significant difference measured between these treatments. In contrast, the late relay intercropping treatment (S3) and CAW exhibited higher boll densities than the early relay intercropping treatments (S1 and S2) at fruiting positions 2–4.

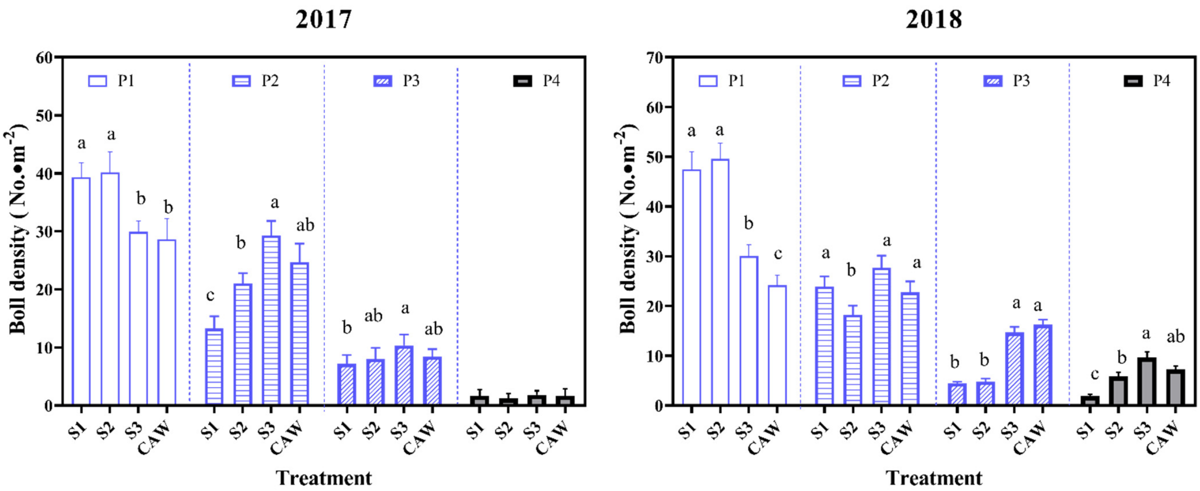


Figure 5. Boll densities measured at four positions in the horizontal direction in the four treatments (P1, the first sympodial position; P2, the second position; P3, the third position; and P4, the fourth position. Different letters on the column represent the significant differences at $p = 0.05$).

3.5.3. Boll Retention Distribution

As shown in Figure 6, compared to CAW, the relay intercropping treatments produced a higher boll retention ratio, and the high boll retention ratio (>0.3) measured on the intercropped cotton was mainly concentrated at the first sympodial positions. However, the sympodial positions with the high boll retention ratio (>0.3) measured under the CAW treatment exhibited a horizontal extension to position 3.

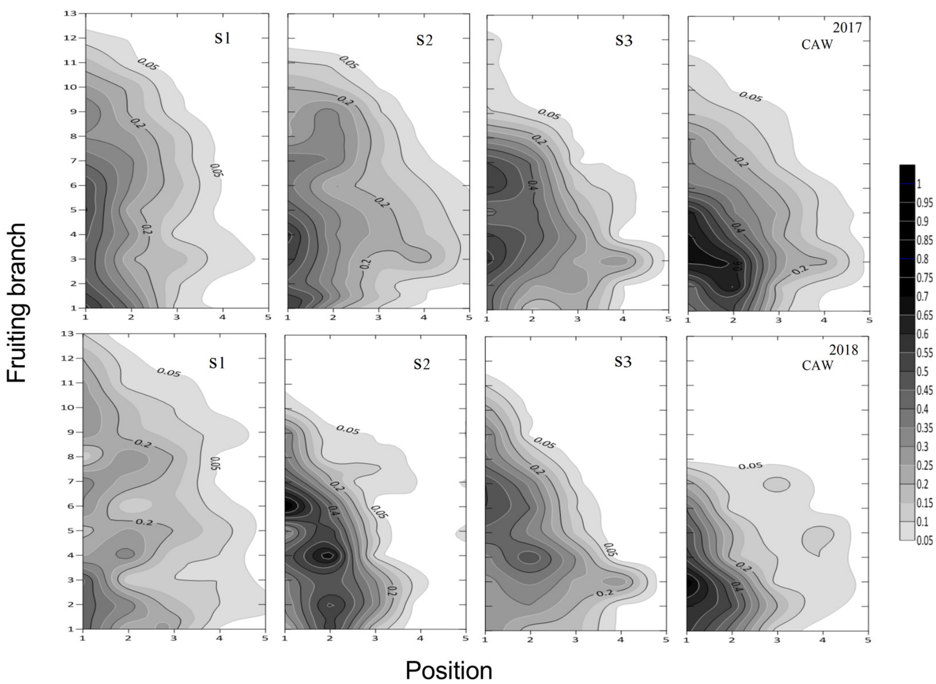
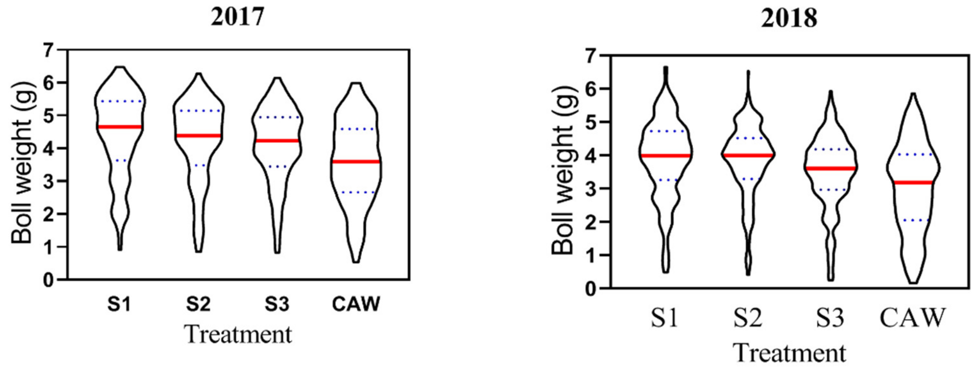


Figure 6. The contour maps of boll retention ratio of each fruiting site in the four treatments.

3.5.4. Boll Weight Distribution

The distribution of the boll weight was investigated (Figure 7), and the boll weight gap between the 1st quartile and the 3rd quartile in CAW was 1.93 (2018); this value was 22.0%, 34.7% and 37.1% greater than those measured under the relay intercropping treatments, indicating that CAW had more tiny bolls with light weights. Moreover, compared with those for the relay intercropping treatments, the boll weights measured at the 1st and 2nd fruiting positions in CAW were significantly reduced by 4.2–16.5% and 7.4–15.7%, respectively (Figure 7b).



(a)

Eigenvalue	**2017**				**2018**			
	S1	**S2**	**S3**	**CAW**	**S1**	**S2**	**S3**	**CAW**
Boll number(N)	**194**	**227**	**232**	**204**	**208**	**218**	**245**	**195**
The minimum	**0.91**	**0.85**	**0.82**	**0.53**	**0.49**	**0.41**	**0.24**	**0.16**
Quartile 1st	**3.64**	**3.49**	**3.48**	**2.67**	**3.26**	**3.29**	**2.93**	**2.05**
Mean value	**4.42**	**4.18**	**4.09**	**3.57**	**3.86**	**3.83**	**3.48**	**3.01**
Quartile 3st	**5.43**	**5.14**	**4.93**	**4.55**	**4.74**	**4.52**	**4.15**	**3.94**
The maximum	**6.48**	**6.28**	**6.15**	**5.99**	**6.65**	**6.52**	**5.92**	**5.86**

(b)

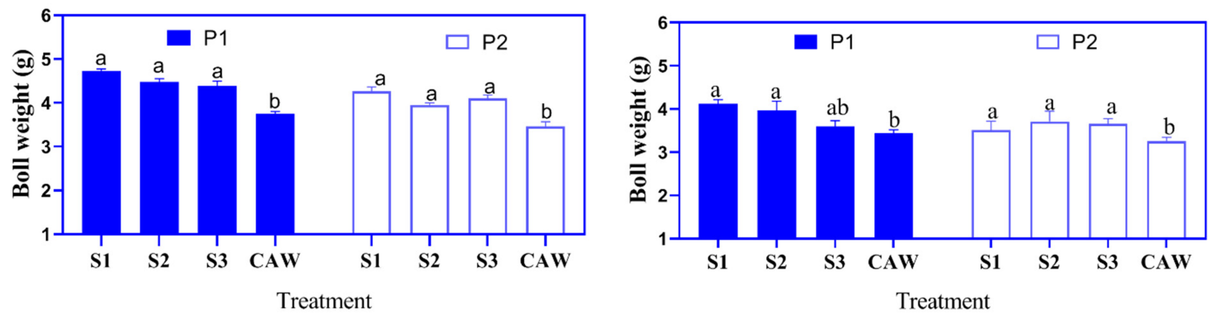


Figure 7. The whole boll weight population distribution and the boll weights measured at different sympodial positions (**a**) the whole distribution of boll weights; (**b**) the boll weights at the first position (P1) and the second position (P2). Different letters on the column represent the significant differences at $p = 0.05$.

4. Discussion

4.1. Relay Intercropping of Short-Season Cotton Greatly Increased the Lint Yield and Fiber Quality Compared to CAW

Intercropping wheat with full-season cotton has played an important role in alleviating competition for land used for grain and cotton production in the Yellow River Basin in recent decades [1,17,27,28]. However, with increased labor costs, mechanization has become an inevitable production management trend [1,3]. Wheat intercropped with full-season cotton, however, is not conducive to mechanized production due to the long intergrowth period. Theoretically, the direct sowing of short-season cotton after wheat might be an ideal alternative to the relay intercropping of full-season cotton in wheat. However, sowing short-season cotton after wheat has been shown to result in significant reductions in cotton yields and fiber quality and thus low production benefits due to less reproductive biomass accumulation, fewer bolls [14,18], and delayed maturity [29–31] in the Yellow River Basin due to insufficient accumulated heat units. The reduction in lint yield also resulted in decreased LER [1,10]. Therefore, relay intercropping of short-season cotton in wheat can achieve earlier cotton sowing and might be an effective way to increase cotton yield and LER. In the present study, the cotton yield and crop maturity were significantly improved in relay intercropping of short-season cotton. The lint yields of cotton in relay intercropping treatments were 32.1–59.8%, 25.7–47.9% and 22.6–44.2% higher than those for CAW (685.6–817.2 $kg \cdot hm^{-2}$), respectively. The relay intercropping treatments increased LER by 0.178–0.208 compared to CAW, which could be attributed to the shortened intergrowth period and enlarged wheat planting area. Additionally, the cotton earliness in the relay intercropping treatments (S1, S2 and S3) was increased by 27.0–42.9%, 25.4–38.5% and 20.5–22.1%, respectively, compared to CAW. Relative to CAW, enhanced fiber quality, especially higher fiber strength and micronaire values, was observed in the relay intercropping treatments. Compared with CAW, the relay intercropping treatments increased the plant and reproductive organ biomass of cotton by 8.7–21.7% and 0.9–23.0%, respectively, due to the longer period (1.4–8.7 days longer) for the accumulation of biomass in the reproductive organs. Additionally, the partitioning coefficient of the reproductive organs and the harvest index were also significantly higher under the relay intercropping treatments. Therefore, compared to CAW, the relay intercropping of short-season cotton in wheat improved the cotton yield, fiber quality and earliness.

4.2. Early Relay Intercropping Improved the Yield Components and Spatiotemporal Distribution of Bolls Compared to Late Relay Intercropping

Altering the cotton sowing date changes the environmental conditions, such as light, heat, and water, and these changes influence cotton growth and further affect the yield and quality of the cotton [10,21]. An appropriate sowing date corresponds to the most suitable heat and light resource availabilities for promoting cotton growth in different growth periods, favors the establishment of a group structure and the development of cotton to ensure timely maturation, and thus results in a high yield, fine fiber quality and high use efficiency of resources [24,32]. Some studies have indicated that early sowing significantly increases the plant height, number of fruiting branches and leaf area index of cotton due to the longer growth period [33], while other studies have shown that late sowing increases plant height due to increased temperatures but does not increase the economic yield [21]. In the current study, although the lint yields of the three relay intercropping treatments were significantly higher than that of CAW, no significant difference was observed in the lint yields among the three relay intercropping treatments.

The yield of cotton is generally determined based on yield components, including the number of bolls (boll retention), boll weight and lint percentage [34,35]. Among the relay intercropping treatments, the numbers of bolls for S1 and S2 were 3.4% and 7.6% higher than S3, respectively. However, the boll weights for S1 and S2 were 4.1% and 7.8% lower than for S3, respectively. There was no significant difference in the lint percentage among the treatments. Therefore, although late sowing produced more bolls, the boll weight was greatly reduced, thus resulting in a reduced lint yield.

Biomass accumulation is the basis for yield formation. Greater biomass accumulation and a reasonable distribution are important prerequisites for improving the yield and fiber quality [36–38]. The initiation and termination time of rapid biomass accumulation are reportedly advanced by late sowing, and the maximum biomass growth rate is reduced, resulting in reduced biomass [28,36]; in contrast, proper early sowing not only induces a greater biomass accumulation but also enhances the quantity of biomass in the reproductive organs and significantly improves the harvest index [37,38]. In this study, the biomass and harvest index of CAW were 8.7–21.7% and 8.0–23.1% lower than for the relay intercropping treatments, respectively, and this result was consistent with the findings of previous studies [15,19,28]. However, it should be noted that the biological yield of late relay intercropping (S3) was 3.4–9.2% higher than that of the early relay intercropping (S1 and S2), and the harvest index was 5.0–9.6% lower. In the present study, it was also found that postponing the sowing date led to an increase in the distribution of biomass to the boll shell. This might be another important reason for the observed decrease in the harvest index for cases with late sowing.

Cotton has an undetermined growth habitat. Bolls form under different environments at different locations on cotton plants, and different boll retention rates and boll weights are observed [39]. In general, bolls located at the first fruiting site have higher weights, higher boll retention rates, and better fiber quality than those at other sites; these are thus the dominant bolls in yield formation [40]. Therefore, increasing the number of bolls at the first fruiting site (boll retention) is very important for improving the yield and fiber quality. In this study, varying sowing dates resulted in obvious differences in the spatial and temporal distributions of bolls. The numbers of bolls and boll weights at the first fruiting site in S1 and S2 were significantly higher than those in S3, while no significant difference was found between S1 and S2. No significant difference was observed in the numbers of bolls formed in the early and middle seasons between S1 and S2, while these values were significantly greater than those for S3.

The cotton earliness of S3 was 8.3–27.5% and 6.4–25.3% lower than for S1 and S2, respectively. No significant difference was observed in crop maturity between S1 and S2. Insufficient accumulated heat units in the late growth period of late sowing slowed the development and maturation of the cotton bolls and resulted in immature bolls at the time of harvest [34,41,42]. The sowing date not only affects the cotton yield but also significantly affects the fiber quality [18,23]. In this study, although no difference was observed in the lint yield, the fiber quality significantly varied among the relay intercropping treatments. The fiber strength and micronaire values measured under S1 and S2 were significantly greater than those measured under S3, indicating that compared to late relay intercropping, early relay intercropping improved the fiber quality. Therefore, based on the advantages of fiber quality and early maturity, the sowing dates of S1 or S2 are recommended as suitable sowing dates for the relay intercropping of short-season cotton in the Yellow River Basin.

5. Conclusions

In this study, compared to late relay intercropping and CAW, early relay intercropping at 20–30 days before wheat harvest considerably increased the lint yield by improving the biomass allocation ratios to the reproductive organs and seed cotton, and by enhancing the boll density at the first fruiting position. In addition, early intercropping significantly improved cotton earliness by reducing the proportion of late season bolls. Fiber quality parameters, including fiber strength and micronaire values, were also improved by early intercropping. Therefore, the early relay intercropping of short-season cotton is a promising alternative to CAW in wheat-cotton double-cropping systems in the Yellow River Basin of China and other regions with similar conditions. This study provides the theoretical support for wheat and cotton double-cropping systems.

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