International Journal of Plant Production 10 (1), January 2016
ISSN: 1735-6814 (Print), 1735-8043 (Online)
www.ijpp.info

GUASNR

Effect of cropping system on cotton biomass accumulation and yield formation in double–cropped wheat–cotton

X. Du[a,b], B. Chen[a], Y. Meng[a], W. Zhao[a], Y. Zhang[a], T. Shen[a], Y. Wang[a], Z. Zhou[a,*]

[a]*Key Laboratory of Crop Growth Regulation, Ministry of Agriculture, Nanjing Agricultural University, Nanjing 210095, Jiangsu Province, PR China.*
[b]*Anhui Key Laboratory of Crop Quality Improvement, Crop Research Institute, Anhui Academy of Agricultural Sciences, Hefei 230031, Anhui Province, PR China.*
*Corresponding author. E-mail: giscott@njau.edu.cn

Received 3 June 2015; Accepted after revision 16 October 2015; Published online 23 November 2015

Abstract

Wheat–cotton double cropping practices on a large scale in cotton belt of the Yellow River Valley and the Yangtze River Valley in China. Field experiments were conducted to determine the effects of wheat–cotton double cropping on cotton biomass accumulation and yield formation during 2011/12 and 2012/13 growing seasons. Two cotton cultivars, Siza 3 (mid–late maturity) and CCRI 50 (early maturity), were used in three cropping systems including monoculture cotton (MC), wheat/intercropped cotton (W/IC) and wheat/direct–seeded cotton (W/DC). Lint yield in double cropping systems were significantly lower than that in monoculture. Compared with MC for Siza 3, lint yield in W/IC and W/DC were decreased by 10.9 and 41.8%, respectively and 9.9 and 35.9% for CCRI 50, respectively. These reductions were largely ascribed to the fewer cotton bolls per unit area. Growth analysis showed that IC showed a pronounced delay in early development due to the initial shading from wheat on cotton seedlings and owing to delayed sowing, DC was easily affected by lower temperature during flowering and boll formation stage. And that consequently was delaying reproductive development, affecting cotton biomass accumulation and distribution and finally limiting crop productivity. Further, the diminished source capacity coupled with inadequate biomass production was the main determinant factor to limit lint yield in W/IC, while the reduced sink capacity with less partition to reproductive organs was the primary factor limiting lint yield in W/DC. Comparing to mid–late maturity of Siza 3, early maturity cultivar of CCRI 50 had a yield advantage in double cropping sequential system, since its shorter growing period.

Keywords: Cotton (*Gossypium hirsutum* L.); Wheat and cotton intercropping; Wheat and cotton sequential cropping; Yield; Growth and development.

Introduction

Cotton is a major cash crop worldwide and cotton grown with wheat is widely practiced as the leading farming system in the Yellow River Valley and the Yangtze River Valley in China (Zhang et al., 2008; Dai and Dong, 2014). Moreover, cotton intercropping with wheat is the predominant system in the existing double–cropping system, which not only requires high labor input, but also inhibits the development of mechanization (Feike et al., 2012; Dai and Dong, 2014). Therefore, there is an urgent need for high production, simplified cultivation and agricultural mechanization systems. Wheat–cotton double cropping in sequence, direct–seeding of short–season cotton after the harvest of wheat, might be an appropriate system for agricultural mechanization (Dai and Dong, 2014; Du et al., 2015). Cotton growth and productivity in relay intercropping have been studied by Zhang et al. (2007, 2008). However, little information is available on cotton growth and productivity in wheat–cotton sequential cropping system.

Previous studies have documented that cotton yield had significant positive correlation with the sink capacity (including carpel growth, seed number, boll abscission, final seed-cotton dry weight and partitioning to fibre), which depended on environmental conditions and photosynthetic source capacity of the plant (Dusserre et al., 2002). It was also found that decreases in boll number per unit area and ultimately yield were closely related to insufficient assimilate for boll production (Yeates et al., 2010a, b). Additionally, wheat–cotton intercropping systems caused cotton yield decrease for 31%-46% comparing to monoculture and this reduction was associated with the declined number of bolls per unit area (Zhang et al., 2007), owing to the later formation of fruits and the reduced sink capacity (Zhang et al., 2008). However, only one late maturity cotton cultivar was used in previous studies regarding on the yield formation of cotton in wheat–cotton intercropping system. The performances of cotton cultivars with different growth periods in this system are still unclear.

Cotton is an indeterminate plant with a full–seasonal development and high–yielding cotton requires a complex balance of assimilate allocation between vegetative and reproductive organs (Jones et al., 1996). Further, it have been consistently reported that cotton yield is determined by biomass accumulation and its proportion partitioned to reproductive organs (Bange and Milroy, 2004; Saleem et al., 2010). Compared to high–yield cotton cultivar, the lower yield cultivars were apparently characterized by a smaller total biomass and less efficient partitioning into reproductive organs (Unruh and Silvertooth, 1996a, b). Therefore, it was hypothesized that the lower yield of double–cropped cotton could be the result of either decreased biomass accumulation or reduced partitioning to reproductive growth and wheat–cotton double cropping could affect the cotton growth and biomass accumulation and thus decreasing cotton yield. This deserves further investigation. The information on the characteristics of cotton growth and development in wheat–cotton double cropping systems will help to understand the response of cotton yield to cropping system and facilitate improving cotton productivity in double cropping system.

The objectives of this study were to (i) examine the effects of cropping systems on cotton growth and development, biomass accumulation and partitioning in wheat–cotton double cropping and (ii) explore the physiological determinants of cotton yield in wheat–cotton double cropping systems and options for improving wheat–cotton double cropping systems.

Materials and Methods

Experimental site

Field experiments were performed at the cotton experimental station of Nanjing Agricultural University (33° 20′ N, 120° 46′ E, 4.5 m a.s.l.), Dafeng City, Jiangsu

Province, China during two growing seasons in 2011/12 and 2012/13. The field soil type is sandy loam, containing 16.5 and 16.1 g/kg organic matter, 22.7 and 20.9 mg/kg available N, 31.2 and 28.6 mg/kg available P and 189.5 and 172.4 g/kg available K before sowing wheat in 2011 and 2012, respectively. Mean daily air temperature and rainfall during the cotton growing season were obtained from a weather station (Campbell AG800, Genetics, USA) located near the experimental site (Figure 1).

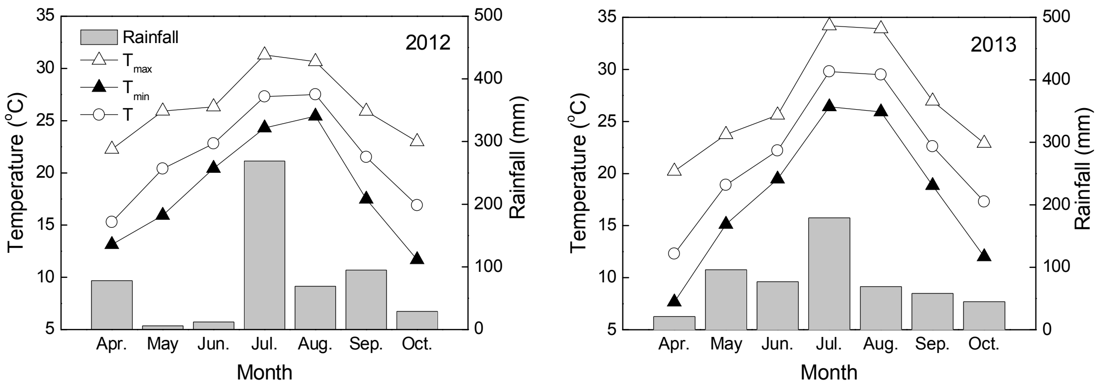

Figure 1. Mean, maximum and minimum daily air temperature and monthly rainfall in Dafeng in 2012 and 2013.

Experimental design

Winter wheat cultivar (*Triticum aestivum* L.) Yangmai 16 and two cotton cultivars (*Gossypium hirsutum* L.), Siza 3 (Mid–late maturity) and CCRI 50 (Early maturity), were used in field experiments. Three cropping systems were conducted with monoculture cotton (MC) as control and two double cropping systems followed the local practices were used, including wheat/intercropped cotton (W/IC) and wheat/direct–seeded cotton (W/DC). In MC and W/IC, cotton seeds were first sown in nutrition beds on 15 April and seedlings with three true leaves were transplanted to the field as described by Dong et al. (2007). In MC, cotton seedlings were transplanted to field on 15 May. In W/IC, winter wheat was sown in strips with interspersed bare soil and cotton seedlings were transplanted to the interspersed soil belts on 15 May. In W/DC, winter wheat was sown as preceding crop in the field and cotton was direct–seeded with a no–till drill to field immediately after harvesting wheat. Detailed information on the experiment design of all systems was described in Du et al. (2015).

The plots were arranged in a split plot design with three replicates. Main plots were assigned to the cropping systems and subplots were assigned to the cotton cultivars with a plot area of 27.5 m^2 (5.0 m×5.5 m). Each plot contained five crop rows with 1.10 m in row spacing and 0.30 m in interplant spacing with a plant density of 30300 plants/ha for Siza 3 and 0.15 m in interplant spacing with a plant density of 60600 plants/ha for CCRI 50. In 2011/12 growing season, winter wheat was sown on 12 November, 2011 and harvested on 4 June, 2012. In 2012/13 growing season, winter wheat was sown on 16 November, 2012 and harvested on 9 June, 2013. Fields were managed following the local cultural practices.

Data collection

Growing stages

Twenty successive plants from the central row of each plot were sampled for averaging the development stages (50% emergence and 50% of plants with squares and 50% of plants with open flowers and 50% of plants with open bolls) (Zhang et al., 2008).

Organ number

Twenty successive plants from the central row of each plot were collected every 15 days and the number of fruit nodes, squares, bolls and opened bolls were observed.

Biomass measurement

Cotton biomass was determined at interval of 15 days from 15 July to 3 October in 2012 and from 13 July to 2 October in 2013. Three plants from each plot were sampled, separated into the vegetative organs (stem, leaf and branch) and reproductive organs (bud, flower and boll). Samples were dried at 105 °C for 30 min and then at 80 °C until reaching a constant weight in a fan–forced oven.

Yield measurement

Cotton yield was measured by hand picking all opened bolls in a 2.0 m row length × 2.2 m width in all plots. 120 opened bolls in each plot were collected on 10 September, 25 September, 10 October and 25 October to weight boll weight and lint percentage after drying. Lint yield was obtained by weighing the lint of each plot after seed cottons were ginned. Twenty cotton plants from three central rows in each plot were randomly tagged at maturity on 28 October in 2012 and 16 October in 2013 to determine the number of mature bolls (>2 cm in diameter) per unit area.

Calculations and data analysis

Microsoft Excel 2003 and Origin 8.0 software were used for data processing. SPSS 11.5 statistical software was employed for variance analysis by using Duncan's new multiple–range test and for regression analysis. The logistic model that has been used extensively to describe the process of cotton biomass accumulation (Yang et al., 2011; Yang et al., 2012) is as follows:

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

where, t (d) is days after emergence, W (kg/ha) is cotton biomass, $W_{\max}$ (kg/ha) is the maximum biomass and a and b are the constants to be found.
From formula (1):

$$t_0 = \frac{a}{b}, \quad t_1 = -\frac{1}{b}\ln\frac{2+\sqrt{3}}{a}, \quad t_2 = -\frac{1}{b}\ln\frac{2-\sqrt{3}}{a} \qquad (2)$$

While $t=t_0$, biomass accumulation has the maximum rate:

$$V_{max} = \frac{-b \times W}{4} \quad (3)$$

During the fast biomass accumulation duration, which 65% of the plant biomass is accumulated and begin at t_1 and end at t_2, W is linear correlation with days after emergence and the average growth rate (V_T).

$$V_T = \frac{W_2 - W_1}{t_2 - t_1} \quad (4)$$

Results

Cotton growth and development

Cotton growing stage

Cropping systems significantly (P<0.001) affected the seedling stage, flowering and boll–formation stage (Table 1). Cotton in W/IC beginning to square, bloom and opening boll was later than that in MC, but the seedling stage, flowering and boll–formation stage of IC was longer than MC. Cotton in W/DC had the shortest seedling stage (9-29 d shorter) and the longest flowering and boll–formatting stage (9-13 d longer) despite no observed differences in squaring stage compared to MC. IC and DC were similar to MC in the whole growth period in 2012, whereas DC had the distinctly shorter growth period (20-23 d longer than MC) in 2013. In addition, there was significant difference (P<0.01) in growing stage between the early maturity cultivar of CCRI 50 and the mid–late maturity cultivar of Siza 3.

Yield and yield components

The dynamics of square number had a single peak and boll number, fruit nodes as well shedding rate were linear (Figure 2). The agronomic characteristics of cotton were significantly (P<0.05) affected by cropping systems and cultivars in two experimental years. Double–cropped cotton showed significantly fewer bolls and fruit nodes and lower shedding rate than monoculture cotton, particularly DC. Compared to MC, total fruit nodes of Siza 3 decreased by 4.7 and 28.5% for IC and DC, respectively, while that of CCRI 50 decreased by 4.6 and 15.9%, respectively. The shedding rate of CCRI 50 was approximately 70.5-75.7% with no significant difference among three cropping systems. In contrast, that of Siza 3 in W/DC (41.3-51.9%) was markedly lower than in other cropping systems (63.1-69.6%).

Table 1. The effect of cropping systems, cultivars and their interaction on cotton growth stages in 2012 and 2013; P values are included.

Cultivar	Cropping system	Development stage (mm–dd)*				Growth period (d)			
		Emergence	Squaring	Blooming	Boll opening	Seedling	Squaring	Flowering and boll–formation	Total
2012									
Siza 3	MC	4-24	6-13	7-10	8-25	50±1.4	27±0.9	46±3.2	123±4.6
	IC	4-24	6-18	7-16	8-28	55±2.3	28±1.6	43±2.8	126±3.9
	DC	6-16	7-27	8-20	10-18	41±1.6	24±2.1	59±3.6	124±2.8
CCRI 50	MC	4-23	6-9	7-1	8-15	47±2.3	22±1.7	45±2.5	114±3.8
	IC	4-23	6-12	7-5	8-19	50±1.9	23±0.8	45±1.9	118±2.6
	DC	6-15	7-20	8-12	10-7	35±1.4	23±1.4	56±3.1	114±3.7
Analysis of variance									
Cropping system (CS)						<0.001	0.216	<0.001	0.134
Cultivar (C)						0.001	0.004	0.445	<0.001
CS×C						0.373	0.148	0.115	0.824
2013									
Siza 3	MC	4-20	6-13	7-6	8-17	54±2.8	23±0.9	42±2.4	119±4.2
	IC	4-20	6-15	7-8	8-19	56±2.8	23±1.0	42±1.9	121±3.1
	DC	6-17	7-15	8-4	9-24	28±1.4	20±0.8	51±3.1	99±2.8
CCRI 50	MC	4-19	6-11	7-3	8-9	53±2.6	22±1.6	37±2.8	112±4.2
	IC	4-19	6-13	7-5	8-12	55±2.4	22±1.4	38±1.9	115±3.9
	DC	6-17	7-11	7-31	9-14	24±1.1	20±1.0	47±3.2	89±2.8
Analysis of variance									
Cropping system (CS)						<0.001	0.073	<0.001	<0.001
Cultivar (C)						0.05	0.445	0.002	0.001
CS×C						0.296	0.85	0.853	0.467

* mm–dd: month–day.
P values are included.
MC, monoculture cotton; IC, intercropped cotton; DC, direct–seeded cotton.

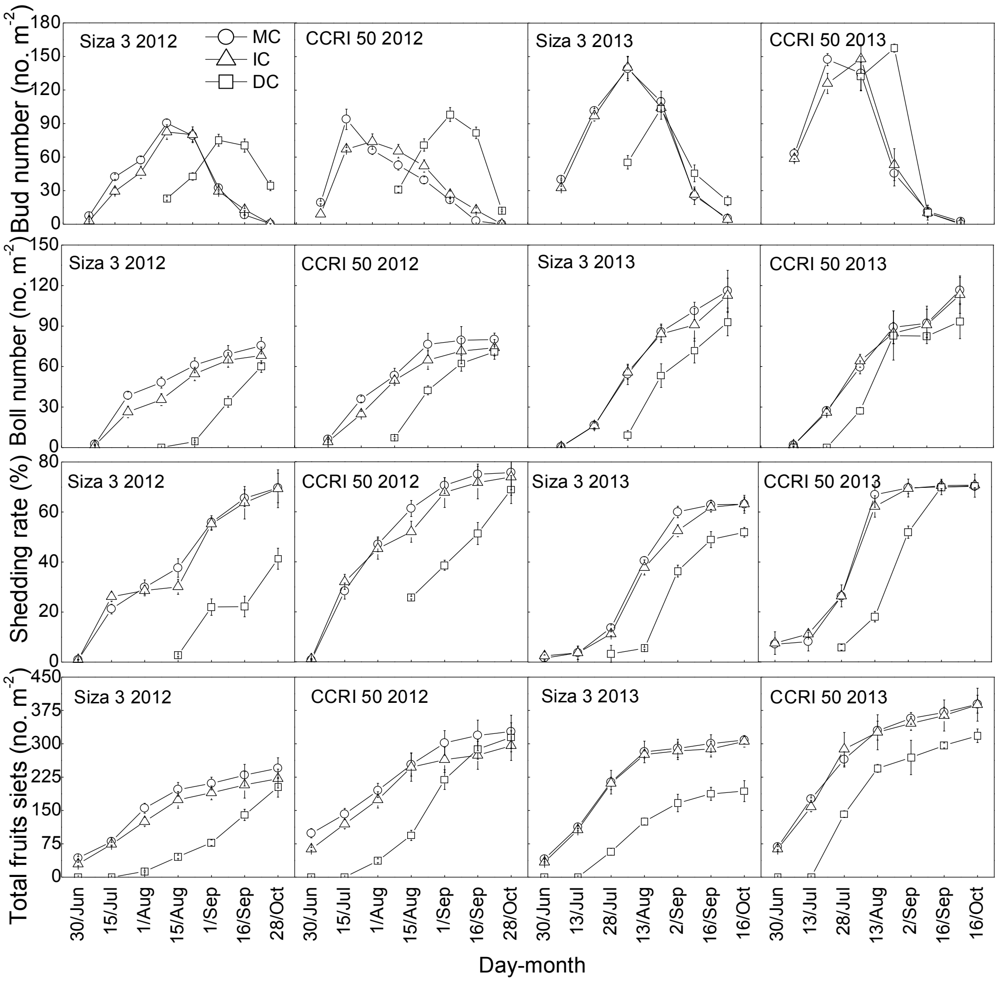

Figure 2. Dynamic of cotton agronomic characters in different cropping systems in 2012 and 2013; Each data point is the mean ± *S.E.* of three replications; MC, monoculture cotton; IC, intercropped cotton; DC, direct–seeded cotton.

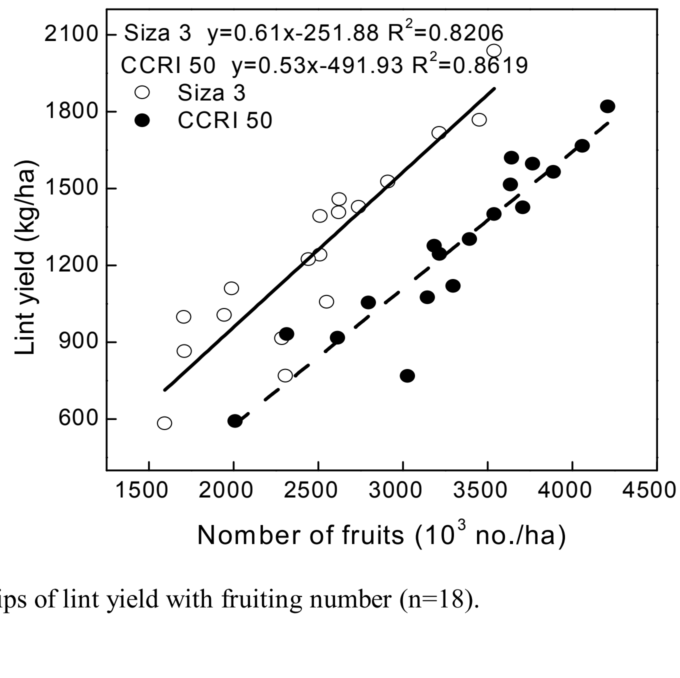

Figure 3. Relationships of lint yield with fruiting number (n=18).

Cropping systems and cultivars had significant effects ($P<0.05$) on lint yield, boll number and boll weight (Table 2). Compared to MC, averaged lint yield of IC and DC were reduced by 10.5 and 43.2% in 2012 and 10.2 and 35.2% in 2013, respectively. Siza 3 had relatively higher yield than CCRI 50 in MC (1400 vs 1379 kg/ha) and W/IC (1248 vs 1243 kg/ha), but much lower yield than CCRI 50 in W/DC (815 vs 883 kg/ha). The lint yield among three cropping systems followed an order of MC>IC>DC across two cultivars and similar trend was observed for both experimental years.

The reduction of lint yield in wheat–cotton double cropping systems were closely associated with the fewer cotton bolls per unit area and reduced boll weight compared with monoculture cotton (Table 2). Importantly, the extent of the decrease in boll number was larger than that tested in boll weight. Averaged over cultivars, cotton boll number per unit area of IC and DC were 90.1 and 62.5% of monoculture in 2012 and 93.5 and 71.9% of monoculture in 2013, respectively. Additionally, yield components also varied over the years, boll number per unit area in 2013 was dramatically higher than that observed in 2012 and thus leading to a significant yield increase of 21.3% in 2013 over in 2012.

Dynamics and simulation of cotton biomass accumulation

Cotton above ground biomass accumulation increased from seedling to physiology maturity, following a logistic growth curve by days after emergence and there were notable differences among three cropping systems (Figure 4). DC had the highest biomass at 108 days after emergence, which was 40 d earlier than other cropping systems. Double–cropped cotton showed a decreased biomass at boll opening with an order of MC>IC>DC. A little reproductive biomass was accumulated until the initiation flowering stage, with no visible difference among three cropping systems. However, the reproductive biomass increased rapidly after the initiation flowering stage, which was 80 days after emergence. Compared with monoculture, the reproductive biomass of cotton in double cropping systems significantly decreased at boll opening in order of MC>IC>DC (Figure 5).

Table 2. Cotton yield and yield components (mean ± S.E.) for different cropping systems.

Cultivar/ cropping system	2012					2013				
	Boll no. (10^3 no. /ha)	Boll weight (g)	Lint percentage (%)	Yield (kg/ha)		Boll no. (10^3 no. /ha)	Boll weight (g)	Lint percentage (%)	Yield (kg/ha)	
				Seed cotton	Lint				Seed cotton	Lint
Siza 3										
MC	753±65.0	5.3±0.14	37.6±0.79	3392±325.6	1275±150.6	1069±86.3	5.1±0.18	38.7±0.69	4634±398.3	1793±165.3
IC	661±85.5	5.2±0.21	38.2±0.89	2921±265.3	1116±121.5	997±75.3	5.0±0.21	38.3±0.82	4237±421.2	1623±110.3
DC	451±39.8	4.9±0.17	37.5±0.46	1878±196.2	704±86.3	723±68.3	4.7±0.18	37.7±0.74	2888±321.7	1089±86.3
CCRI 50										
MC	802±98.3	4.7±0.11	40.0±0.91	3203±436.2	1281±163.2	1093±110.3	4.7±0.14	39.8±0.76	4366±521.3	1737±189.3
IC	740±62.5	4.6±0.13	40.5±0.76	2893±321.3	1172±102.3	1024±100.6	4.5±0.16	39.5±0.38	3916±356.6	1547±106.3
DC	521±49.4	4.4±0.20	38.4±0.48	1948±210.3	748±65.3	831±85.3	4.4±0.20	38.6±0.68	3107±213.2	1200±76.3
P value										
Cropping system (CS)	<0.001	0.014	0.015	<0.001	<0.001	<0.001	0.014	0.008	<0.001	<0.001
Cultivar (C)	0.006	<0.001	<0.001	0.003	0.032	0.021	0.001	0.001	<0.001	0.709
CS×C	0.737	0.791	0.109	<0.001	0.314	0.156	0.507	0.808	<0.001	0.010

S.E., standard error of the means.
MC, monoculture cotton; IC, intercropped cotton; DC, direct–seeded cotton.

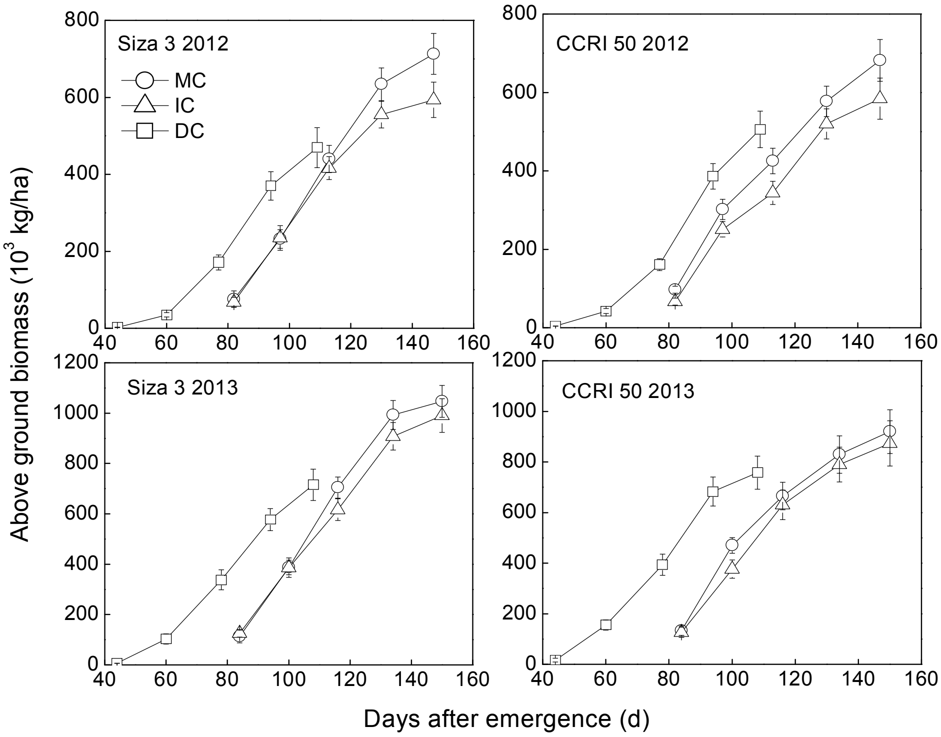

Figure 4. Cotton above ground biomass accumulation under different cropping systems in 2012 and 2013; Each data point is the mean ± *S.E.* of three replications; MC, monoculture cotton; IC, intercropped cotton; DC, direct–seeded cotton.

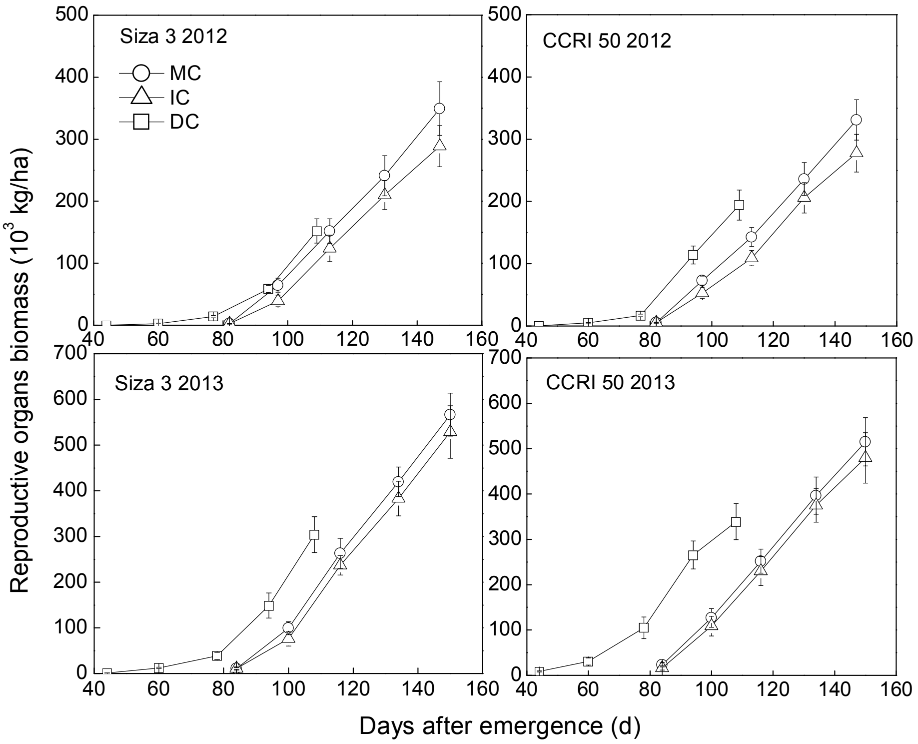

Figure 5. Cotton reproductive biomass accumulation under different cropping systems in 2012 and 2013; Samples of the reproductive included squares, flowers and bolls; Each data point is the mean ± *S.E.* of three replications; MC, monoculture cotton; IC, intercropped cotton; DC, direct–seeded cotton.

Dynamic accumulation of cotton above ground biomass as days after emergence was simulated by using the formula (1) and differences were observed among three cropping systems (Table 3). During the fast biomass accumulation duration, MC had the highest average rate (147.6 kg/ha/d) and the longest accumulation duration (31-42 d) in three cropping systems. IC had the same biomass accumulation duration but 10.9% decreased averaged rate as MC. DC showed 25-29 d of biomass accumulation duration and 6.4% lower average rate over MC.

Difference also existed among cropping systems in cotton reproductive biomass accumulation progress (Table 3). MC had the longest fast biomass accumulation duration (36-40 d) and which was 1-7 and 9-23 d longer than IC and DC, respectively. As compared to MC, the averaged accumulation rate of IC and DC were reduced by 5.9 and -2.2% for Siza 3 and 4.5 and -11.1% for CCRI 50, respectively.

Table 3. Eigen values of cotton biomass accumulation under different cropping systems in 2012 and 2013.

Year/ cultivar	Cropping system	Cotton above ground biomass		Reproductive biomass	
		Fast biomass accumulation duration (d)	V_T* (kg/ha/d)	Fast biomass accumulation duration (d)	V_T (kg/ha/d)
2012					
Siza 3	MC	33.6	128.2	39.1	61.2
	IC	30.0	116.7	32.5	56.4
	DC	25.3	114.5	27.8	64.4
CCRI 50	MC	42.3	98.9	40.4	56.4
	IC	39.8	91.0	36.1	51.4
	DC	26.4	121.9	17.6	69.6
2013					
Siza 3	MC	31.2	200.9	36.0	101.4
	IC	37.4	162.6	35.7	96.6
	DC	29.4	152.0	26.7	101.8
CCRI 50	MC	32.5	162.4	39.8	84.7
	IC	32.5	155.7	36.9	83.3
	DC	28.6	164.0	24.8	87.1

* V_T is the average biomass accumulation rate during the fast biomass accumulation duration.
MC, monoculture cotton; IC, intercropped cotton; DC, direct–seeded cotton.

Cotton biomass partitioning

Cotton biomass accumulation and partition were dramatically ($P<0.001$) affected by cropping system and cultivar (Table 4). Double–cropped cottons exhibited distinct decreases in biomass and the biomass ratio of ‘reproductive/ (vegetative + reproductive)’, but increases in the biomass ratio of ‘leaf/shoot’ and ‘leaf/boll’. Compared with MC, the biomass per plant of IC and DC reduced by 10.0 and 18.1% for Siza 3 and 8.2 and 18.0% for CCRI 50 in 2012, 6.7 and 27.5% for Siza 3 and 5.5 and 16.3% for CCRI 50 in 2013, respectively. Double–cropped cotton had noticeably lower partition ratio to reproductive organs than monoculture cotton did in two experimental seasons, particularly DC showing 32.3-44.8% lower than MC. Also, differences in biomass partition were detected between two cotton cultivars, with CCRI 50 having a higher partition ratio to the reproductive in double cropping sequential system.

Lint yield and boll number had significantly positive ($P<0.05$) correlations with cotton biomass and the reproductive biomass, but had little significant correlations with the vegetative biomass in three cropping systems (Table 5). Further, little significant correlation was noted among boll weight, lint percentage and cotton biomass.

Table 4. The effects of cropping systems on cotton biomass partition (mean ± S.E.) in 2012 and 2013.

Cultivar /cropping system	Above ground biomass* (kg/ha)		The biomass ratio of reproductive/ (vegetative +reproductive) (%)		The biomass ratio of leaf/shoot (%)		The biomass ratio of leaf/boll (%)	
	2012	2013	2012	2013	2012	2013	2012	2013
				Siza 3				
MC	7928±586.0	11063±786.5	49.0±0.68	54.2±0.92	28.7±0.36	26.0±0.68	29.9±0.46	22.0±0.38
IC	7136±432.7	10324±869.3	48.6±0.73	53.3±0.85	32.9±0.29	26.6±0.46	34.5±0.86	23.4±0.42
DC	6493±653.7	8019±756.3	32.3±0.54	42.5±0.73	37.7±0.41	30.0±0.42	78.9±1.17	40.7±0.50
				CCRI 50				
MC	7020±865.6	9513±789.8	48.5±0.56	55.9±0.69	31.3±0.46	26.8±0.41	33.2±0.48	21.1±0.34
IC	6441±546.4	8992±875.4	47.5±0.98	54.8±0.73	34.4±0.68	26.1±0.28	37.6±0.54	21.6±0.29
DC	5758±498.7	7962±569.6	38.4±0.65	44.8±0.81	41.7±0.59	25.8±0.35	66.7±0.93	31.8±0.46
				P value				
Cropping system (CS)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Cultivar (C)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
CS×C	<0.001	<0.001	<0.001	0.124	<0.001	<0.001	<0.001	<0.001

* Cotton biomass produced at boll opening.
MC, monoculture cotton; IC, intercropped cotton; DC, direct–seeded cotton.

Table 5. Correlation coefficients between cotton yield and cotton biomass accumulation in 2012 and 2013 (n=6); P values are included.

Correlation with	Reproductive+ vegetative	Reproductive	Vegetative
	Siza 3		
Seed cotton	0.004	<0.001	0.212
Lint	0.008	0.001	0.259
Boll number	0.001	<0.001	0.158
Boll weight	0.576	0.390	0.711
Lint percentage	0.795	0.553	0.455
	CCRI 50		
Seed cotton	0.003	<0.001	0.243
Lint	0.002	<0.001	0.238
Boll number	0.001	<0.001	0.171
Boll weight	0.879	0.611	0.359
Lint percentage	0.053	0.032	0.383

Discussion

Lint yield in wheat–cotton double cropping systems observed in this study varying from 704 to 1524 kg/ha in double cropping systems, which was significantly lower than that of monoculture cotton (1275-1793 kg/ha). It was suggested that wheat–cotton double cropping decreased the lint yield of cotton by delaying reproductive growth and diminishing source and sink capacity.

Cotton development in wheat–cotton double cropping systems

A previous study has been reported that the decrease of cotton productivity in wheat–cotton intercropping systems was closely related to the delay of the reproductive development (Zhang et al., 2007). The results obtained in the current revealed that cotton in W/IC showed the delay in fruiting formation, contributed to fewer fruits and bolls and thereby yielding less lint. Because of the initial shading from wheat on cotton seedlings, IC showed a pronounced delay in early development, as reported by Zhang et al. (2008). Nonetheless, the growth delay (6-12 days) of the intercropped cotton reported in Zhang et al. (2008) was longer than that observed in this research (2-5 days). This may be mainly associated with its longer coexistent period (50 days) than this study (20 days), which caused by cotton direct–sown instead of transplanting and in turn aggravated the shading from wheat on cotton seedling. Owing to delayed sowing, DC was easily affected by lower temperature during flowering and boll formation (Figure 1) and hence diminished reproductive growth (Reddy et al., 1992; Reddy et al., 1993). The findings indicated that it was significant for enhancing cotton productivity to overcome the growth development disadvantage caused by the combination growth with wheat in double cropping systems. In addition, early maturity cultivar of CCRI 50 had a yield advantage with respect to mid–late maturity cultivar in double cropping sequential system, since the shorter growth duration alleviated the developmental delay. Thus, cotton cultivar with relatively shorter growth duration could be strongly recommended for wheat–cotton double cropping systems.

Sink and source limitation in intercropping and sequential cropped cotton

Cotton yield was determined by sink capacity (fruit) and source capacity (photosynthesis) (Dusserre et al., 2002; Cawoy et al., 2007). It has been reported that shade diminished cotton sink capacity and caused a lower lint yield (Dusserre et al., 2002) and similar result was observed for relay–intercropped cotton (Zhang et al., 2008). It was found that double cropping reduced cotton source capacity as a result of lower LAI and reduced radiation interception during growing season (Du et al., 2015). The current further found that sink capacity of cotton in wheat–cotton double cropping systems was reduced for the delay and decrease of fruiting nodes, bolls and boll weight as compared with monoculture cotton. The reduced source capacity for cotton in wheat–cotton double cropping systems accompanied with a decreased biomass accumulation. In contrast, the diminished sink capacity contributed to a declined biomass distribution to reproductive organs, resulting in smaller fruiting nodes, fewer bolls and lower boll weight. The finding that IC displayed significant lower biomass (Table 4) and higher shedding ratio compared with MC (Figure 2) indicated that source capacity played the key role in determining lint yield in W/IC. DC showed significantly low partitioning of biomass into the reproductive organs, decreased boll weight and lower shedding ratio than MC, suggesting that sink capacity played the key role in determining lint yield in W/DC.

Relationship between biomass and lint yield

Crop productivity depends on biomass accumulation and the effective partitioning of assimilate to the reproductive organs (Specht et al., 1999; Bange and Milroy, 2004). The results of the present study demonstrated it again (Table 5). Therefore, lower biomass production or lower partition to the reproductive might be an explanation for lower lint yield in double cropping systems. The inadequate biomass production was a major factor limiting yield formation of IC, as documented in soybean (Mayers et al., 1991a, b). Nonetheless, the combination of insufficient biomass and lower partition to the reproductive contributed to a reduced lint yield of DC, which agreed well with the results of Stern (1965) in cotton.

Practical implications

Developing mechanized cotton production in China was the inevitable tendency facing increasing challenges from labor shortage. In current double cropping systems, wheat–cotton sequential cropping system was considered to adapt for mechanization (Dai and Dong, 2014). This cropping system had the higher annual productivity (Du et al., 2015), but the lower cotton lint yield than wheat–cotton intercropping system. Therefore, agronomic measures should be strengthened in the future to improve cotton productivity in wheat–cotton sequential cropping system and to accelerate mechanized cotton farming. These measures include: (a) Selecting of short–season cotton to alleviate the delay in reproductive growth; (b) Increasing fruiting nodes and bolls to boost lint yield though increasing plant density and optimizing irrigation and nutrient management; (c) Using harvest aid chemicals to improve timing and facilitate cotton harvesting; (d) Improving biomass accumulation and partition to reproductive organs by field management, such as use of growth regulator.

Conclusion

(i) Intercropped cotton showed a pronounced delay in early development and sequential cropped cotton was affected by lower temperature during flowering and boll formation stage and this was considered an eco–physiological 'bottle neck' finally limiting cotton productivity.
(ii) Compared to monoculture cotton, double cropping significantly decreased lint yield in order of MC>IC>DC.
(iii) Diminished source capacity with inadequate biomass accumulation played the key role in limiting lint yield formation in W/IC, while the reduced sink capacity with less partition to reproductive organs was the main determinant limiting lint yield formation in W/DC.
(iv) Compared to mid–late maturity cultivar, the early maturity cultivar had a yield advantage in double cropping sequential system.

Acknowledgments

This research was supported by the Special Fund for Agro–scientific Research in the Public Interest (201203096), the National Natural Science Foundation of China (31271654) and Jiangsu Collaborative Innovation Center for Modern Crop Production (JCIC-MCP).

References

Bange, M.P., Milroy, S.P., 2004. Growth and dry matter partitioning of diverse cotton genotypes. Field Crops Res. 87, 73-87.

Cawoy, V., Lutts, S., Ledent, J.F., Kinet, J.M., 2007. Resource availability regulates reproductive meristem activity, development of reproductive structures and seed set in buckwheat (Fagopyrum esculentum). Physiologia Plantarum. 131, 341-353.

Dai, J.L., Dong, H.Z., 2014. Intensive cotton farming technologies in China: achievements, challenges and countermeasures. Field Crops Res. 155, 99-110.

Dong, H.Z., Li, W.Z., Li, Z.H., Zhang, D.M., 2007. Enhanced plant growth, development and fiber yield of Bt transgenic cotton by an integration of plastic mulching and seedling transplanting. Ind. Crop Prod. 26, 298-306.

Du, X.B., Chen, B.L., Shen, T.Y., Zhang, Y.X., Zhou, Z.G., 2015. Effect of cropping system on radiation use efficiency in double–cropped wheat–cotton. Field Crops Res. 170, 21-31.

Dusserre, J., Crozat, Y., Warembourg, F.R., Dingkuhn, M., 2002. Effects of shading on sink capacity and yield components of cotton in controlled environments. Agronomie. 22, 307-320.

Feike, T., Doluschitz, R., Chen, Q., Graeff-Hönninger, S., Claupein, W., 2012. How to overcome the slow death of intercropping in the North China Plain. Sustainability. 4, 2550-2565.

Jones, M.A., Wells, R., Guthrie, D.S., 1996. Cotton response to seasonal pattern of flower removal: II. Growth and dry matter allocation. Agron. J. 36, 639-645.

Mayers, J.D., Lawn, R.J., Byth, D.E., 1991a. Agronomic studies on soybean [Glycinemax (L.) Merrill] in the dry Season of the tropics. I. Limits to yield imposed by phenology. Aust. J. Agric. Res. 42, 1075-1092.

Mayers, J.D., Lawn, R.J., Byth, D.E., 1991b. Agronomic studies on soybean [Glycinemax (L.) Merrill] in the dry Season of the tropics. III. Effect of artificial photoperiod extension on phenology, growth and seed yield. Aust. J. Agric. Res. 42, 1109-1121.

Reddy, K.R., Hodges, H.F., Mckinion, J.M., 1993. Temperature effects on pima cotton leaf growth. Agron. J. 85, 681-686.

Reddy, K.R., Reddy, V.R., Hodges, H.F., 1992. Temperature effects on early season cotton growth and development. Agron. J. 84, 229-237.

Saleem, M.F., Bilal, M.F., Awais, M., Shahid, M.Q., Anjum, S.A., 2010. Effect of nitrogen on seed cotton yield and fiber qualities of cotton (*Gossypium hirsutum* L.) cultivars. The J. Anim. Plant Sci. 20 (1), 23-27.

Specht, J.E., Hume, D.J., Kumudini, S.V., 1999. Soybean yield potential–a genetic and physiological perspective. Crop Sci. 39, 1560-1570.

Stern, W.R., 1965. The seasonal growth characteristics of irrigated cotton in a dry monsoonal environment. Aust. J. Agric. Res. 16, 347-366.

Unruh, B.L., Silvertooth, J.C., 1996a. Comparison between upland and a pima cotton cultivars I. Growth and yield. Agron. J. 88, 583-589.

Unruh, B.L., Silvertooth, J.C., 1996b. Comparison between upland and a pima cotton cultivars II. Nutrient uptake and partitioning. Agron. J. 88, 589-593.

Yang, G., Tang, H., Nie, Y., Zhang, X., 2011. Responses of cotton growth, yield and biomass to nitrogen split application ratio. Eur. J. Agron. 35, 164-170.

Yang, G.Z., Tang, H.Y., Tong, J., Nie, Y.C., Zhang, X.L., 2012. Effect of fertilization frequency on cotton yield and biomass accumulation. Field Crops Res. 125, 161-166.

Yeates, S.J., Constable, G.A., McCumstie, T., 2010a. Irrigated cotton in the tropical dry season. I. Yield, its components and crop development. Field Crops Res. 116, 278-289.

Yeates, S.J., Constable, G.A., McCumstie T., 2010b. Irrigated cotton in the tropical dry season. II: Biomass accumulation, partitioning and RUE. Field crops Res. 116, 290-299.

Zhang, L., van der, Werf, W., Zhang, S., Li, B., Spiertz, J.H.J., 2007. Growth, yield and quality of wheat and cotton in relay strip intercropping systems. Field Crops Res. 103, 178-188.

Zhang, L., van der, Werf, W., Zhang, S., Li, B., Spiertz, J.H.J., 2008. Temperature–mediated developmental delay may limit yield of cotton in relay intercrops with wheat. Field Crops Res. 106, 258-268.