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Variation of Nitrogen, Phosphorus, and Potassium Contents in Drip-Irrigated Cotton at Different Yield Levels under Combined Effects of Nitrogen, Phosphorus and Potassium

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Abstract: To elucidate the variation characteristics of nitrogen (N), phosphorus (P), and potassium (K) content and accumulation in cotton at different yield levels, a two-year experiment was conducted using cotton variety Lumianyan 24 under four N treatments (506, 402.5, 299, and 195.5 kg ha^{-1}, designated as N1, N2, N3, and N4, respectively). The four P and K fertilization ratios were (PK-M1, 25% P and K applied at squaring stage (SS) and 75% at the bloom-bolling stages (BS)), 50%:50% (PK-M2, 50% P and K applied at each stage), 75%:25% (PK-M3, 75% P and K applied at SS and 25% at the BS) and 100%:0% (PK-M4, total P and K applied at SS). The results showed that the N content (Nc), P content (Pc), and K content (Kc) of cotton plants at high yield levels were 23.3%, 44.2%, and 31.6% higher than those at low yield levels. In addition, the reproductive organs maintained higher Pc and Kc at high yield levels, and the Nc, Pc, and Kc exhibited positive linear correlations with yield, while Nc/Pc, Nc/Kc, and Kc/Pc had significant negative correlations with yield. In conclusion, seed cotton yield was mainly limited by Nc at low yield levels and affected by Pc and Kc at high yield levels. Then, when 0.85 < Nc/Kc < 1.0 at the full squaring stage (FS), 0.8 < Nc/Kc < 1.0 at the full flowering stage (FF), 4.3 < Nc/Pc < 6.7 at the early-full bolling stage (EFB) and 4.9 < Nc/Pc < 7.1 at the late-full bolling stage (LFB), there is a high yield potential of 7000–9000 kg ha^{-1}. Furthermore, yields can be improved by reducing the application of N during the growing period and increasing the application of P fertilizer during the later growth period.

Keywords: cotton; fertilization management; yield level

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1. Introduction

Cotton (*Gossypium hirsutum* L.) is one of the most widely grown crops in China, and is vital for the region's economic development and food security [1,2]. Fertilizers, including nitrogen (N), phosphorus (P), and potassium (K), are excessively applied by farmers to obtain higher yields and quality of cotton [3–5]. The application of fertilizers in China is 2.1-fold higher than the international standard application quantity, leading to lower soil fertility, higher production costs, and environmental pollution [6–9]. Thus, achieving high yield potential with limited fertilizer input is a challenge for sustainable agriculture.

Rational fertilization management can reduce production costs without reducing yields [5,10], but the variation in N, P, and K content of cotton at different yield levels during critical growth stages remains to be studied. Research has demonstrated that N, P, and K contents and accumulation could provide a reliable evaluation of the crop growth conditions and yield predictions [11,12]. Several studies have used unmanned aerial vehicles, satellite remote sensing [13–15], machine vision, and neural networks to monitor the nutritional status of crops [16,17]. However, the above studies mainly focused on the methods and platforms without considering that the different nutrient distribution leads to different cotton yields. Furthermore, studies on the changes in nutritional status and threshold ranges under different yield levels are rarely discussed. Therefore, exploring the nutrient distribution and content thresholds of N, P, and K in cotton at high-yield levels is a guide to transforming low-yielding fields into high-yielding ones.

The N to P ratio (N/P), N to K ratio (N/K), and K to P ratio (K/P) in plants could be potential indicators of nutrient availability [18] and also can be used to determine which element is a limited factor for the plant at certain growth stage, providing reasonable fertilization measures for improving crop yield and quality [19]. Koerselman and Meuleman verified that N/P greater than 16 was limited by P, N/P less than 14 was limited by N, and N/P between 14 and 16 was limited by both N and P [20]. However, Güsewell suggested using N/P greater than 20 and less than 10 as criteria for evaluating the N and P limitation of the plant [21]. Some studies have shown that high N/K increases plant biomass, affects biomass accumulation and distribution, and accelerates leaf senescence and mortality [22]. Moreover, the K/P in plants can reflect the relative utilization and effectiveness of K and P and predict deficiencies of K and P [18]. Most studies considered single elements of N, P, and K, neglecting the interaction between different nutrients [23]. A few researchers have studied different N, P, and K fertilizer management simultaneously, but only for application rate treatments [24], and have not involved different N levels in combination with P and K application ratios. Especially for drip-irrigated cotton, there are some research limitations on the combination of N, P, and K management to estimate cotton nutrient requirements and predict yield potential.

Thus, this experiment focused on the interactive effects between N, P, and K fertilizers and considered four different N treatments combined with four different P and K management (PK-M) to explore the changes in N, P, and K content and accumulation in drip-irrigated cotton using different fertilization management procedures. Moreover, changes in the ratio of N, P, and K content and accumulation were used to determine the nutritional limiting factors of cotton, and yield prediction models were developed with Nc/Pc and Nc/Kc at different growth stages. The results of this study will provide support for fertilization management of cotton.

2. Materials and Methods

2.1. Experimental Site

A two-year field experiment was conducted at two different experimental sites (44°18′ N, 86°02′ E and 44°32′ N, 85°97′ E) at Shihezi University, Xinjiang, China, during the growing seasons of 2018 and 2019. The soil of the experimental site is a sandy loam and the physicochemical properties of the soil (0–20 cm in depth) were determined annually, with a 2-year average of Alkaline N 146.20 mg kg^{-1}, Olsen P 45.16 mg kg^{-1}, Available K 69.05 mg kg^{-1} and Organic matters 25.60 g kg^{-1} at a pH of 8.10. Changes in air temperature during the cotton growing season from 2018 to 2019 in Shihezi are given in Figure 1. The precipitation and sunshine duration were 211.7 mm and 2077.3 h in 2018 and 142.0 mm and 1843.1 h in 2019, respectively.

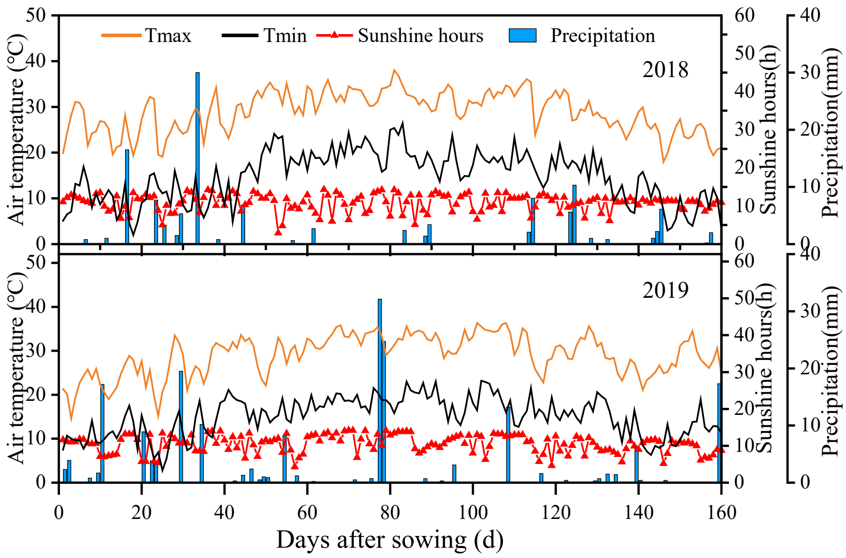

Figure 1. Weather conditions during cotton growing season in Shihezi, Xinjiang, China in 2018–2019.

2.2. Experimental Design and Field Management

The cotton cultivar "Lumianyan 24" was used in this experiment under four levels of N applications combined with four different P and K application ratios. These four levels of N application were 506 kg ha^{-1} (N1), 402.5 kg ha^{-1} (N2, the local conventional N application rate of farmers), 299 kg ha^{-1} (N3), and 195.5 kg ha^{-1} (N4). Under each N treatment, the four different P and K fertilization ratios were 25%: 75% (PK-M1, 25% P and K applied at squaring stage (SS) and 75% at the bloom-bolling stages (BS)), 50%: 50% (PK-M2, 50% P and K applied at each stage), 75%: 25% (PK-M3, 75% P and K applied at SS and 25% at the BS) and 100%: 0% (PK-M4, total P and K applied at SS). A schematic diagram of the fertilization distribution in the 2018–2019 test plots is shown in Figure 2. The phosphorus (P_2O_5) and potassium (K_2O) fertilizer application rates were 108 and 97.2 kg ha^{-1}. The fertilizers used as N, P, and K sources were urea, $NH_4H_2PO_4$, and K_2SO_4, respectively. Fertilizers were applied using a drip irrigation system. Cotton was irrigated by mulched drip irrigation at a frequency of 7–10 days, depending on air temperature and precipitation at different growing stages. The irrigation amount of 4900 m^3 ha^{-1} was applied for eight and nine irrigation frequencies in 2018 and 2019. For water and fertilizer management strategies, refer to Table 1.

Table 1. Application of nitrogen (N), phosphorus (P), and potassium (K) rates, and irrigation scheme.

Irrigation Date		Irrigation Amount (m^3 ha^{-1})	N1 (kg ha^{-1})	N2 (kg ha^{-1})	N3 (kg ha^{-1})	N4 (kg ha^{-1})	PK-M1 (kg ha^{-1})		PK-M2 (kg ha^{-1})		PK-M3 (kg ha^{-1})		PK-M4 (kg ha^{-1})	
							P	K	P	K	P	K	P	K
2018	20 June	580	63.3	50.3	37.4	24.4	54.0	48.6	13.5	12.2	27.0	24.3	40.5	36.3
	1 July	580	63.3	50.3	37.4	24.4	54.0	48.6	13.5	12.2	27.0	24.3	40.5	36.3
	11 July	560	63.3	50.3	37.4	24.4	-	-	13.5	12.2	9.0	8.1	4.5	4.1
	20 July	570	63.3	50.3	37.4	24.4	-	-	13.5	12.2	9.0	8.1	4.5	4.1
	30 July	570	63.3	50.3	37.4	24.4	-	-	13.5	12.2	9.0	8.1	4.5	4.1
	8 August	680	63.3	50.3	37.4	24.4	-	-	13.5	12.2	9.0	8.1	4.5	4.1
	17 August	680	63.3	50.3	37.4	24.4	-	-	13.5	12.2	9.0	8.1	4.5	4.1
	24 August	680	63.3	50.3	37.4	24.4	-	-	13.5	12.2	9.0	8.1	4.5	4.1
	Total	4900	506.4	402.4	299.2	195.2	108.0	97.2	108.0	97.6	108.0	97.2	108.0	97.2

Table 1. *Cont.*

	Irrigation Date	Irrigation Amount (m^3 ha^{-1})	N1 (kg ha^{-1})	N2 (kg ha^{-1})	N3 (kg ha^{-1})	N4 (kg ha^{-1})	PK-M1 (kg ha^{-1})		PK-M2 (kg ha^{-1})		PK-M3 (kg ha^{-1})		PK-M4 (kg ha^{-1})	
							P	K	P	K	P	K	P	K
2019	14 June	480	56.2	44.7	33.2	21.7	36.0	32.4	9.0	8.1	18.0	16.2	27.0	24.3
	22 June	480	56.2	44.7	33.2	21.7	36.0	32.4	9.0	8.1	18.0	16.2	27.0	24.3
	30 June	520	56.2	44.7	33.2	21.7	36.0	32.4	9.0	8.1	18.0	16.2	27.0	24.3
	9 July	520	56.2	44.7	33.2	21.7	-	-	13.5	12.2	9.0	8.1	4.5	4.1
	18 July	520	56.2	44.7	33.2	21.7	-	-	13.5	12.2	9.0	8.1	4.5	4.1
	25 July	630	56.2	44.7	33.2	21.7	-	-	13.5	12.2	9.0	8.1	4.5	4.1
	3 August	630	56.2	44.7	33.2	21.7	-	-	13.5	12.1	9.0	8.1	4.5	4.0
	12 August	630	56.2	44.7	33.2	21.7	-	-	13.5	12.1	9.0	8.1	4.5	4.0
	18 August	490	56.2	44.7	33.2	21.7	-	-	13.5	12.1	9.0	8.1	4.5	4.0
	Total	4900	505.8	402.3	298.8	195.3	108.0	97.2	108.0	97.2	108.0	97.2	108.0	97.2

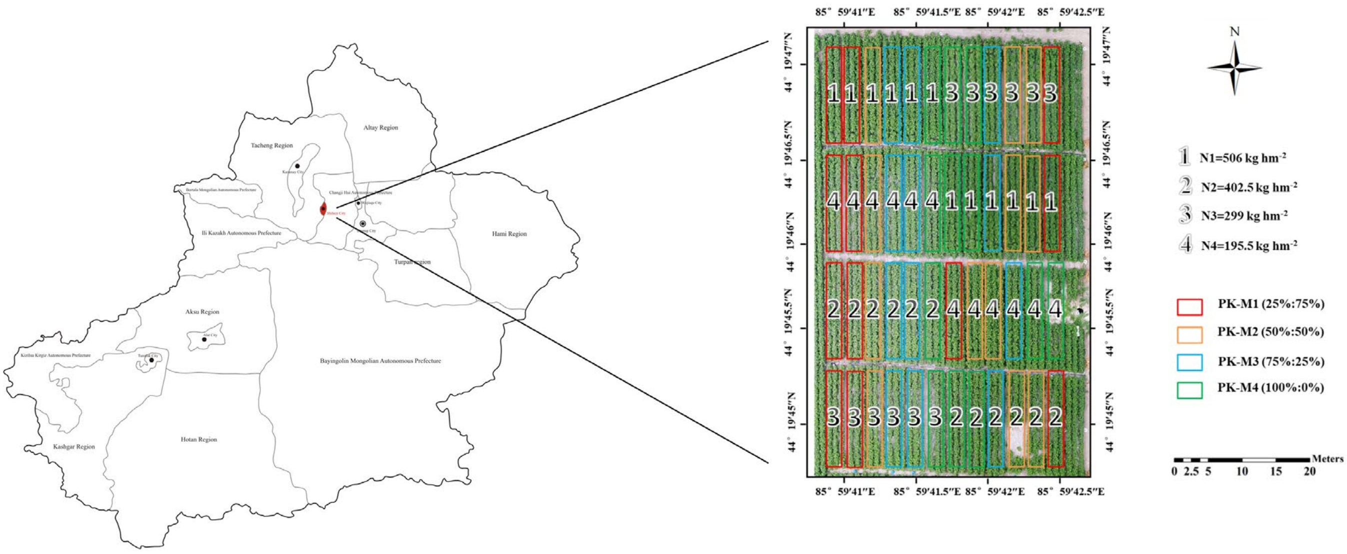

Figure 2. Schematic diagram of the fertilization distribution in the 2018–2019 test plots. Note: The experimental plots at both sites are of the same design.

Furthermore, forty-eight experimental plots, each with a size of 33.75 m^2 and a completely randomized design, were used in this experiment. The cotton was grown using a sparse planting mode, with one film comprised of three pipes and three rows, and equal row spacing planting (76 cm) and plant length (10 cm). Pest and disease control, cotton topping, and other field management techniques were consistent with cotton fields in the region. The seeds were sown on 21 April 2018 and 24 April 2019.

2.3. Sample Collection and Determination

We sampled a total of five growth stages, each with a sample size of 16 (average of three replicates), resulting in a total sample size of 160 for both years. Three cotton plants were selected from each plot at the full square stage (FS), the full flowering stage (FF), the early-full bolling stage (EFB), the late-full bolling stage (LFB), and the boll-opening stage (BO), and divided into leaves, stems and reproductive organs. Afterward, the different parts were placed at 105 °C for 30 min and then dried at 80 °C until their weights were constant [5,10]. The Nc, Pc, and Kc in cotton leaves, stems, and reproductive organs were estimated, as well as the N accumulation (Na), P accumulation (Pa), and K accumulation (Ka) in cotton plants. Total N was determined by the Kjeldahl method [25], total P was estimated using the vanadium molybdenum yellow colorimetric method [26], and total K was assessed by the flame photometer method [27]. The Na of each organ is equal to the product of the dry matter weight of each organ (t ha^{-1}) and its Nc (%), and the Na (g m^{-2}) of the plant is the sum of the Na of each organ.

After the boll was fully opened, an unsampled area of 6.75 m^2 was selected from each plot for yield measurement. The number of harvested plant and bolls were counted, and the biomass of 50 fully opened bolls was weighed. Additionally, single boll weight and seed yield were calculated. Based on the survey results, the seed cotton yield was divided into four yield levels: low yield, medium yield, medium-high yield, and high yield, according to the method of Zhong et al. [28–30].

2.4. Data Analysis

One-way ANOVA was used to analyze the differences in Nc/Pc, Nc/Kc, and Kc/Pc at different yield levels for the five growth stages. Data were processed using Excel 2016 and plotted using Origin 2021b (OriginLab, Northampton, MA, USA). The significance of differences was analyzed using the LSD method with SPSS 20.0 software, and the significance level was set at $\alpha = 0.05$.

3. Results

3.1. Descriptive Statistical Analysis of Samples with Different Yield Levels

In this study, seed cotton yield variation ranged from 3750 to 6750 and 6000 to 9000 kg ha^{-1} in 2018 and 2019, with a total sample size of 160 for both years. The yield of 80 annual samples was equally classified into four levels: low, medium, medium-high, and high yield, for a total of eight yield levels in two years. As shown in Table 2, both 2018 and 2019 yields were normally distributed across the yield range. In 2018, the highest number of samples was distributed at yield levels of 5250–6000 kg ha^{-1} and the content of N, P, and K reached maximum values. In 2019, the highest distribution of sample numbers was found in the yield level range of 7500–8250 kg ha^{-1}, with the largest N, P, and K contents occurring at yield levels of 6750–7500 kg ha^{-1}. The maximum Nc was 49.1 g kg^{-1}, 3.5 times higher than the minimum value (11.0); the maximum Pc was 8.1 g kg^{-1}, 5.2 times higher than the minimum value (1.3); and the maximum Pc was 52.1 g kg^{-1}, 1.5 times higher than the minimum value (21.1).

Table 2. Descriptive statistical analysis of samples at different yield levels.

Year	Yield Level (kg ha^{-1})	Sample Size	Nc			Pc			Kc		
			Max	Min	CV (%)	Max	Min	CV (%)	Max	Min	CV (%)
2018	[3750–4500)	10	34.0	15.3	30.3	4.9	1.1	48.2	30.2	16.5	20.8
	[4500–5250)	25	44.2	17.2	28.5	6.6	1.4	45.1	40.8	19.7	20.2
	[5250–6000)	30	47.1	18.4	27.6	7.4	1.7	42.8	45.7	22.9	18.5
	[6000–6750]	15	42.3	20.6	43.8	7.4	2.1	40.8	44.3	25.6	16.0
2019	[6000–6750)	20	42.5	11.0	35.7	7.4	1.3	42.6	47.6	21.1	22.0
	[6750–7500)	20	49.1	13.1	33.7	8.1	2.2	36.6	52.1	23.7	21.0
	[7500–8250)	30	47.4	15.0	32.2	8.0	2.4	34.2	50.7	25.3	19.8
	[8250–9000]	10	45.6	20.1	29.2	7.9	2.8	33.6	49.0	29.5	18.9
2018–2019	Total	160	49.1	11.0	-	8.1	1.1	-	52.1	16.5	-

Note: Nc represents nitrogen content, Pc phosphorus content, and Kc potassium content; CV represents variation coefficient.

3.2. Characteristics of N, P, and K Content and Distribution at Different Yield Levels

Consistent trends of N, P, and K contents were found in 2018 and 2019, which decreased gradually along with the growth stage and reached the minimum point at BO (Figure 3). In the same growth stage, the N, P, and K contents of cotton increased with the increase in yield, and higher values were found in the reproductive organs. In 2018, the average N, P, and K content of cotton plants in the lowest and highest yield levels were 71.7 and 92.9 g kg^{-1}, 8.1 and 13.4 g kg^{-1}, and 67.6 and 103.0 g kg^{-1}, respectively. Furthermore, in 2019, the average N, P, and K content of cotton plants in the lowest and highest yield levels were 80.3 and 93.9 g kg^{-1}, 12.6 and 15.5 g kg^{-1}, and 102.3 and 113.4 g kg^{-1}, respectively. In two years, the Nc, Pc, and Kc at high yield levels were 23.3%, 44.2%, and 31.6% higher than those at low yield levels, respectively.

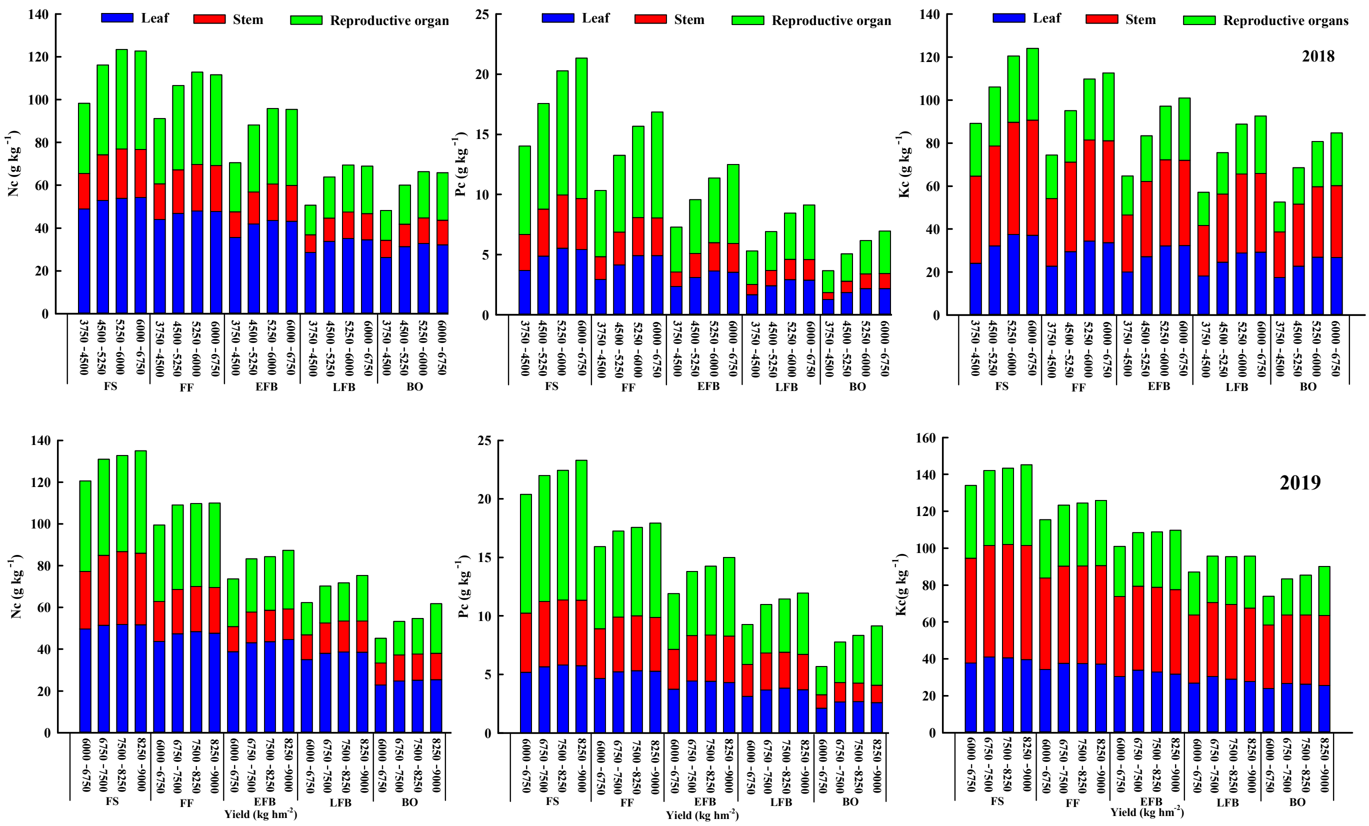

Figure 3. Variation characteristics of nitrogen content (Nc), phosphorus content (Pc), and potassium content (Kc) in cotton at different yield levels.

The distribution ratios of N, P, and K contents in the nutritional organs were 0.67, 0.53, and 0.73, respectively, and in the reproductive organs were 0.33, 0.47, and 0.27 (Table 3). In 2018, the ratio of Nc of reproductive organs to total plant (Nr/Nt) increased with the yield at the level of 3750–6000 kg ha^{-1}, with no significant differences at the level of 5250–6750 kg ha^{-1}, indicating that the higher cotton yield was less affected by Nc. The proportion of P and K distribution in reproductive organs increased with yield in 2018 and 2019, suggesting that cotton was limited by P and K fertilizer at high yield levels. The Pc of the different organs showed that reproductive organs > leaves > stems, indicating that reproductive organs had a high demand for P during cotton growth. However, the Kc was greatest in the stems, with an average distribution ratio of 0.73 for the nutritional organs, which was 1.7 times higher than that in reproductive organs.

Table 3. Characteristics of nitrogen content (Nc), phosphorus content (Pc), and potassium content (Kc) and distribution at different yield levels.

Ratio	Growth Stage	2018				2019			
		[3750–4500)	[4500–5250)	[5250–6000)	[6000–6750]	[6000–6750)	[6750–7500)	[7500–8250)	[8250–9000]
Nv/Nt	FS	0.67	0.64	0.62	0.62	0.64	0.65	0.65	0.64
	FF	0.67	0.63	0.62	0.62	0.63	0.63	0.64	0.63
	EFB	0.67	0.64	0.63	0.63	0.69	0.69	0.70	0.68
	LFB	0.73	0.70	0.68	0.68	0.75	0.75	0.75	0.71
	BO	0.71	0.70	0.68	0.66	0.74	0.70	0.69	0.61
Nr/Nt	FS	0.33	0.36	0.38	0.38	0.36	0.35	0.35	0.36
	FF	0.33	0.37	0.38	0.38	0.37	0.37	0.36	0.37
	EFB	0.33	0.36	0.37	0.37	0.31	0.31	0.30	0.32
	LFB	0.27	0.30	0.32	0.32	0.25	0.25	0.25	0.29
	BO	0.29	0.30	0.32	0.34	0.26	0.30	0.31	0.39
Pv/Pt	FS	0.48	0.50	0.49	0.45	0.50	0.51	0.51	0.49
	FF	0.47	0.52	0.52	0.48	0.56	0.57	0.57	0.55
	EFB	0.49	0.53	0.53	0.48	0.60	0.60	0.59	0.55
	LFB	0.47	0.53	0.54	0.50	0.63	0.62	0.60	0.56
	BO	0.50	0.55	0.55	0.49	0.57	0.55	0.51	0.45
Pr/Pt	FS	0.52	0.50	0.51	0.55	0.50	0.49	0.49	0.51
	FF	0.53	0.48	0.48	0.52	0.44	0.43	0.43	0.45
	EFB	0.51	0.47	0.47	0.52	0.40	0.40	0.41	0.45
	LFB	0.53	0.47	0.46	0.50	0.37	0.38	0.40	0.44
	BO	0.50	0.45	0.45	0.51	0.43	0.45	0.49	0.55
Kv/Kt	FS	0.73	0.74	0.74	0.73	0.71	0.71	0.71	0.70
	FF	0.73	0.75	0.74	0.72	0.73	0.73	0.73	0.72
	EFB	0.72	0.75	0.74	0.71	0.73	0.73	0.72	0.71
	LFB	0.73	0.74	0.74	0.71	0.73	0.74	0.73	0.70
	BO	0.74	0.75	0.74	0.71	0.79	0.77	0.75	0.70
Kr/Kt	FS	0.27	0.26	0.26	0.27	0.29	0.29	0.29	0.30
	FF	0.27	0.25	0.26	0.28	0.27	0.27	0.27	0.28
	EFB	0.28	0.25	0.26	0.29	0.27	0.27	0.28	0.29
	LFB	0.27	0.26	0.26	0.29	0.27	0.26	0.27	0.30
	BO	0.26	0.25	0.26	0.29	0.21	0.23	0.25	0.30

Note: Nv represents nitrogen content of vegetative organs, Nr represents nitrogen content of reproductive organs, Nt represents total plant nitrogen content, and Pv, Pr, Pt, Kv, Kr, and Kt are similar.

3.3. Variation Characteristics of N, P, and K Accumulations in Cotton at Different Yield Levels

Cotton N, P, and K accumulations increased and then decreased along with the growth stages. In the same growth stage, the cotton N, P, and K accumulations increased along with the increased yield. N, P, and K accumulations reached a maximum in 2018 at the EFB and in 2019 at the LFB, while the N, P, and K accumulations reached a minimum at the FS (Figure 4). The average accumulation of N, P, and K throughout the growing stage was 17.8, 2.2, and 20.1 g m^{-2} in 2018, and 28.4, 5.0, and 38.2 g m^{-2} in 2019, respectively. The accumulation of N, P, and K in 2019 was 1.6, 2.3, and 1.9 times higher than in 2018. At the EFB stage, the maximum accumulation of N, P, and K in cotton plants appeared at the yield level of 6000–6750 kg ha^{-1}, and the maximum values were 32.1, 4.45 and 36.3 g m^{-2}, respectively, which were 78.3%, 56.4% and 96.7% higher than the minimum value (the yield level of 3750–4500 kg ha^{-1} in 2018). At the LFB, the maximum accumulation of N, P, and K in cotton plants appeared at the yield level of 8250–9000 kg ha^{-1}, and the maximum values were 59.2, 11.1 and 78.0 g m^{-2}, respectively, which were 50.5%, 66.7% and 36.4% higher than the minimum value (the yield level of 6000–6750 kg ha^{-1} in 2019).

3.4. Dynamic Changes of Cotton Nc/Pc, Nc/Kc, and Kc/Pc at Different Yield Levels

The Nc/Pc of cotton leaves was significantly greater than that of stems and reproductive organs (2018 and 2019). In 2018, in the same yield level, the Nc/Pc gradually increased along with the growth stages, with a maximum value of 20.79 in leaves at the BO stage. Two years' data exposed that the values of Nc/Pc were higher in lower yield levels (3750–4500 kg ha^{-1}) than in higher yield levels (8250–9000 kg ha^{-1}) in all organs

(Table 4). For example, the values of Nc/Pc of 4500–5250 kg ha^{-1} at the FS, FF, EFB, LFB, and BO stages were 20.8%, 28.0%, 29.9%, 21.8%, and 27.5%, respectively, higher than those at a yield level of 6000–6750 kg ha^{-1} in 2018. At yield levels of 5250–6750 kg ha^{-1}, cotton leaves, stems, and reproductive organs all maintained a low level of Nc/Pc, indicating that a low level of Nc/Pc was conducive to increased yields.

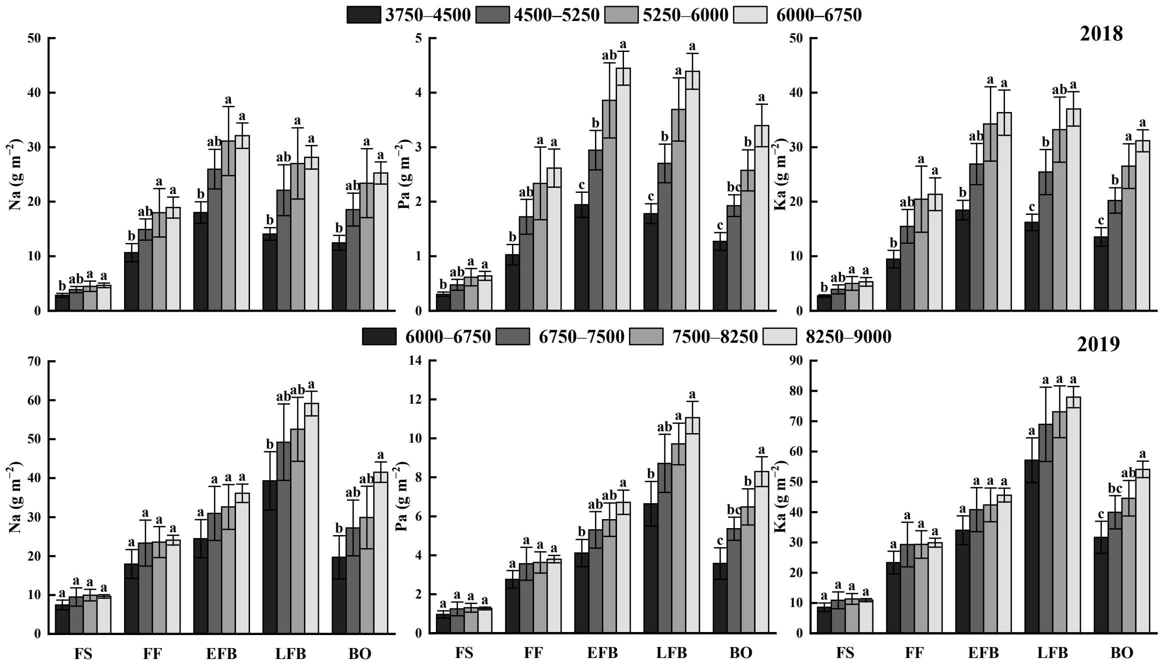

Figure 4. Variation characteristics of nitrogen accumulation (Na), phosphorus accumulation (Pa), and potassium accumulation (Ka) in cotton at different yield levels. Note: Lowercase letters represent the significance of differences in Na, Pa or Ka at different yield levels, $p < 0.05$.

The Nc/Kc of different cotton organs showed leaves > reproductive organs > stems (in 2018 and 2019). In 2018, the values of Nc/Kc in leaves decreased along with growth stages at different yield levels, while the trend was inconsistent in 2019 (Table 5). For stems, there were no significant differences among yield levels at the same growth stage, reaching a maximum value of 0.53 (3750–4500 kg ha^{-1}) at FF in 2018 and 0.57 (7500–8250 kg ha^{-1}) at FS in 2019. For reproductive organs, Nc/Kc was significantly greater at FS and FF than at other growth stages and minimal at yield levels of 6000–6750 kg ha^{-1} in 2018 and 2019. Leaves, stems, and reproductive organs all kept a low Nc/Kc at the yield level of 5250–6750 kg ha^{-1}, implying that maintaining high Kc in the yield range of 5250–6750 kg ha^{-1} was beneficial for yield increases. However, with the increase in yield level, there was little difference in the Nc/Kc in the 7500–9000 kg ha^{-1} yield range, indicating that a higher yield level was less affected by Kc.

The values of Kc/Pc in all organs increased along with the growth stages, and the values in stems were higher than in other organs in both years. Moreover, from annual data, the values of Kc/Pc in lower yield levels were higher than those in higher yield levels for all organs, and there were no significant differences in higher yield levels (Table 6). Based on the above results in Nc, Pc, Kc, Nc/Pc, and Nc/Kc, the changes of Kc/Pc indicated that the yield potential was easily affected by P fertilizer than K from a lower yield level to a higher yield level.

Table 4. Dynamic changes of cotton nitrogen content/phosphorus content (Nc/Pc) at different yield levels.

	Yield Level (kg ha^{-1})	Leaf				Stem				Reproductive Organs			
		[3750–4500)	[4500–5250)	[5250–6000)	[6000–6750]	[3750–4500)	[4500–5250)	[5250–6000)	[6000–6750]	[3750–4500)	[4500–5250)	[5250–6000)	[6000–6750]
2018	FS	13.34 ± 0.5 a	11.03 ± 1.4 b	9.86 ± 0.9 b	10.08 ± 0.8 b	5.52 ± 0.2 c	5.52 ± 0.4 c	5.21 ± 0.2 bc	5.32 ± 0.1 bc	4.44 ± 0.0 bc	4.76 ± 0.7 bc	4.53 ± 0.8 bc	3.94 ± 0.2 d
	FF	14.98 ± 0.3 a	11.57 ± 1.6 b	9.96 ± 1.3 bc	9.85 ± 1.2 bc	8.87 ± 0.0 cd	7.66 ± 0.2 de	7.02 ± 0.6 def	6.88 ± 0.6 ef	5.53 ± 0.0 fg	6.17 ± 1.1 efg	5.72 ± 0.9 efg	4.82 ± 0.3 g
	EFB	15.16 ± 0.2 a	13.60 ± 0.9 ab	12.18 ± 1.1 b	12.22 ± 0.7 b	9.88 ± 0.7 c	7.80 ± 0.2 d	7.29 ± 0.7 d	7.16 ± 0.8 df	6.16 ± 0.0 df	7.04 ± 1.4 df	6.60 ± 1.1 df	5.42 ± 0.2 f
	LFB	17.12 ± 0.3 a	14.49 ± 1.3 b	12.42 ± 1.7 b	12.31 ± 1.8 b	9.75 ± 1.2 c	8.69 ± 0.7 cd	7.53 ± 0.8 cde	7.22 ± 0.6 def	4.97 ± 0.2 f	5.93 ± 1.3 ef	5.70 ± 1.2 ef	4.87 ± 0.2 f
	BO	20.79 ± 0.9 a	17.39 ± 1.7 b	15.39 ± 1.6 bc	14.95 ± 1.3 bc	14.07 ± 0.9 c	11.38 ± 0.5 d	10.02 ± 0.9 de	9.36 ± 0.7 de	7.64 ± 0.3 ef	8.04 ± 1.5 ef	7.77 ± 1.7 ef	6.32 ± 0.4 f
	Yield level (kg ha^{-1})	**[6000–6750)**	**[6750–7500)**	**[7500–8250)**	**[8250–9000]**	**[6000–6750)**	**[6750–7500)**	**[7500–8250)**	**[8250–9000]**	**[6000–6750)**	**[6750–7500)**	**[7500–8250)**	**[8250–9000]**
2019	FS	9.65 ± 0.7 a	9.16 ± 0.6 ab	8.95 ± 0.3 b	8.99 ± 0.3 ab	5.45 ± 0.5 d	5.98 ± 0.5 cd	6.28 ± 0.1 c	6.13 ± 0.1 c	4.27 ± 0.1 e	4.27 ± 0.2 e	4.15 ± 0.1 e	4.09 ± 0.0 e
	FF	9.41 ± 0.5 a	9.09 ± 0.3 a	9.08 ± 0.3 a	9.01 ± 0.1 a	4.47 ± 0.6 d	4.56 ± 0.1 cd	4.62 ± 0.1 cd	4.77 ± 0.0 cd	5.21 ± 0.3 bc	5.49 ± 0.6 b	5.26 ± 0.47 bc	5.02 ± 0.0 bcd
	EFB	10.44 ± 0.7 a	9.81 ± 0.8 a	9.89 ± 0.3 a	10.37 ± 0.3 a	3.47 ± 0.3 d	3.71 ± 0.6 cd	3.78 ± 0.4 cd	3.69 ± 0.1 cd	4.79 ± 0.1 b	4.67 ± 0.5 b	4.35 ± 0.2 bc	4.20 ± 0.2 bcd
	LFB	11.21 ± 0.3 a	10.48 ± 0.8 b	10.12 ± 0.3 b	10.41 ± 0.1 b	4.28 ± 0.7 cd	4.60 ± 0.3 cd	4.83 ± 0.2 c	4.96 ± 0.0 c	4.51 ± 0.3 cd	4.27 ± 0.4 cd	3.98 ± 0.4 d	4.19 ± 0.2 cd
	BO	10.98 ± 1.1 a	9.60 ± 1.5 ab	9.43 ± 0.5 ab	9.83 ± 0.7 ab	9.51 ± 1.6 ab	8.12 ± 1.0 b	7.97 ± 0.9 b	8.50 ± 1.2 b	4.83 ± 0.6 c	4.61 ± 0.1 c	4.15 ± 0.9 c	4.72 ± 0.1 c

Note: The different lowercase letters in the same row represent significant differences in Nc/Pc at different yield levels ($p < 0.05$).

Table 5. Dynamic changes of cotton nitrogen content/potassium content (Nc/Kc) at different yield levels.

	Yield Level (kg ha^{-1})	Leaf				Stem				Reproductive Organs			
		[3750–4500)	[4500–5250)	[5250–6000)	[6000–6750]	[3750–4500)	[4500–5250)	[5250–6000)	[6000–6750]	[3750–4500)	[4500–5250)	[5250–6000)	[6000–6750]
2018	FS	2.04 ± 0.0 a	1.69 ± 0.2 b	1.47 ± 0.2 bc	1.47 ± 0.1 bc	0.41 ± 0.0 d	0.46 ± 0.0 d	0.44 ± 0.0 d	0.42 ± 0.0 d	1.33 ± 0.0 c	1.53 ± 0.2 bc	1.52 ± 0.2 bc	1.38 ± 0.1 bc
	FF	1.94 ± 0.0 a	1.63 ± 0.2 ab	1.42 ± 0.1 b	1.43 ± 0.1 b	0.53 ± 0.0 c	0.49 ± 0.1 c	0.46 ± 0.0 c	0.45 ± 0.0 c	1.51 ± 0.0 b	1.65 ± 0.3 ab	1.54 ± 0.2 b	1.34 ± 0.0 b
	EFB	1.77 ± 0.0 a	1.56 ± 0.1 ab	1.37 ± 0.1 bc	1.35 ± 0.1 bc	0.45 ± 0.0 d	0.43 ± 0.0 d	0.42 ± 0.0 d	0.43 ± 0.0 d	1.26 ± 0.0 c	1.48 ± 0.2 bc	1.42 ± 0.3 bc	1.22 ± 0.0 c
	LFB	1.57 ± 0.0 a	1.39 ± 0.1 ab	1.25 ± 0.1 b	1.19 ± 0.1 bc	0.35 ± 0.0 e	0.35 ± 0.0 e	0.33 ± 0.0 e	0.33 ± 0.0 e	0.90 ± 0.0 d	0.99 ± 0.1 cd	0.95 ± 0.2 d	0.83 ± 0.0 d
	BO	1.50 ± 0.0 a	1.39 ± 0.1 ab	1.25 ± 0.1 bc	1.21 ± 0.1 bc	0.38 ± 0.0 e	0.37 ± 0.0 e	0.36 ± 0.0 e	0.35 ± 0.0 e	1.01 ± 0.0 cd	1.07 ± 0.1 cd	1.03 ± 0.2 cd	0.90 ± 0.0 d
	Yield level (kg ha^{-1})	**[6000–6750)**	**[6750–7500)**	**[7500–8250)**	**[8250–9000]**	**[6000–6750)**	**[6750–7500)**	**[7500–8250)**	**[8250–9000]**	**[6000–6750)**	**[6750–7500)**	**[7500–8250)**	**[8250–9000]**
2019	FS	1.32 ± 0.0 a	1.26 ± 0.1 ab	1.28 ± 0.0 a	1.31 ± 0.0 a	0.48 ± 0.0 d	0.55 ± 0.1 d	0.57 ± 0.0 d	0.55 ± 0.0 d	1.10 ± 0.0 c	1.13 ± 0.0 bc	1.11 ± 0.0 c	1.12 ± 0.0 bc
	FF	1.28 ± 0.0 ab	1.27 ± 0.0 abc	1.29 ± 0.0 a	1.28 ± 0.0 ab	0.38 ± 0.1 d	0.40 ± 0.0 d	0.41 ± 0.0 d	0.41 ± 0.0 d	1.16 ± 0.0 bc	1.22 ± 0.1 abc	1.17 ± 0.1 abc	1.14 ± 0.0 c
	EFB	1.28 ± 0.0 b	1.28 ± 0.0 b	1.33 ± 0.1 ab	1.40 ± 0.0 a	0.27 ± 0.0 d	0.32 ± 0.0 d	0.33 ± 0.0 d	0.32 ± 0.0 d	0.84 ± 0.0 c	0.87 ± 0.0 c	0.85 ± 0.0 c	0.87 ± 0.0 c
	LFB	1.31 ± 0.0 ab	1.26 ± 0.1 b	1.34 ± 0.1 ab	1.39 ± 0.0 a	0.32 ± 0.1 e	0.36 ± 0.0 e	0.37 ± 0.0 e	0.38 ± 0.0 e	0.66 ± 0.0 d	0.71 ± 0.1 cd	0.70 ± 0.1 cd	0.77 ± 0.0 c
	BO	0.95 ± 0.0 abc	0.93 ± 0.0 abcd	0.96 ± 0.0 ab	1.00 ± 0.0 a	0.30 ± 0.0 e	0.34 ± 0.0 e	0.33 ± 0.0 e	0.33 ± 0.0 e	0.76 ± 0.1 d	0.81 ± 0.1 bcd	0.78 ± 0.1 cd	0.89 ± 0.0 abcd

Note: The different lowercase letters in the same row represent significant differences in Nc/Kc at different yield levels ($p < 0.05$).

Table 6. Dynamic changes of cotton potassium content/phosphorus content (Kc/Pc) at different yield levels.

	Yield Level (kg ha^{-1})	Leaf				Stem				Reproductive Organs			
		[3750–4500)	[4500–5250)	[5250–6000)	[6000–6750]	[3750–4500)	[4500–5250)	[5250–6000)	[6000–6750]	[3750–4500)	[4500–5250)	[5250–6000)	[6000–6750]
2018	FS	6.56 ± 0.4 c	6.56 ± 0.3 c	6.73 ± 0.2 c	6.85 ± 0.1 c	13.58 ± 0.5 a	12.09 ± 0.9 b	11.93 ± 1.0 b	12.64 ± 0.1 b	3.33 ± 0.1 d	3.12 ± 0.1 d	2.99 ± 0.1 d	2.86 ± 0.0 d
	FF	7.73 ± 0.2 c	7.10 ± 0.3 c	7.01 ± 0.3 c	6.88 ± 0.2 c	16.77 ± 0.8 a	15.46 ± 0.4 b	15.17 ± 0.4 b	15.12 ± 0.8 b	3.66 ± 0.0 d	3.74 ± 0.1 d	3.72 ± 0.1 d	3.59 ± 0.1 d
	EFB	8.55 ± 0.3 c	8.72 ± 0.2 c	8.85 ± 0.2 c	9.08 ± 0.3 c	21.85 ± 0.6 a	18.09 ± 0.9 b	17.29 ± 0.6 b	16.75 ± 1.1 b	4.90 ± 0.0 d	4.75 ± 0.3 d	4.66 ± 0.3 d	4.44 ± 0.0 d
	LFB	10.92 ± 0.0 d	10.41 ± 0.2 d	9.92 ± 0.5 d	10.29 ± 0.7 d	27.83 ± 1.8 a	25.34 ± 1.2 ab	22.58 ± 1.3 bc	21.59 ± 1.7 c	5.54 ± 0.1 e	5.97 ± 0.4 e	6.04 ± 0.3 e	5.89 ± 0.2 e
	BO	13.83 ± 0.7 c	12.48 ± 0.7 c	12.36 ± 0.2 c	12.34 ± 0.1 c	37.60 ± 2.9 a	31.15 ± 1.8 b	27.89 ± 1.4 b	27.03 ± 1.7 b	7.58 ± 0.0 d	7.50 ± 0.4 d	7.61 ± 0.3 d	7.01 ± 0.4 d
	Yield level (kg ha^{-1})	**[6000–6750)**	**[6750–7500)**	**[7500–8250)**	**[8250–9000]**	**[6000–6750)**	**[6750–7500)**	**[7500–8250)**	**[8250–9000]**	**[6000–6750)**	**[6750–7500)**	**[7500–8250)**	**[8250–9000]**
2019	FS	7.33 ± 0.4 b	7.25 ± 0.2 b	6.97 ± 0.1 b	6.88 ± 0.1 b	11.28 ± 0.5 a	10.93 ± 0.8 a	11.13 ± 0.6 a	11.08 ± 0.1 a	3.89 ± 0.1 c	3.78 ± 0.0 c	3.73 ± 0.0 c	3.67 ± 0.0 c
	FF	7.36 ± 0.5 b	7.19 ± 0.5 b	7.03 ± 0.3 b	7.05 ± 0.0 b	11.73 ± 0.5 a	11.33 ± 0.3 a	11.28 ± 0.4 a	11.60 ± 0.1 a	4.51 ± 0.0 c	4.50 ± 0.1 c	4.51 ± 0.0 c	4.39 ± 0.0 c
	EFB	8.19 ± 0.5 c	7.65 ± 0.3 c	7.44 ± 0.2 c	7.39 ± 0.3 c	12.85 ± 0.3 a	11.78 ± 0.6 b	11.66 ± 0.5 b	11.49 ± 0.0 b	5.73 ± 0.2 d	5.33 ± 0.3 de	5.11 ± 0.1 de	4.82 ± 0.2 e
	LFB	8.57 ± 0.5 b	8.30 ± 0.3 bc	7.57 ± 0.6 cd	7.48 ± 0.1 cd	13.71 ± 0.2 a	12.81 ± 0.8 a	13.21 ± 0.5 a	13.19 ± 0.1 a	6.89 ± 0.5 de	6.05 ± 0.2 ef	5.70 ± 0.1 f	5.41 ± 0.3 f
	BO	11.60 ± 1.5 c	10.30 ± 1.0 c	9.80 ± 0.3 c	9.87 ± 0.8 c	31.83 ± 4.1 a	24.70 ± 3.8 b	24.07 ± 1.7 b	25.61 ± 1.2 b	6.58 ± 1.0 c	5.64 ± 0.5 c	5.31 ± 0.1 c	5.30 ± 0.3 c

Note: The different lowercase letters in the same row represent significant differences in Kc/Pc at different yield levels ($p < 0.05$).

3.5. Dynamic Changes of Cotton Na/Pa, Na/Ka, and Ka/Pa at Different Yield Levels

Overall, cotton plant Na/Pa, Na/Ka, and Ka/Pa decreased with increasing yield levels in both 2018 and 2019, signifying that high P and K accumulation were beneficial to reaching higher yield levels, while P fertilizer was more effective in increasing yields. In 2018, Na/Pa differences were less pronounced as the growth stage developed, Na/Ka was smaller at LFB and BO, and Ka/Pa reached a maximum at BO. However, these three indicators gradually declined in 2019 with the development of the growth stage, having smaller values at the BO. The mean values of Na/Pa, Na/Ka, and Ka/Pa for the whole growing stage were 8.3, 0.91, and 9.1 in 2018, which were 36%, 20%, and 14% higher than those in 2019, respectively. In 2018, there were greater differences for Na/Pa, Ka/Pa, and Na/Ka throughout the growth stages at different yield levels, and in 2019 there were small differences at the FS and FF and large differences at later growth stages (Figure 5).

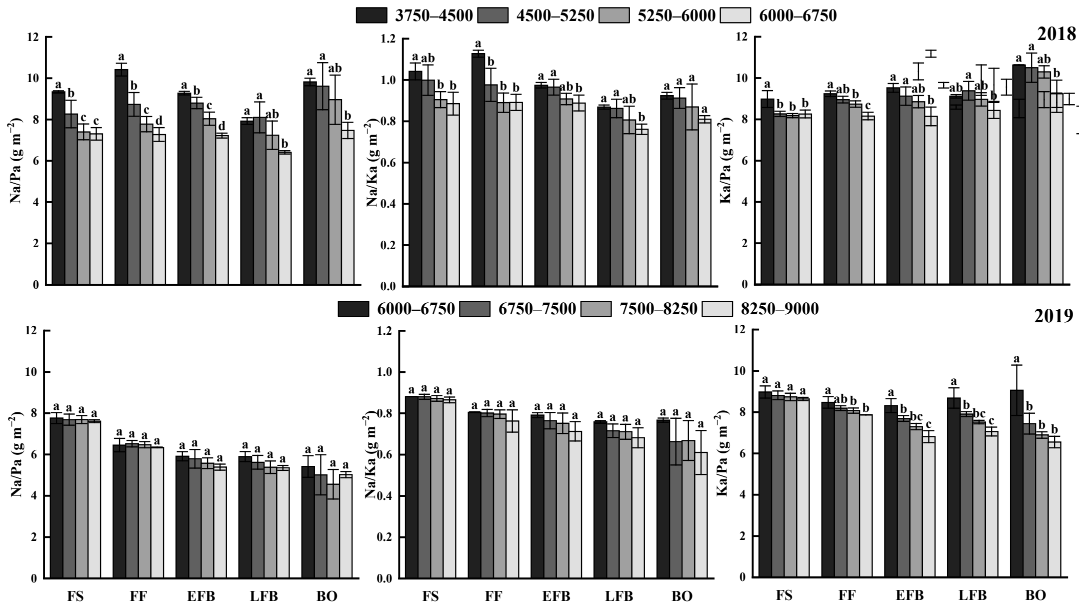

Figure 5. Dynamic changes of nitrogen accumulation/phosphorus accumulation (Na/Pa), nitrogen accumulation/potassium accumulation (Na/Ka), and potassium accumulation/phosphorus accumulation (Ka/Pa) in cotton at different yield levels. Note: Lowercase letters represent the significance of differences in Na/Pa, Na/Ka or Ka/Pa at different yield levels, $p < 0.05$.

3.6. Establishing Models of Seed Cotton Yield and Plant Nc/Pc, Nc/Kc

The correlation analysis and modeling data for this study were sourced from 2018 and 2019, with a sample size of 32 for each growth stage and a total of 160 samples. The correlation analysis highlighted the higher correlation between seed cotton yield and Nc, Pc, Kc, Nc/Pc, Nc/Kc, and Kc/Pc (Table 7). The yield was significantly and positively correlated with Nc at FS but poorly correlated at later growth stages, implying that the effect of N fertilizer on cotton yield was mainly in the early growth stage. The yield was positively correlated with Pc and Kc, reaching a significant level of 0.01, with a maximum correlation coefficient of 0.88. The yield was negatively correlated with Nc/Pc, Nc/Kc, and Kc/Pc, with the largest correlation coefficient of 0.90. The higher correlation coefficients between yield and nutrient parameters were selected to make scatter plots at the FS, FF, EFB, and LFB. Furthermore, linear models were developed. However, modeling yield prediction during the BO was not practical for production guidance; thus, the data from the BO were discarded.

Table 7. Correlation analysis between seed cotton yield and nutrient characteristics of nitrogen, phosphorus, and potassium.

Growth Stage	Seed Cotton Yield (kg ha^{-1})				
	FS	FF	EFB	LFB	BO
Nc	0.63 **	0.22	−0.03	0.45 **	−0.1
Pc	0.81 **	0.81 **	0.87 **	0.88 **	0.82 **
Kc	0.86 **	0.79 **	0.75 **	0.64 **	0.62 **
Nc/Pc	−0.68 **	−0.85 **	−0.90 **	−0.89 **	−0.91 **
Nc/Kc	−0.87 **	−0.89 **	−0.83 **	−0.58 **	−0.78 **
Kc/Pc	−0.2	−0.80 **	−0.90 **	−0.88 **	−0.67 **

Note: The significance of differences was analyzed using the LSD method with SPSS 20.0 software. ** represents a significant correlation at the 0.01 level; Nc represents nitrogen content, Pc phosphorus content, and Kc potassium content; FS represents full square stage, FF represents full flowering stage, EFB represents early-full bolling stage, LFB represents late-full bolling stage and BO represents boll-opening stage.

The yield prediction models based on Nc/Kc and Nc/Pc were established at different growth stages (Figure 6). Yield and Nc/Kc had a high fit at the FS and FF, indicating that sufficient K fertilizer supply in the early stage of cotton growth is the premise of the high yield. Moreover, the coefficients of determination for Nc/Pc and yield modeling reached significant correlations of 0.82 and 0.80 in the EFB and LFB, respectively, representing that the P fertilizer application plays an important role in the later growth stages of cotton. Overall, when 0.85 < Nc/Kc < 1.0 at FS, 0.8 < Nc/Kc < 1.0 at FF, 4.3 < Nc/Pc < 6.7 at EFB, and 4.9 < Nc/Pc < 7.1 at LFB, there is a high yield potential of 7000–9000 kg ha^{-1}.

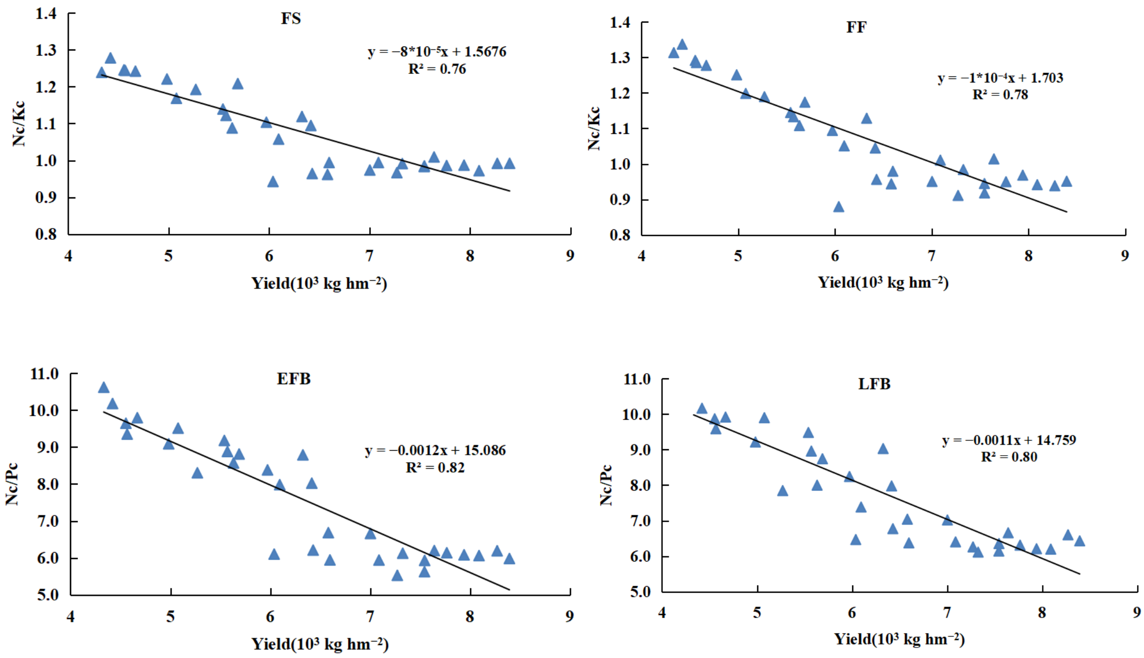

Figure 6. The model of cotton yield established by plant nitrogen content/potassium content (Nc/Kc) and nitrogen content/phosphorus content (Nc/Pc).

4. Discussion

The N, P, and K deficiencies are limiting factors for yield potential [31–33]. There are different distributions and contents of N, P, and K in plants at different yield levels. Therefore, the N, P, and K contents are essential indicators for yield improvement [34]. Some studies have shown that total N, P, and K accumulations in cotton and seed cotton yield increase with increasing fertilizer application within an optimal range of applications. Conversely, the accumulation of total N, P, and K and seed cotton yield decrease was also reported [35]. Another study concluded that increased uptake of N, P, and K, especially in reproductive organs, could increase cotton yield, similar to the results of our experiment [36,37]. This study found that N, P, and K contents in cotton mostly increased with increasing yield levels in both years and kept a flat trend in higher yield level, while N, P, and K accumulation mostly increased with increasing yield levels. Increasing the application of N, P, and K fertilizers within a certain range is beneficial in increasing yield level, while over-applied fertilizers adversely affect yield increase. In addition, P and K concentrations in the reproductive organs of cotton increased with increasing yield levels in the experiment. In contrast, Nc increased to around 50 g kg^{-1} and maintained a stable level, suggesting that higher cotton yield levels are less affected by Nc and more by P and K content, especially in the reproductive organs. At different yield levels, the variation range of cotton N, P, and K content in 2019 was small, and the variation in 2018 was large, indicating that under low yield levels, there was a significant yield increase benefit of N, P, and K fertilizer, consistent with Blaise et al. [38]. There were also few differences in N, P, and K contents in cotton between two years, but significant differences in N, P, and K accumulation, which could be due to the effect of insufficient water pressure in the pipeline at LFB in 2018, resulting in lower growth and dry matter than in 2019. Figure 4 illustrates that with the increase in the yield level, the accumulation of N, P, and K exhibited an upward trend, indicating that the accumulation of N, P, and K could be a good judge of the yield potential of cotton.

The ratio of N, P, and K content is a useful indicator for measuring and evaluating the yield potential and can be used for nutrient status analysis at different growth stages [39]. Niu and Qiu et al. stated that wheat seed yield was influenced by Nc/Kc, with optimal Nc/Kc promoting healthy plant growth, while imbalanced Nc/Kc led to plant growth disorders [40,41]. In a study by Gaj et al. on the Nc/Pc, Nc/Pc, and Kc/Pc of different maize varieties, it was found that the yield of ES Paroli SG varieties was mainly influenced by Pc, Kc, Nc/Pc, and Kc/Pc, while the yield of ES Palazzo varieties was most dependent on Kc and Nc/Pc [42]. In this study, a higher yield in 2019 with lower Nc/Pc was observed, especially during the FF stage, indicating the demand for P fertilizer was higher in the later stages of cotton growth. Additionally, increased P applications would be beneficial to obtain high yield potential, consistent with the study by Gong et al., who concluded that cotton's nutrient requirements show an earlier and higher demand for N and a slightly later but longer-lasting demand for P [43]. Further, under lower yield levels, the Nc/Kc of cotton reproductive organs initially increased and then decreased as yield increased, peaking at yields of 4500–5250 kg ha^{-1}, with no significant differences between yield levels when yields increased to 6750 kg ha^{-1}, similar to the finding of Xin et al. that N fertilizer should be increased in low-yielding fields [44]. Sireesha et al. verified that the mean Nc/Pc, Nc/Kc, and Kc/Pc in the third leaf of sugarcane in the high-yielding areas were 9.65, 1.21, and 0.78, while Nc/Pc, Nc/Kc, and Kc/Pc in the low yielding areas were 11.02, 1.25, and 0.85 [45]. This is similar to the finding of this study that Nc/Kc, Nc/Pc, and Kc/Pc were negatively correlated with yield (Table 7), which further indicates that more P and K fertilizers, especially P fertilizer, were needed to obtain high yield.

N, P, and K, as indispensable and abundant elements in cotton growth, are directly linked to yield [46–48]. This study demonstrated a significant linear relationship between Pc and yield. Total N, P, and K accumulation were significantly and positively correlated with seed cotton yield. The positive correlation coefficient between boll nutrient uptake and yield was higher than that of leaves and stems [4,49]. Tariq et al. and López et al. analyzed Kc in different organs of cotton and showed that Kc in leaves and stems was significantly and positively correlated with boll weight, boll number per plant, and seed cotton yield. They concluded Kc in leaves and stems could be used to predict seed cotton yield [50,51]. Also, similar results were found in other crops, where soil conductivity was positively correlated with yield in winter wheat and maize, mainly attributed to higher N, P, and K nutrients [52–54]. In this study, N, P, and K content were all positively correlated with yield, with a lower correlation between Nc and yield at the FB and a higher correlation among Pc, Kc, and yield at FB, suggesting that the main limiting factors for high yield are P and K, especially P fertilizer. The above results agree with the study of Chi et al., who found that higher yield potential might need a relative increase in P and K requirements during the bloom-bolling stage of cotton [55]. Moreover, the correlations between Nc/Pc and Kc/Pc and yield were highest at the FB, indicating that maintaining high Pc at late growth stages promotes cotton yield. Therefore, P fertilizer could be shifted back to actual fertilizer management, similar to the study stating that increased application of P fertilizers during late growth could increase yield and efficiency in cotton [56,57]. However, this study analyzed all sources of N, P, K in cotton and neglected the different sources of N, P, K, not only from fertilizer but also from the soil. Therefore, I consider that separating the fertilizer NPK from the soil NPK would be more beneficial for efficient fertilizer management strategies, which is the objective of this study for further development.

5. Conclusions

In this study, we found that the Nc, Pc, and Kc of cotton plants at high yield levels were 23.3%, 44.2%, and 31.6% higher than those at low yield levels. Seed cotton yield was mostly restricted by Nc at lower yield levels and easily affected by Pc and Kc at higher yield levels, especially affected by Pc. Then, the models based on Nc/Pc, Nc/Kc, and seed cotton yield at different yield levels are effective in predicting the yield potential of cotton. When $0.85 < Nc/Kc < 1.0$ at FS, $0.8 < Nc/Kc < 1.0$ at FF, $4.3 < Nc/Pc < 6.7$ at EFB, and $4.9 < Nc/Pc < 7.1$ at LFB, there is a high yield potential of 7000–9000 kg ha^{-1}. Furthermore, our recommended strategy for efficient fertilization is to reduce the application of N fertilizer (N3 in this study) during the growing period and to increase the application of P fertilizer during the later growth period (PK-M2 in this study).

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