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Cotton N rate could be reduced further under the planting model of late sowing and high-density in the Yangtze River valley

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Abstract

Background: An optimal N rate is one of the basic determinants for high cotton yield. The purpose of this study was to determine the optimal N rate on a new cotton cropping pattern with late-sowing, high density and one-time fertilization at the first flower period in Yangtze River Valley, China. A 2-year experiment was conducted in 2015 and 2016 with a randomized complete block design. The cotton growth process, yield, and biomass accumulation were examined.

Results: The results showed that N rates had no effect on cotton growing progress or periods. Cotton yield was increased with N rates increasing from 120 to 180 kg·hm^{-2}, while the yield was not increased when the N rate was beyond 180 kg·hm^{-2}, or even decreased (9~29%). Cotton had the highest biomass at the N rate of 180 kg·hm^{-2} is due to its highest accumulation speed during the fast accumulation period.

Conclusions: The result suggests that the N rate for cotton could be reduced further to be 180 kg·hm^{-2} under the new cropping pattern in the Yangtze River Valley, China.

Keywords: Cotton, N rate, Growth, Yield, Biomass

Background

China was the second-largest cotton producer in the world (FAO 2016), but the highest yield was obtained by a large amount of N consumption (FAO 2017). Therefore, minimizing the investment, including reducing fertilizer application is becoming more and more important to ensure sustainable agricultural development in China (Dai et al. 2017; Luo et al. 2018). N is a vital nutrient for cotton, and an optimal N rate is conducive to cotton growth for different growing patterns (Rochester et al. 2007). However, more N was applied than cotton needed, because farmers always worry about a possible yield reduction due to the reduced N rate (Diomides et al. 2009).

Cotton biomass and yield were significantly affected by N rates. The highest cotton yield was achieved under the optimal N rate (Stamatiadis et al. 2016). Excessive N would promote vegetative growth, delay the maturity and/or increase rotten/fallen bolls (Rinehardt et al. 2005; Gerik et al. 1998; Jackson and Gerik 1990). On the other hand, insufficient N would result in lower biomass, a poorer plant development, premature senescence and/or a yield reduction (Clawson et al. 2008; Zhang et al. 2012). The highest yield was observed closely associated with higher biomass and its accumulation speed during FAP, especially for reproductive organs (Xue et al. 2008). Read et al. (2006) reported that the cotton vegetative growth could be coordinated with its reproductive growth with an appropriate N rate.

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In recent years, in line with the reduction of investment, a new cotton planting pattern was practiced successfully. It is characterized with direct sowing in middle May, a higher density of 6 plants per m^2 and a lower N rate of 225 $kg{\cdot}hm^{-2}$ in the Yangtze River Valley, without compromising cotton yield (Yang et al. 2011; Yang et al. 2012; Yang et al. 2013). In addition, one-time fertilization at the first flower was proved sufficient under this planting model (Khan et al. 2017; Shahbaz et al. 2018). However, could the N rate be reduced further as reported by Boquet and Breitenbeck (2000) and Rochester et al. (2009).

We hypothesized that a lower N rate than 225 $kg{\cdot}hm^{-2}$ should be possible under this planting model due to a shorter growing season and a bigger population. Therefore, this study was to verify the hypothesis based on cotton yield and its components, N assimilation rate, and dry matter accumulation.

Materials and methods

Experimental site and cultivar

This study was conducted in the growing season of 2015 and 2016 at the experimental site of Huazhong Agricultural University (30°37-N latitude, 114°21-E longitude, 23 m above sea level) in the middle reaches of the Yangtze River valley with Huamian-3 109 (*Gossypium hirsutum* L.). The soil was yellow-brown clay loam and contained 11.6 $g{\cdot}kg^{-1}$ organic matter, 95.5 $mg{\cdot}kg^{-1}$ available N, 15.1 $mg{\cdot}kg^{-1}$ P_2O_5, and 132.4 $mg{\cdot}kg^{-1}$ K_2O within the 0~20 cm layer. The average temperature and rainfall from April to November was presented in Fig. 1.

Experimental design and field management

There were five treatments (N rates): N120, N150, N180, N210, N240 represents applied nitrogen 120, 150, 180, 210, 240 $kg{\cdot}hm^{-2}$, respectively. Fertilizers were used to supply N, P_2O_5 (54 $kg{\cdot}hm^{-2}$), K_2O (180 $kg{\cdot}hm^{-2}$), and B (15 $kg{\cdot}hm^{-2}$), including urea (46.3% N), superphosphate (12% P_2O_5), potassium chloride (59% K_2O) and borate (10% B). All the fertilizers were mixed and applied in wide rows at the appearance of the first flower (58 days after emergence (DAE) in 2015 and 60 DAE in 2016).

This experiment was arranged in a randomized complete block design with four replicates, each plot was 12 m in the row length and 2.28 m in the row width, and 6 rows including both narrow (10 cm) and wide (66 cm) rows. Cotton was sown on May 20th, 2015 and May 18th, 2016, with manual hill-dropping 3~5 seeds per hill to obtain 10 $plant{\cdot}m^{-2}$, and cotton is managed according to local agronomic practices.

Data collection

Growth period

The date of emergence, squaring, flowering, and boll-opening was investigated within fifteen successively and fixed hills/plants of each plot.

Yield and yield components

Seed cotton was harvested four times (September 23rd, October 14th and 21st, and November 2nd) in 2015 and twice (October 9th and November 5th) in 2016, which was weighed after drying of each plot, including the fallen open bolls from the ground. The number of bolls per square meter was recorded from the whole plot before plant withdrawal (the last harvest) while the boll weight and the lint percentage were calculated by 100 randomly sampled bolls from the second harvest.

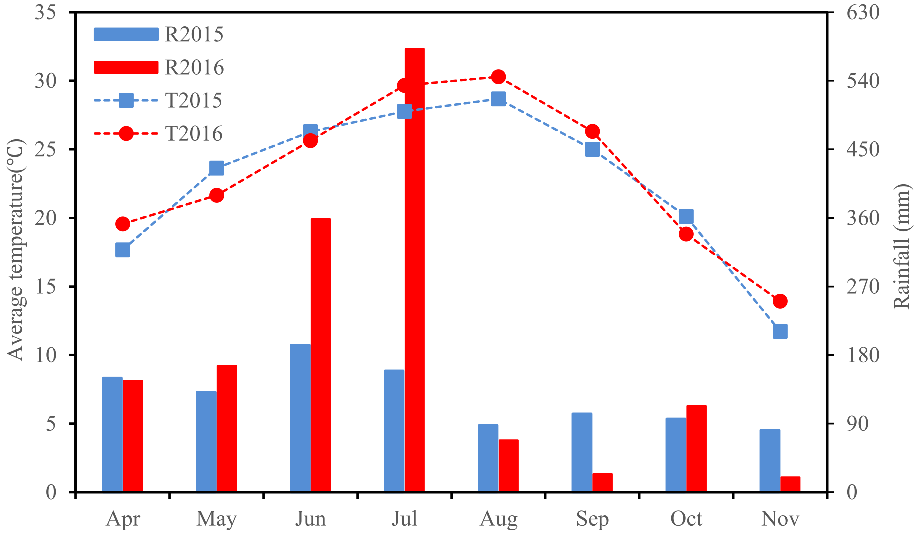

Fig. 1 Monthly weather summary during the cotton growing season in 2015 and 2016. T and R represented temperature and rainfall, respectively

Biomass accumulation and distribution

Biomass was sampled at 20, 40, 60, 80, 100, 120, 140 DAE in two growing seasons. Nine continuous plants (27 plants at 20 DAE) were taken from each treatment and separated into three parts, including vegetative organs (root, stem, stem leaves), reproductive organs (squares, flowers, bolls), and reproductive relative organs (branches, branch leaves). Biomass was determined after oven-drying at 105 °C for 30 min and then turn to 75 °C to reach constant weight.

Data processing and analysis

Microsoft® Excel® 2019 was used for data processing and figure drawing. SPSS Statistics 21.0 software was applied to do ANOVA analyses. Means were separated using LSD test at a 5% probability level. DPS software was used to describe the progress of the logistic equation for biomass accumulation (Yang et al. 2011).

$$Y = \frac{K}{1 + ae^{bt}} \tag{1}$$

where Y ($g{\cdot}m^{-2}$) means the biomass at t, t (d) means DAE, K (g) is the maximum biomass, a and b are constants.

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

When $t = t_0$, biomass accumulation reachs the fastest speed V_{max}; a and b are constants from formula (1).

$$V = \frac{-bk}{4}{}_{\max} \tag{3}$$

The period was defined as the biomass fast accumulation period (FAP), at FAP 58% biomass accumulated, which begins at t_1 and terminates at t_2. During FAP, the average speed of biomass accumulation was described as:

$$V_T = \frac{Y_2 - Y_1}{t_2 - t_1} \tag{4}$$

Results

Cotton growth period

N rate had no effect on cotton growth periods in both years (Table 1). However, comparing with the results in 2015, the period from sowing to seedling emergence in 2016 was 2 d longer due to lower temperature in May, the squaring period was 2~5 d shorter due to enough water supply and higher temperature in July, while boll setting period was 4~7 d longer due to less rainfall in August and September of 2016 (Fig. 1).

Yield and yield components

Cotton yield both in seed cotton and lint increased when the rate of N increased from 120 to 180 $kg{\cdot}hm^{-2}$, but remained the same in 2015 or decreased in 2016 after being increased more than 180 $kg{\cdot}hm^{-2}$, and the yield difference resulted from boll numbers per ground area (Table 2). The average of seed cotton yield among the treatments in 2016 was higher than that in 2015, while the lint yield performed the other way round due to a higher lint percentage in 2015.

Table 1 Cotton growth stage and period under different N rate in 2015 and 2016

Treatments	Growth stages (m-d)				Growth period / d			
	Emergence	Squaring	First bloom	Boll opening	Seedling	Squaring	Boll setting	Total
2015								
N120	5–27	7–13	8–5	9–21	47a	23a	47a	117a
N150	5–27	7–13	8–5	9–21	47a	23a	47a	117a
N180	5–27	7–13	8–4	9–20	47a	22a	47a	116a
N210	5–27	7–13	8–4	9–20	47a	22a	47a	116a
N240	5–27	7–13	8–3	9–20	47a	21a	48a	116a
2016								
N120	5–27	7–13	8–1	9–23	47a	19a	53a	119a
N150	5–27	7–13	7–31	9–22	47a	18a	53a	118a
N180	5–27	7–13	7–31	9–23	47a	18a	54a	119a
N210	5–27	7–13	7–31	9–23	47a	18a	54a	119a
N240	5–27	7–13	8–1	9–22	47a	19a	52a	118a

Means in the same column and the same year followed by different letters are significantly different ($P < 0.05$) according to LSD test at 0.05 probability level by SPSS 21.0

Table 2 Cotton yield and its components for different N rate in 2015 and 2016

Treatments	Bolls no. / (m^{-2})	Boll weight / g	Lint percentage / %	Yield /($kg\cdot hm^{-2}$)	
				Seed cotton yield	Lint cotton yield
2015					
N120	67.6b	3.43a	46.1a	2 319.0c	1 066.7c
N150	74.8ab	3.29a	47.2a	2 457.5b	1 155.0b
N180	77.1ab	3.78a	47.0a	2 912.4a	1 368.8a
N210	86.2a	3.37a	47.1a	2 900.7a	1 363.3a
N240	86.2a	3.43a	47.2a	2 956.1a	1 389.4a
2016					
N120	61.2b	3.91a	40.3a	2 390.9c	962.9c
N150	72.6ab	3.94a	39.1a	2 859.6ab	1 117.7b
N180	78.4a	4.01a	40.1a	3 142.4a	1 260.1a
N210	70.5ab	4.04a	38.9a	2 849.5b	1 109.7b
N240	58.5b	3.81a	41.3a	2 226.9c	920.4c

Means in the same column and the same year followed by different letters are significantly different ($P < 0.05$) according to LSD test at 0.05 probability level by SPSS 21.0

Among cotton yield components, N180 achieved the second most or the most boll numbers per square meter when compared with other treatments in two years. N120 reduced the number of bolls significantly by 12.3% in 2015 and 21.9% in 2016, respectively, while higher rates of N than N180 treatments caused fewer boll numbers in the rainy season (2016). The rate of N showed no differences in boll weight and lint percentage. However, in 2015, the boll weight was 12.2% lower, but the lint percentage was 17.5% higher than those in 2016, respectively.

Cotton N assimilation rates

N application rates significantly affected cotton N assimilation rates with a consistent trend in two years. N assimilation rate in 2015 was obviously higher than that in 2016 (Fig. 2).

The low N assimilation rate at 60 DAE combined with N application in this date and absorbed nitrogen from the soil. Between 79 and 119 DAE, the rate of N assimilation increased with N application rate, especially for N application from 120 to 180 $kg\cdot hm^{-2}$. There was no significant difference between N180, N210 and N240 treatmetns, but they were significantly higher than N120 and N150 in 97 and 119 DAE (except in 97 DAE of 2016). For the last sampling date, the highest N assimilation rate was observed in N180, the reason could be N180 was a suitable N rate in this study.

Cotton plant biomass (CPB) accumulation

Patterns of increasing CPB resembled an "S"-shaped growth curve for the entire growing period, differing in rates of accumulation after fertilization treatments (Fig. 3). Prior to fertilization, the CPB rate of accumulation was slow with no differences observed among treatments in both years. After fertilization, the N rate significantly affected CPB, causing a rapid accumulation of biomass among treatments. About 20 days after fertilization (80 DAE), the differences of CPB among treatments were apparent, although there were no differences among N240, N210 and N180 treatments. However, from 97 DAE to the last sampling date, CPBs among these treatments were all significantly higher than those of N150 and N120. Moreover, this trend was seen in the second growing season, and CPBs in 2016 was greater than those in 2015.

The pattern of accumulation of vegetative organ biomass (VOB) across treatments displayed a quadratic curve. VOB was influenced by rainfall. VOB in 2016 was nearly twice as much as that in 2015 at the last sampling date. The increases of VOB rates were slow and similar for all treatments prior to 60 DAE, and then treatment rates branched after fertilization, differing widely when plants reached the last sampling date in both years. In this experiment, VOB increased over time and more obviously after N application. In addition, the highest VOB was observed from N240 after fertilization across the different growing seasons (Fig. 3).

Accumulation of reproductive organ biomass (ROB) began at the squaring stage at 47 DAE in both years of study (Table 1); ROB in 2016 was slightly lower than ROB in 2015 (Fig. 3). A small amount of ROB accumulated at 60 DAE (in the squaring stage). Subsequently, the increases in ROB rates escalated with plant growth and N application, especially in the later growing season. As the amount of N increased across treatments, the

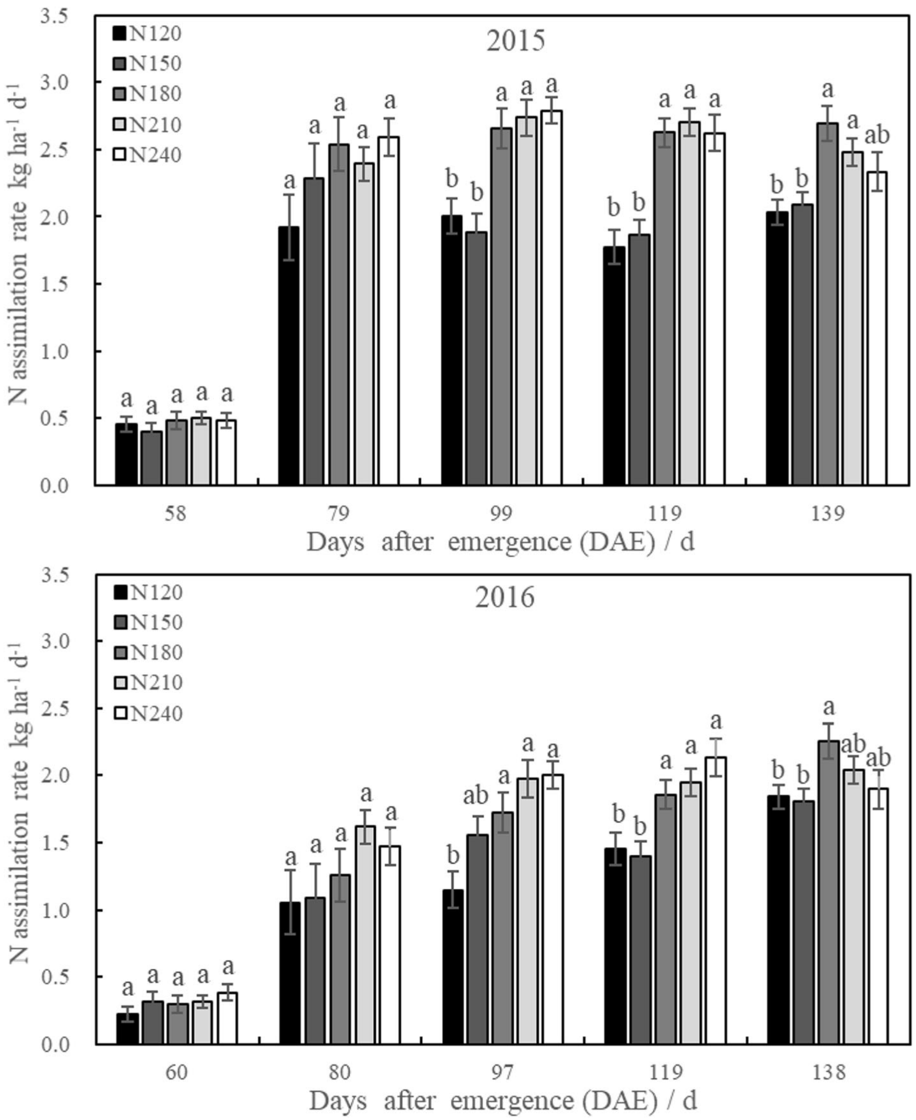

Fig. 2 Accumulation of N assimilation of the cotton plant at different stages varying the treatments during the 2015 and 2016 growing seasons

maximum ROB was observed in N180 in the second growing season compared to that in all other treatments. Treatments were sorted and ranked by ROB values into three groups: N210, N180 > N120, N240 > N150.

Treatments in the first two sampling dates (20 and 41 DAE) lacked the accumulation of relative reproductive organ biomass (R. ROB). Values of R. ROB were similar among treatments at 60 DAE. After 60 DAE, R. ROB gradually increased with plant growth and N application. In the two growing seasons, N application benefitted R. ROB, particularly in the later growing season. Faster rates and more accumulation of R. ROB occurred in the rainy season and the values of R. ROB differed greatly among treatments. Trends in R. ROB were similar to trends in VOB across different treatments (Fig. 3).

Simulation of biomass accumulation

Logistic eq. (1) was used to describe biomass accumulation over time (DAE), and the unknown parameters of equations (a and b) were calculated from (2)–(4). Although different coefficients of determination were calculated among different cotton parts or treatments, all *P* values were less than 0.005 for two years (Table 3).

There was a fast accumulation period (FAP) of CPB throughout the entire duration of plant growth, the average start and termination dates of the FAP were 71 DAE and 107 DAE in the first growing season, respectively, and 81 DAE and 130 DAE in the latter growing season, respectively. The total of FAP in 2015 was 36 days and in 2016 was 49 days. The average rates of accumulation during the FAP differed among treatments. The

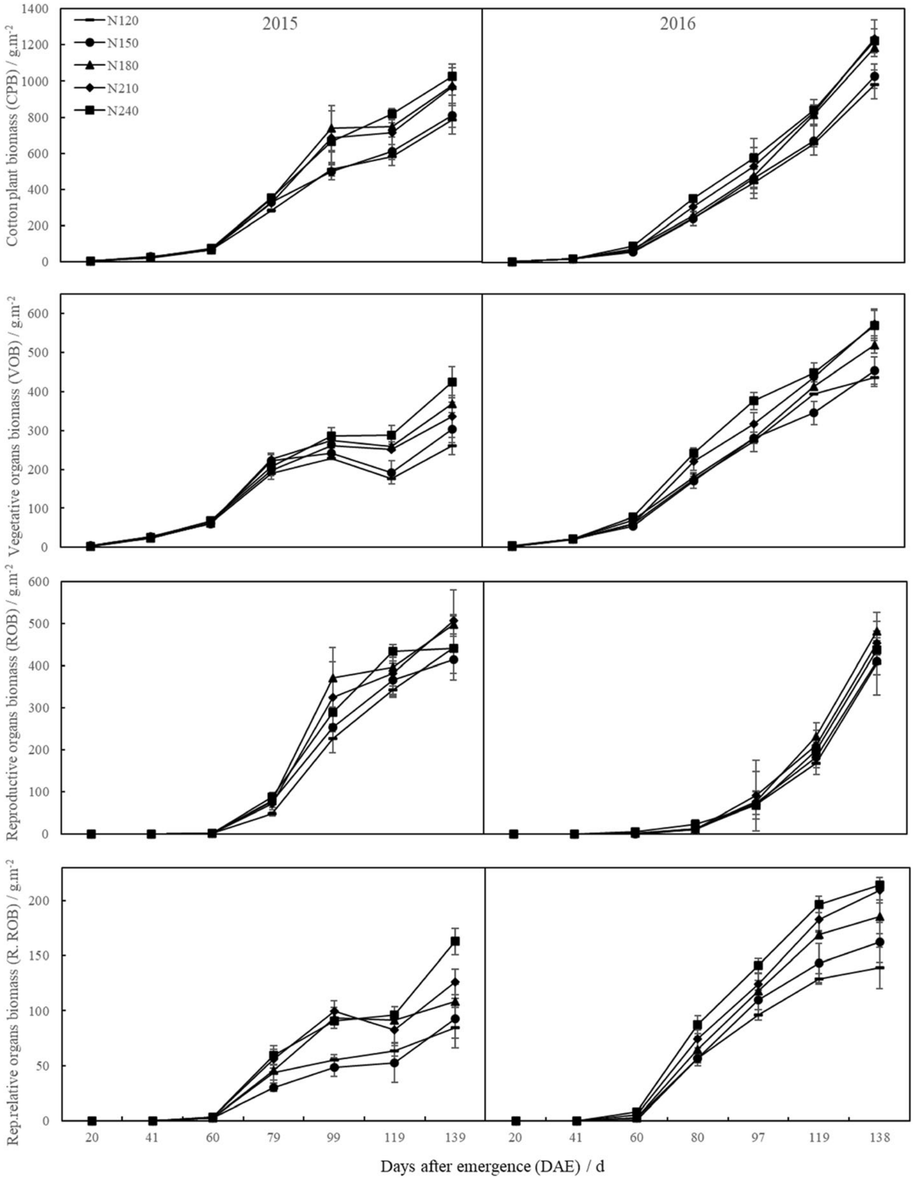

Fig. 3 Effect of different N rates on cotton plant biomass (CPB), vegetative organ biomass (VOB), reproductive organ biomass (ROB) and reproductive relative organ biomass (R. ROB) accumulation in 2015 and 2016. Error bar shows SE of means

maximum average rate was observed in N180 in every year, but the duration of the FAP was shorter in N180 than in the rest of the treatments. Although N120 and N150 had the longest duration of FAP, the rates of biomass accumulation were significantly lower in 2015. In the rainy season (2016), the average rate of biomass accumulation was lower but showed a similar trend to that of the previous year. The increasing application rates of N across treatments prolonged the duration of the FAP in 2016. The maximum rate of biomass accumulation was consistent with the average rate of accumulation in every year (Table 4).

On average, the start and end dates of VOB accumulation during the FAP were 13 d and 24 d earlier and lasted 11 d shorter than their corresponding dates and FAP for CPB in 2015, and were 16 d and 13 d earlier and lasted 3 d shorter than the respective dates and FAP for CPB in 2016 (Table 4). The average and maximum rates of accumulation of VOB during the FAP were half that of CPB, and a few treatments had rates of 67% lower than rates of CPB across the two seasons. For N treatments within the application range of 120~210 kg·hm^{-2}, N application positively correlated with duration of VOB accumulation in 2015 but not in 2016.

Table 3 Regression equations of cotton plant biomass accumulation in the field affected by different N rates in 2015 and 2016

Treatment	2015		2016	
	Regression equation	*P*	Regression equation	*P*
Cotton plant biomass (CPB)				
N120	$y = 786.982\ 9/(1 + 5.598\ 6e^{-0.062\ 273t})$	0.000 3	$y = 980.733\ 3/(1 + 5.691\ 7e^{-0.061\ 461t})$	0.000 1
N150	$y = 811.292\ 8/(1 + 4.971\ 3e^{-0.059\ 909t})$	0.000 7	$y = 1\ 027.866\ 7/(1 + 6.148\ 2e^{-0.057\ 452t})$	0.000 0
N180	$y = 975.770\ 3/(1 + 7.9451e^{-0.093\ 036t})$	0.000 6	$y = 1\ 186.786\ 7/(1 + 6.384\ 5e^{-0.059\ 150t})$	0.000 0
N210	$y = 969.271\ 1/(1 + 7.160\ 7e^{-0.079\ 408t})$	0.000 8	$y = 1\ 236.666\ 7/(1 + 5.129\ 0e^{-0.043\ 108t})$	0.000 0
N240	$y = 1\ 027.845\ 8/(1 + 7.963\ 3e^{-0.081\ 425t})$	0.000 1	$y = 1\ 221.900\ 0/(1 + 5.304\ 2e^{-0.051\ 483t})$	0.000 1
Vegetative organ biomass (VOB)				
N120	$y = 260.475\ 2/(1 + 9.347\ 4e^{-0.136\ 101t})$	0.001 6	$y = 436.250\ 0/(1 + 4.580\ 8e^{-0.044\ 042t})$	0.000 1
N150	$y = 304.022\ 1/(1 + 8.185\ 4e^{-0.124\ 564t})$	0.000 6	$y = 454.466\ 7/(1 + 4.378\ 4e^{-0.034\ 633t})$	0.000 3
N180	$y = 368.666\ 9/(1 + 7.523\ 5e^{-0.104\ 923t})$	0.004 9	$y = 520.433\ 3/(1 + 4.799\ 6e^{-0.041\ 825t})$	0.000 0
N210	$y = 335.545\ 8/(1 + 5.750\ 5e^{-0.080\ 168t})$	0.001 5	$y = 574.200\ 0/(1 + 4.524\ 8e^{-0.036\ 627t})$	0.000 2
N240	$y = 423.951\ 3/(1 + 4.658\ 3e^{-0.068\ 321t})$	0.000 9	$y = 569.866\ 7/(1 + 4.643\ 4e^{-0.046\ 620t})$	0.000 0
Reproductive organ biomass (ROB)				
N120	$y = 441.844\ 5/(1 + 10.234\ 6e^{-0.105\ 497t})$	0.000 3	$y = 405.609\ 3/(1 + 11.406\ 5e^{-0.107\ 567t})$	0.000 0
N150	$y = 414.200\ 6/(1 + 10.500\ 9e^{-0.111\ 224t})$	0.000 3	$y = 411.200\ 0/(1 + 11.835\ 2e^{-0.114\ 011t})$	0.000 0
N180	$y = 498.375\ 7/(1 + 10.855\ 3e^{-0.117\ 894t})$	0.000 3	$y = 481.103\ 3/(1 + 13.842\ 1e^{-0.131\ 804t})$	0.000 0
N210	$y = 507.545\ 3/(1 + 10.761\ 0e^{-0.111\ 712t})$	0.000 3	$y = 453.466\ 7/(1 + 14.864\ 0e^{-0.137\ 449t})$	0.000 0
N240	$y = 441.066\ 2/(1 + 11.070\ 0e^{-0.119\ 538t})$	0.000 1	$y = 438.100\ 0/(1 + 15.860\ 4e^{-0.144\ 476t})$	0.000 0
Reproductive relative organ biomass (R. ROB)				
N120	$y = 84.663\ 2/(1 + 5.864\ 1e^{-0.067\ 732t})$	0.003 9	$y = 138.883\ 3/(1 + 7.433\ 6e^{-0.076\ 408t})$	0.000 0
N150	$y = 93.070\ 1/(1 + 5.072\ 9e^{-0.059\ 136t})$	0.001 6	$y = 162.200\ 0/(1 + 7.241\ 6e^{-0.071\ 859t})$	0.000 0
N180	$y = 108.727\ 7/(1 + 5.011\ 3e^{-0.054\ 274t})$	0.000 1	$y = 185.250\ 0/(1 + 6.836\ 9e^{-0.065\ 929t})$	0.000 0
N210	$y = 126.180\ 0/(1 + 4.835\ 3e^{-0.058\ 124t})$	0.004 8	$y = 209.416\ 7/(1 + 5.751\ 7e^{-0.050\ 508t})$	0.000 1
N240	$y = 162.828\ 3/(1 + 4.606\ 6e^{-0.050\ 356t})$	0.003 6	$y = 213.933\ 3/(1 + 5.828\ 8e^{-0.050\ 712t})$	0.000 0

However, the common feature observed in rates of accumulation was the pattern of increase and then decrease in both years. Among the treatments, the highest rates occurred in N180 (average and maximum rates were 8.48 and 9.67 $\mathrm{g{\cdot}m^{-2}{\cdot}d^{-1}}$, respectively) in 2015.

In the first growing season, ROB accumulation was initiated at 25 d and terminated at 48 d later than those of VOB, and lasted for 2 d less than VOB. In the second season, ROB had a higher rate of accumulation than VOB in the FAP, despite having a later starting date than the previous year. However, the end date was 7 days later. Both the average and maximum accumulation rates of ROB were faster compared with those of VOB, especially in 2016 (Table 4). In the two growing seasons and among all treatments, N180 had the highest rate of accumulation of cotton biomass, VOB, ROB, and R. ROB. At N application rates of greater than 180 $\mathrm{kg{\cdot}hm^{-2}}$, rates of accumulation of cotton biomass, VOB, ROB, and R. ROB did not increase significantly. At the application rate of less than 180 $\mathrm{kg{\cdot}hm^{-2}}$, the rate of ROB accumulation in the FAP was significantly lower.

The start date of R. ROB always occurred between that of VOB and ROB, and the end date of R. ROB was the latest in both years (Table 4). Great differences were observed between the start and the end dates of the FAP and rates of accumulation between the different years for R. ROB. In the rainy season (2016), the main observations of FAP and the rates of accumulation of R. ROB were remarkably greater than those in 2015. The duration of the FAP was similar for the two growing seasons and the difference is less than three days. Overall, greater N application rates were more beneficial to prolonging the duration and increasing rates of accumulation; however, they may delay the FAPs under certain conditions.

Discussion

Our new cotton cultivation model of N application had no difference in cotton growth stages and periods in both years (Table. 1). A previous study has reported boll-setting period can be prolonged by increasing the N application rate (Yeates et al. 2010), however, Bange and

Table 4 Eigenvalues of cotton plant biomass accumulation in the field were affected by different N rates in 2015 and 2016

Treatment	2015					2016				
	t_1 DAE / d	t_2 DAE / d	Δt / d	V_T / (g·m^{-2}·d^{-1})	V_M / (g·m^{-2}·d^{-1})	t_1 DAE / d	t_2 DAE / d	Δt / d	V_T / (g·m^{-2}·d^{-1})	V_M / (g·m^{-2}·d^{-1})
Cotton plant biomass										
N120	68.8	111.0	42.2	10.75	12.25	71.2	114.0	42.9	13.21	15.07
N150	61.0	104.9	43.9	10.66	12.15	84.1	129.9	45.8	12.94	14.76
N180	71.3	99.5	28.3	19.90	22.69	85.7	130.2	44.5	15.39	17.55
N210	73.6	106.7	33.1	16.88	19.24	88.4	149.5	61.1	11.69	13.33
N240	81.6	113.9	32.3	18.35	20.92	76.9	127.7	50.8	13.88	15.84
Average	71.3	107.2	35.9	15.31	17.45	81.3	130.3	49.0	13.42	15.31
Vegetative organ biomass (VOB)										
N120	59.0	78.3	19.3	7.78	8.86	60.4	109.1	48.7	5.17	5.89
N150	55.1	76.2	21.1	8.31	9.47	68.6	127.6	59.0	4.45	5.07
N180	59.2	84.2	25.0	8.48	9.67	67.2	118.0	50.8	5.91	6.74
N210	55.3	88.0	32.8	5.90	6.73	68.8	125.3	56.5	5.87	6.69
N240	58.9	87.4	28.5	6.57	7.24	58.7	105.3	46.5	7.07	8.07
Average	57.5	82.8	25.3	7.41	8.39	64.7	117.1	52.3	5.69	6.49
Reproductive organ biomass (ROB)										
N120	84.5	109.4	24.9	10.22	11.65	93.8	118.3	24.5	9.56	10.91
N150	82.6	106.2	23.6	10.10	11.51	92.3	115.4	23.1	10.28	11.72
N180	80.9	103.2	22.3	12.89	14.69	95.0	115.0	20.0	13.90	15.86
N210	84.5	108.1	23.5	12.43	14.17	91.9	109.7	17.9	13.66	15.58
N240	81.6	103.6	22.0	11.56	13.18	94.1	111.2	17.1	13.87	15.82
Average	82.8	106.1	23.3	11.44	13.04	93.4	113.9	20.5	12.26	13.98
Reproductive relative organ biomass (R. ROB)										
N120	67.2	106.0	38.8	1.26	1.43	80.0	114.5	34.5	2.33	2.65
N150	63.6	108.0	44.5	1.21	1.38	82.4	119.1	36.7	2.55	2.91
N180	68.0	116.4	48.4	1.29	1.48	83.7	123.7	40.0	2.68	3.05
N210	60.6	105.8	45.2	1.61	1.83	87.8	139.9	52.1	2.32	2.64
N240	65.3	117.4	52.1	1.80	2.05	89.0	140.9	51.9	2.38	2.71
Average	64.9	110.7	45.8	1.43	1.63	84.6	127.6	43.0	2.45	2.80

DAE indicates days after emergence (d). t_1 and t_2 are the beginning and terminating days of the fast accumulation period (FAP), respectively. Δt indicates the duration of FAP, $\Delta t = t_2 - t_1$. V_T and V_M are the average and maximum accumulation speed during FAP, respectively.

Milroy (2004) showed that excessive N will shorten the boll-setting period. The results of this experiment at the highest N application rates supported Bange and Milroy's (2004) results (Table 1). In addition, the squaring and boll-setting periods were quite different between the two years. More rainfall occurred during the seedling stage in 2016 and the highest temperature occurred in the squaring stage, resulting in early flowering. Thus, the squaring period was shortened and the boll-setting period was prolonged.

Higher cotton yield was observed in N180 in both growing seasons, and N rates of greater than 180 kg·hm^{-2} were not beneficial to yield. On the contrary, greater N rates resulted in serious reductions in yield (Table 2). Both N deficiency and excess are not conducive to increasing cotton yield (Gerik et al. 1998). Nitrogen deficiency causes reductions in yield, leaf area and carbon dioxide assimilation capacity (Reddy et al. 2004). On the other hand, excess N causes a spindly plant and causes bolls to fall off (Rochester 2012). Therefore, optimal applications of N must be determined to increase cotton yield (Dong et al. 2012). Boquet and Breitenbeck (2000) found positive correlations between yield and N application rates from 0 to 80 kg·hm^{-2}; we obtained a similar conclusion where the better N rate was less than 180 kg·hm^{-2} (Table 2). The yield variation in this study was primarily attributed to the increase in the number of bolls per unit area.

The big difference of the N assimilation rate between two growing seasons caused the biomass accumulation more in 2016 (rainy season), and the increased speed of N assimilation rate was slower than biomass accumulated, producing “dilution effects” as described by Lemaire et al. (2008). After pollination, the assimilation rate of N increased rapidly. This is probably due to the increased demand for N and the absorption capacity of cotton in the boll-setting stage, which was also reported by Luo et al. (2020). N180 had higher or the highest assimilation rate in this study, suggesting that the fertilization rate should be reduced in field-grown cotton that late-sown treatments at high densities, under this model, N180 had a higher speed of nitrate absorption to avoid nutrient loss and possible matched cotton biomass accumulation for increased cotton N use efficiency and yield (Yeates et al. 2010).

Biomass accumulation is vitally important to achieving higher cotton yield (Zurwellera et al. 2019) and the supply of N was important to biomass accumulation. In this study, dry matter production was positively affected by N rates for the measures of VOB and R. ROB. However, excessive N negatively affected ROB accumulation (Fig. 3). Among the treatments, N180 showed the highest or higher dry matter accumulation in both years, the second-lowest application rate tested for this study. N180 had the highest rates of accumulation during the FAP for CPB, VOB, and especially ROB (Table 4). Thus, N application rates influence cotton yield by affecting biomass accumulation. Reports have indicated that N application enhances cotton yield by increasing the rate of accumulation of reproductive organs measured in dry weight (Yang et al. 2012; Brodrick et al. 2012; Dexter et al. 2017). Our results showed large differences between the two growing seasons. Of the rainy season in 2016, ROB was lower than that in 2015. We surmise that the greater amount of rain caused the cotton to grow too vigorously, resulting in an imbalance in the source-sink relationship in plant growth and massive shedding of reproductive organs (Li et al. 2017; Wang et al. 2018). At the same time, the number of fallen bolls in the rainy season caused delayed maturity. In this study, the main source of yield variation was the number of bolls per unit area (Table 2). Overall, the results in this study suggested that applying 180 kg·hm^{-2} N in this cotton cropping pattern was feasible and effective to achieve a higher cotton yield.

Conclusions

Under the new cotton cropping patterns, high yields and N assimilation rates were obtained from N180 compared with other N treatments in both years. Application rates of N more than 180 kg·hm^{-2} resulted in drastically lower yields. The most prominent feature in biomass accumulation was observed in N180 which had the highest rate of accumulation during FAPs of CPB, VOB, and ROB. And for the late-sown field-grown cotton under higher densities in the Yangtze River Valley of China, it is feasible to decrease the N application rate to 180 kg·hm^{-2} and apply the fertilizer once to fields when plants begin to flower.

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Authors’ contributions
Yang GZ designed the study. Song XH carried out the study, wrote the main manuscript text and prepared all figures. Huang Y and Yuan Y helped to fulfill the experiment, Shahbaz AT and Biangkham S gave their hands to analyze the data. All authors reviewed and approved the final manuscript.

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Availability of data and materials
The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

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Not applicable.

Consent for publication
Not applicable.

Competing interests
All the authors confirm that the work described here has not been published previously, and is not under consideration for publication elsewhere. The manuscript is approved by all authors, and has no any actual or potential conflict of interest with other people or organizations.

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