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Effects of Different Nitrogen Allocation Ratios and Period on Cotton Yield and Nitrogen Utilization

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Abstract: Choosing the proper fertilizer regime for a crop in a given location remains challenging to increase yield, profitability, environmental growth protection, and sustainability. However, the nutrient demand characteristics of cotton in the North China Plain are different at various growth stages. Therefore, we choose the local superior cotton variety (Lumian 532) with high yield as the material, in the present study, we assessed the cotton yield, biomass accumulation and distribution, nitrogen absorption and utilization efficiency, and other parameters by setting four nitrogen allocation ratios (3:5:2, 0:10:0, 3:7:0, and 0:7:3) when the nitrogen application rates were 0, 150, 220, and 300 kg hm^{-2}. The results showed that when the nitrogen application rate was 300 kg hm^{-2}, the growth index, biomass, nitrogen content, and yield of Lumian 532 were the highest, while the nitrogen partial productivity (12.2 and 12.8) was the lowest. When the nitrogen application rate was 220 kg hm^{-2} and the nitrogen allocation ratio was 3:5:2, the agronomic nitrogen use efficiency (3.2 and 3.5) and nitrogen physiological (24.8 and 25.0) was achieved. When the nitrogen application rate was 150 kg hm^{-2}, the nitrogen partial productivity (20.6 and 20.9) was the highest. In conclusion, the biomass accumulation and distribution, nitrogen use efficiency, yield, and yield composition of Lumian 532 could be effectively regulated by appropriate nitrogen application rate and nitrogen allocation ratio. Therefore, to optimize the yield and improve the nitrogen use efficiency, the optimal nitrogen application rate of Lumian 532 was 220 kg hm^{-2}, and the optimal nitrogen allocation ratio was 3:5:2 in the North China Plain. The results provided practical basis for nutrient demand, cotton yield and ecological protection in different growth stages of cotton in North China Plain.

Keywords: cotton; nitrogen split ratio; biomass accumulation; nitrogen accumulation; nitrogen utilization

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1. Introduction

As an important and widely planted cash crop, cotton (*Gossypium barbadense* L.) has the highest yield of fiber crops [1]. The growth and development of cotton are affected by genetic, environmental, and cultural factors [2]. Among them, nitrogen is involved in all processes of cotton plant metabolism, which is one of the primary limiting factors for cotton quality and high yield [3]. Therefore, the application of nitrogen fertilizer has been emphasized as a critical measure to improve cotton yield [4]. In actual agricultural production, when the nitrogen uptake of the crop is deficient, the growth of above-ground parts and roots of crops is significantly inhibited [5,6], hindering the formation of reproductive organs and fruit development [7]. Negative environmental impacts caused by excessive nitrogen application of cotton are harmful to both consumers and growers [8]. Therefore, proper nitrogen application during the growth process can enhance cotton yield and fiber quality [9,10].

There are significant differences in nutrient demand characteristics of cotton at various growth stages [11]. The demand of nitrogen fertilizer was high in the early flowering period and decreased in the later growing period [12]. Nitrogen (N) is a key component of chlorophyll, nucleic acids, and amino acids in plants [13]. Prior to flowering, a moderate increase in nitrogen will promote the growth of crop roots [5]. The accumulation of above-ground biomass will be promoted at the flowering stage [6]. It promotes the development of reproductive organs and fruits in the later stages of growth [7]. Kumar et al. [14] have found that nitrogen plays a vital role in plant growth and leaf area, which will further affect the biomass and yield of crops. Therefore, compared with other growth periods, cotton absorbs the most nitrogen at the flowering stage [15]. However, Luo et al. [16] have shown that a small amount of fertilization at the early flowering stage of cotton is more beneficial to the utilization of cotton nutrients. Moreover, the effect of fertilization in the early flowering period is better than that in other stages. Wu et al. [7] have reported that an appropriate amount of nitrogen fertilizer applied at the later growth stage of cotton can improve the chlorophyll content and photosynthetic rate of cotton leaves and delay leaf senescence. Similarly, Raphael et al. [17] have shown that fertilization in the later growth stage of cotton will affect the formation of photosynthates, thus improving cotton yield.

The yield and quality of cotton are also affected by the proportional application of nitrogen fertilizer during its growing period. Liu et al. [12] have shown that one-time input of nitrogen fertilizer leads to a decrease in the cotton harvest index and seed cotton yield. However, Luo et al. [18] have suggested that one-time fertilization at the beginning of flowering can improve lint yield and dry-matter weight. Nitrogen application can improve the yield and quality of winter wheat by regulating its antioxidant capacity [19]. Under the condition of a certain nitrogen application rate, a fixed nitrogen allocation ratio of 40% at the flowering stage can enhance cotton biomass, harvest index, and yield [20]. However, Li et al. [21] have applied 270 kg hm^{-2} nitrogen and found that 70% fertilization at the flowering stage can promote nitrogen uptake and utilization efficiency of cotton. Similarly, the study of Cetin and Uzen [22] has proved that under a certain nitrogen application rate, a reasonable nitrogen application frequency is beneficial to the accumulation of cotton yield. Therefore, it is important to determine the appropriate nitrogen application period and proportion in improving cotton yield and reducing nitrogen loss.

Improving cotton nitrogen use efficiency (NUE) remains one of the key factors in ensuring the sustainable development of cotton production [23]. Irrational application of nitrogen fertilizer can cause a significant decrease in NUE in farmland [24] and an increase in production cost, while the yield benefit remains unchanged. Genotype, irrigation amount, nitrogen application amount, nitrogen application frequency and agronomic methods all affected nitrogen-use efficiency [12,25]. Eliezer et al. [26] have shown that the lack of nitrogen in the early stage of cotton results in a decrease in NUE. However, Iqbal et al. [27] have shown that reducing the nitrogen supply can improve NUE. Therefore, how to improve the utilization rate of nitrogen fertilizer is a major challenge to be solved by all the scientists engaged in agricultural work at present.

The North China Plain is one of the three major cotton producing areas in China [28]. Most studies have focused on the effects of nitrogen application on cotton yield and fiber quality. However, there are few studies on the proportion and period of nitrogen fertilizer application in cotton in the North China Plain, and the conclusions remain controversial. Therefore, the dynamic changes of nitrogen uptake in cotton plants were studied through the proportion and period of nitrogen application in cotton. The nitrogen content and proportion of cotton were optimized to explore the nitrogen demand in the critical period of cotton. We hypothesized that one-time fertilization with a nitrogen application rate over 300 kg hm^{-2} could neither improve NUE nor increase seed cotton yield by optimizing biomass accumulation and allocation. In the present study, we aimed to determine the effects of the nitrogen application ratio and nitrogen allocation ratio at different periods on (a) biomass accumulation and allocation, (b) cotton yield and yield composition, and (c) NUE. Collectively, our findings provided a theoretical and practical basis for the efficient use of nitrogen fertilizer in the North China Plain.

2. Materials and Methods

2.1. Experimental Sites and Cultivars

Two field experiments were conducted at different locations in China in 2020. The first experiment was carried out in Ningjin experimental area (116.47° E, 37.39° N). The second experiment was conducted in Changyi City (119.24° E, 39.52° N). In Ningjin experimental area, the soil organic matter content was 10.5 g kg^{-1}, the alkali-hydrolyzed nitrogen content was about 63.86 mg kg^{-1}, the available phosphorus content was 20.1 mg kg^{-1}, the available potassium content was 115.0 mg kg^{-1}, and pH was 8.38. In the Changyi experimental area, the soil organic matter content was 12.1 g kg^{-1}, the alkali-hydrolyzed nitrogen content was about 86.1 mg kg^{-1}, the available phosphorus content was 38.0 mg kg^{-1}, the available potassium content was 125.3 mg kg^{-1}, and pH was 8.6. The information on temperature and rainfall in the two experimental areas is shown in Figure 1.

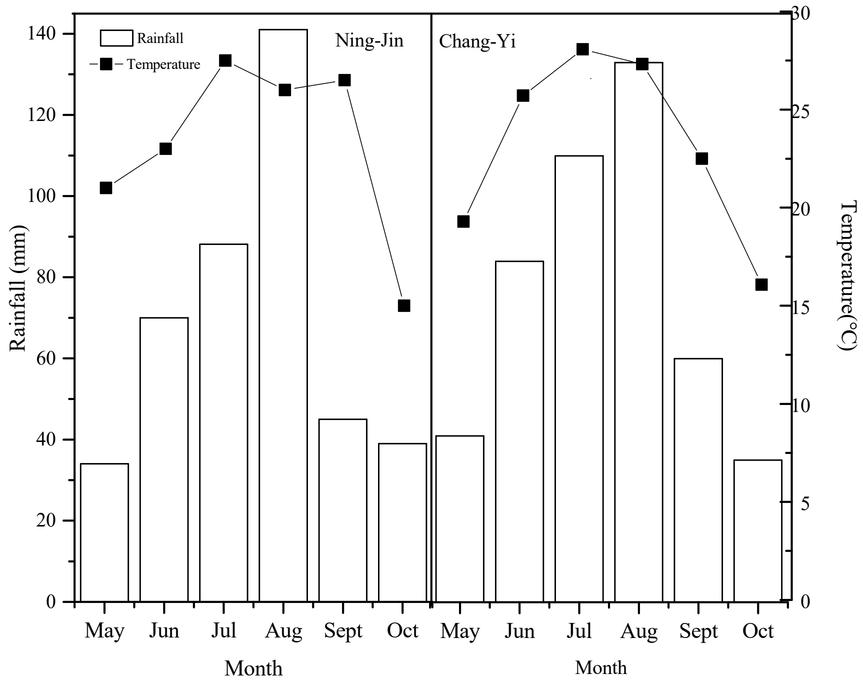

Figure 1. Average temperature and rainfall for cotton growing months in 2020.

Shan Dong dominant cotton variety, Lumian 532, was used in the experiment. Lumian 532 is an early-maturing variety with rapid emergence, stable growth throughout the growth period, high yield, and high resistance and other advantages.

2.2. Experimental Design and Field Management

There were seven treatments in our experiment (Table 1). The plots were assigned according to four nitrogen application (in the form of urea) rates: 0, 150, 220, and 300 kg hm^{-2}, hereafter referred to as N0, N1, N2, and N3, respectively. The experimental plots with a nitrogen application rate of 220 kg hm^{-2} were further divided into four groups according to four nitrogen allocation ratios (3:5:2; 0:10:0; 3:7:0; and 0:7:3), hereafter referred to as N2a, N2b, N2c, and N2d, respectively.

Table 1. Proportion and period of nitrogen fertilizer application in each treatment.

Treatment	Fertilization Period and Proportion	The Nitrogen Application Rate
N2a	Seeding period:First flowering stage:Full bloom period = 3:5:2	220 kg hm^{-2}
N2b	Seeding period:First flowering stage:Full bloom period = 0:10:0	220 kg hm^{-2}
N3	Seeding period:First flowering stage:Full bloom period = 3:5:2	300 kg hm^{-2}
N2c	Seeding period:First flowering stage:Full bloom period = 5:7:0	220 kg hm^{-2}
N1	Seeding period:First flowering stage:Full bloom period = 3:5:2	150 kg hm^{-2}
N2d	Seeding period:First flowering stage:Full bloom period = 0:7:3	220 kg hm^{-2}
N0	No fertilizer	0 kg hm^{-2}

Note: N2a, N2b, N3, N2c, N1, N2d and N0 represent the proportion of nitrogen fertilizer applied.

The plots were arranged in random blocks and repeated three times, with a total of 21 plots. The experiment was carried out in Ningjin and Changyi according to the same treatment, and the total area of each experimental area was 0.1 hm^2. The length of each plot was 10 m, and the planting density was 90,000 plants per hectare with six rows and a row spacing of 66 cm. The ridges of 0.3 m were left between each plot, and drains of 1 m were left between the ridges to discharge rainwater. Test fertilizer: urea (46% nitrogen) was used as nitrogen fertilizer, and the amount of fertilizer applied was according to the experimental layout. The phosphorus fertilizer dosage was (P_2O_5) 54 kg hm^{-2}. The potassium fertilizer dosage (K_2O) was 180 kg hm^{-2}. The fertilization depth was 10–15 cm. Both P and K fertilizers were used as base fertilizers.

The seeds were sown between 21 and 24 May. The second true leaf of the cotton seedling was expanded and fixed according to the density required by the test. Irrigation, fertilization, chemical control, and other field management were uniform.

2.3. Index Determination

2.3.1. Plant Traits

A total of 20 cotton plants were selected from each plot to investigate plant height, number of fruit branches, and boll number in September [29]. Their averages were taken as plant traits per plant.

2.3.2. Plant Biomass

Cotton was sampled for the dry matter at the stages of emerging bud, flowering, full flower (the first flower on the fourth fruit branch), and opening. The samples were weighed according to the reproductive organs (buds and flower bolls) and vegetative organs (roots, stems, and leaves). Four plants were taken from each plot, placed in an oven at 105 °C for 30 min, and dried at 80 °C to constant weight, and the biomass of each plant was recorded [29].

2.3.3. Nutrient Content of Reproductive and Vegetative Organs [30]

Four cotton plants were taken from each plot at the bud, flowering, full flower, and opening stages. There were three replicates for each treatment. The reproductive organs and vegetative organs were dried separately and crushed using a 1 mm sieve. Subsequently, 0.1 g of the sample was weighed, and then the nitrogen content of plants was determined by KjeLSampler K-37.

2.3.4. Production

Briefly, 20 cotton plants with uniform and continuous growth were selected in the middle four rows of each plot. According to the number of fruit branches, it was divided into two parts. The number of bolls was recorded and weighed. After tying the flowers, the lint was weighed to calculate the lint yield [20].

2.3.5. Nitrogen-Related Conversion Rate [21]

$$\text{NAE (kg/kg)} = (\text{Y} - \text{Y0})/\text{F};$$

$$\text{NPE (kg/kg)} = (\text{Y} - \text{Y0})/(\text{N} - \text{N0});$$

$$\text{PFPN (kg/kg)} = \text{Y}/\text{F}.$$

where NUE represents agronomic nitrogen use efficiency; Y and Y0 are the cotton grain yield obtained (kg ha^{-1}) in the presence or absence of nitrogen treatment, respectively; F is the nitrogen applied; NAE represents agronomic nitrogen use efficiency; NPE represents nitrogen physiological efficiency; N and N0 are the total nitrogen uptake of plants in the presence or absence of nitrogen treatment, respectively; and PFPN represents the partial factor productivity of nitrogen.

2.4. Statistical Analysis

Excel (Microsoft Office, 2019) was used for data processing and statistical analysis, Origin8.0 software was used for plotting, and the LSD method was used for the significance test.

2.5. Statement

Plants (either cultivated or wild), including the collection of plant material, complied with relevant institutional, national, and international guidelines and legislation.

3. Results

3.1. Nitrogen Application Rate and Nitrogen Allocation Ratio Affect the Growth Characteristics of Cotton

The nitrogen application rate and nitrogen allocation ratio significantly affected cotton growth traits (Table 2). In the Ningjin and Changyi experimental areas, the same nitrogen application rate had no significant difference on the growth characteristics of cotton in different experimental areas. Both N2a and N3 treatments significantly increased plant height, fruit branch number, and boll number of cotton in Ningjin and Changyi experimental areas, while there was no significant difference between N2a and N3 treatments. The plant height, fruit branch number, and boll number were significantly higher in Ningjin N2a than those values in N2b by 7.3, 22.3, and 8.4%, respectively. The plant height, fruit branch number, and boll number were significantly higher in Changyi N2a than those values in N2b by 16.4, 28.9, and 21.1%, respectively. The plant height, fruit branch number, and boll number in Ningjin N2a were slightly higher (15.5, 50.8, and 11.0%) than those values in N0. The plant height, fruit branch number, and boll number of Changyi N2a were increased by 21.5, 49.9, and 52.2% compared with N0, respectively.

Table 2. Plant traits under different nitrogen treatments.

Treatment	Plant Height (cm)		Branch Number		The Bell Number	
	Ning-Jin	Chang-Yi	Ning-Jin	Chang-Yi	Ning-Jin	Chang-Yi
N2a	75.2 a	78.2 a	9.2 a	9.8 a	10.3 a	10.9 a
N2b	70.1 e	67.2 e	7.5 c	7.6 c	9.5 c	9.0 c
N3	74.8 b	76.0 b	9.1 a	9.6 a	10.1 a	11.1 a
N2c	74.2 c	75.2 b	8.4 b	8.3 b	10.0 b	10.3 b
N1	74.1 c	73.6 c	8.3 b	8.6 b	9.8 b	9.6 c
N2d	73.1 d	69.5 d	8.3 b	7.5 c	9.6 c	9.5 c
N0	65.1 f	64.3 f	6.1 d	6.6 d	9.3 d	8.8 d

Notes: N2a, N2b, N3, N2c, N1, N2d and N0 represent the proportion of nitrogen fertilizer applied. Different lowercase letters in the same column indicated significant differences in plant traits among different nitrogen application treatments ($p < 0.05$).

3.2. Dry Matter of Reproductive and Vegetative Organs

The application of nitrogen fertilizer in a certain proportion during the growing period is more conducive to the accumulation of plant dry matter. As the growth period advanced, the cotton dry-matter weight was gradually increased (Figure 2) in Ningjin and Changyi experimental areas. In the two experimental areas, the dry-matter weight of N2a, N3, N2c, and N1 treatments was significantly higher than those of N2b, N2d, and N0 treatments in the bud stage. In the bud stage, the dry-matter weight of vegetative organs accounted for 94.5, 91.4, 95.1, 96.4, 94.3, 93.4, and 93.4%, of the total dry weight in the above-mentioned treatments, respectively. In the Ningjin and Changyi experimental areas, the N3 treatment had the highest dry-matter weight at the flowering stage, which was 47.9 and 50.0% higher than that of the N1 treatment, respectively. In the flocculation period, the dry-matter weight of the N2a treatment in Ningjin and Changyi experimental areas was significantly increased by 5.7 and 8.1% than that in the N2c treatment, respectively. In the flocculation stage, the dry matter of reproductive organs was increased more, and N2a treatment was significantly higher than N0 treatment by 84.6 and 103.3%. At the same time, the dry-matter weight of vegetative organs accounted for 64.8, 76.9, 64.4, 65.6, 73.7, 69.9, and 74.0% of the total dry weight, respectively.

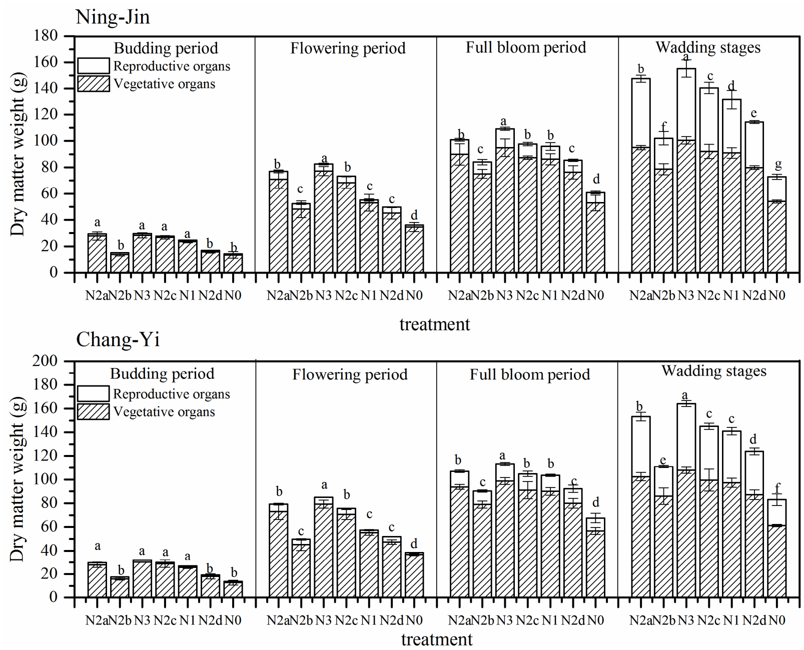

Figure 2. Dry matter accumulation in vegetative and reproductive organs of cotton. N2a, N2b, N3, N2c, N1, N2d and N0 represent the proportion of nitrogen fertilizer applied. The small letters in the figure indicate that there were significant differences in dry matter among different nitrogen treatments ($p < 0.05$).

3.3. Effects of Different Nitrogen Application Ratios on the Nitrogen Content of Cotton

The nitrogen content and allocation ratio affected nitrogen content in reproductive and vegetative organs of cotton (Figure 3). With the development of the growth period, the ratio of total content to the mass of cotton was decreased gradually. At the budding stage, the total nitrogen mass ratio of the N3 treatment was the highest in both test areas. Moreover, the total nitrogen mass ratio of N3 and N2c treatments in the Ningjin experimental area was 15.6 and 17.8% higher than that in the N1 and N2d treatments, respectively. In addition, the total nitrogen mass ratio of N3 and N2c treatments in the Changyi experimental area was 12.5 and 15.1% higher than that in the N1 and N2d treatments, respectively. At the flowering stage, the total nitrogen content in the Ningjin and Changyi experimental areas treated with N3 was 9.1 and 8.9% higher than that that treated with N2a, respectively. The total nitrogen content treated by N3 was 5.9 and 6.8% higher than that treated by N2c in the Ningjin and Changyi experimental areas, respectively. In the flocculation period, the total nitrogen content of the N3 treatment was 11.0 and 10.5% higher than that of the N1 treatment in the Ningjin and Changyi experimental areas.

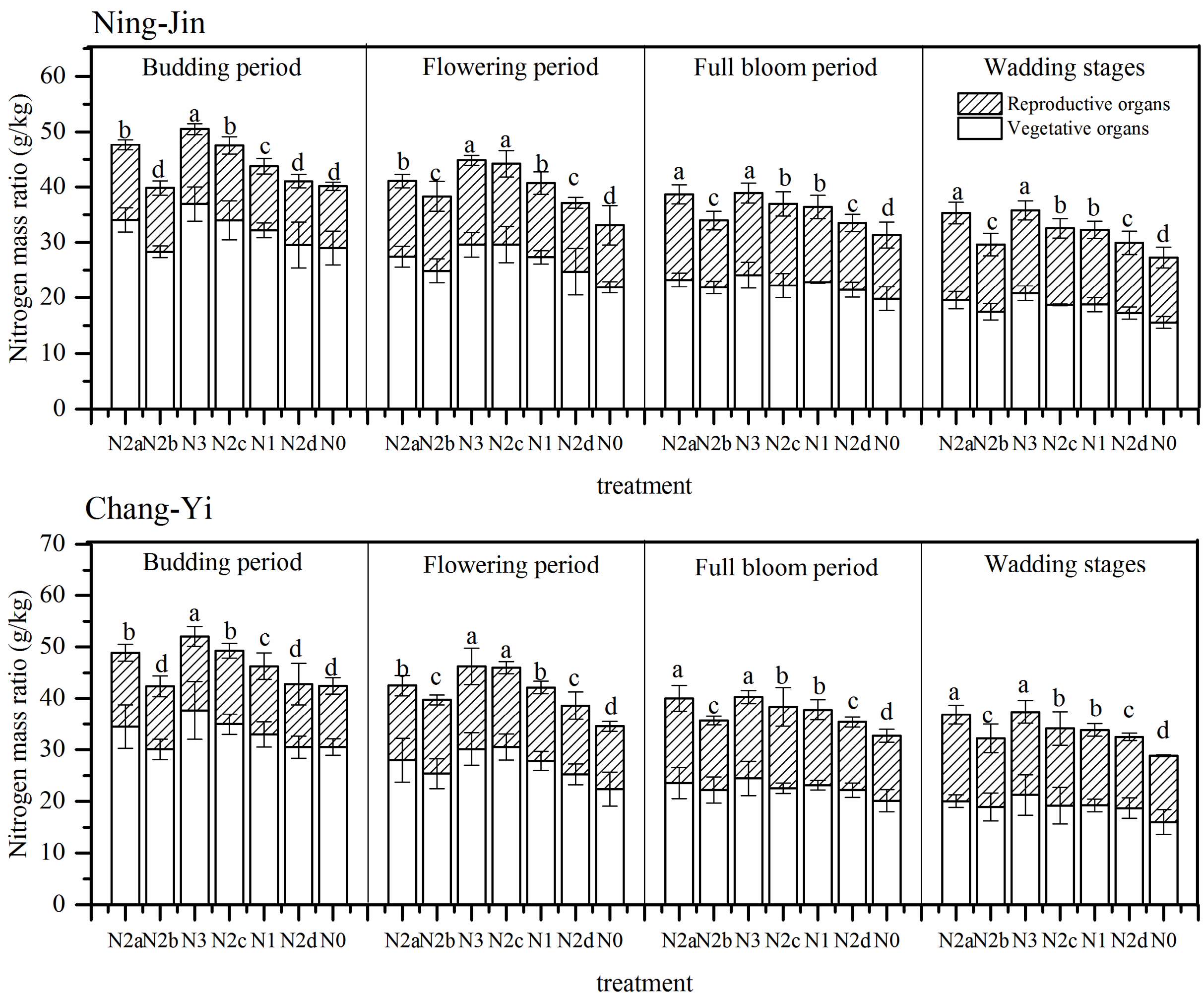

Figure 3. Mass ratio of nitrogen content in vegetative and reproductive organs of cotton. N2a, N2b, N3, N2c, N1, N2d and N0 represent the proportion of nitrogen fertilizer applied. Small letters in the figure indicate significant differences in the mass ratio of nitrogen in cotton under different treatments ($p < 0.05$).

3.4. Effects of Different Nitrogen Treatments on Cotton Yield and Component Factors

The boll density and single-boll weight of cotton could be significantly changed by adjusting the nitrogen application rate and nitrogen application ratio, thus increasing the yield of seed cotton and lint (Table 3). The results showed that the boll density, boll weight, seed cotton, and lint cotton yield of the N3 treatment were the highest in the Ningjin and Changyi experimental areas. In contrast, the boll density, boll weight, seed cotton, and lint yield of the N0 treatment were the lowest. The grain cotton yield of the N3 treatment in the Ningjin experimental area was 5.0 and 18.5% higher than that of the N2a and N1 treatments, respectively. The lint yield of the N3 treatment was 5.9 and 5.0% higher than that of the N2a treatment in the Ningjin and Changyi experimental areas, respectively. The grain cotton yield of the N3 treatment in the Changyi experimental area was 5.7 and 23.4% higher than that of the N2a and N1 treatments, respectively. However, the grain cotton yield of the N2a treatment in the Ningjin and Changyi experimental areas was 21.9 and 21.6% higher than that of the N2b treatment, respectively.

Table 3. Cotton yield and constituent factors under different nitrogen treatments.

Treatment	Boll Density (no./m^2)		Single Boll Weight (g)		Seed Cotton Yield (kg/ha)		Lint Weight (kg/ha)	
	Ning-Jin	Chang-Yi	Ning-Jin	Chang-Yi	Ning-Jin	Chang-Yi	Ning-Jin	Chang-Yi
N2a	90.9 b	93.1 b	4.2 b	4.3 b	3497.8 b	3669.3 b	1447.2 b	1518.4 b
N2b	85.5 d	86.1 e	3.8 d	4.0 d	2869.7 d	3018.4 d	1189.7 d	1250.0 d
N3	92.7 a	97.9 a	4.3 a	4.4 a	3671.1 a	3840.1 a	1532.8 a	1594.9 a
N2c	86.9 c	88.9 cd	4.1 c	4.2 c	3053.1 c	3178.4 c	1251.7 c	1303.1 c
N1	87.2 c	89.5 c	4.1 c	4.2 c	3094.4 c	3143.1 c	1268.7 c	1288.6 c
N2d	86.4 c	87.7 de	4.1 c	4.2 c	2901.8 d	3048.8 d	1227.6 d	1276.6 d
N0	80.1 e	79.2 f	3.7 e	3.9 e	2793.7 e	2897.4 e	1121.4 e	1187.9 e

Notes: N2a, N2b, N3, N2c, N1, N2d and N0 represent the proportion of nitrogen fertilizer applied. Different lowercase letters in the same column indicated significant differences in cotton yield and constituent factors among different nitrogen treatments ($p < 0.05$).

3.5. Effects of Different Nitrogen Application Treatments on the Nitrogen Utilization of Cotton

The effects of agronomic NUE, NPE, and PFPN were different (Table 4). In terms of NUE and NPE, the results of Ningjin and Changyi showed N2a > N3 > N1 > N2c > N2d > N2b. In the Ningjin and Changyi experimental areas, the NUE of N2a was 10.3 and 12.9% higher than that of N3, and the NPE of N2a was 7.8 and 5.9% higher than that of N3, respectively. In terms of PFPN, the results of Ningjin and Changyi exhibited N1 > N2a > N2c > N2b > N2d > N3. In the Ningjin and Changyi experimental areas, the PFPN of N2a was 29.5% and 29.7% higher than that of N3, respectively.

Table 4. Nitrogen utilization rate of cotton under different nitrogen application treatments.

Treatment	Agronomic Nitrogen Use Efficiency (kg/kg)		Nitrogen Physiological Efficiency (kg/kg)		Nitrogen Partial Productivity (kg/kg)	
	Ning-Jin	Chang-Yi	Ning-Jin	Chang-Yi	Ning-Jin	Chang-Yi
N2a	3.2 a	3.5 a	24.8 a	25.0 a	15.8 b	16.6 b
N2b	0.3 e	0.5 e	6.2 f	7.1 f	13.0 d	13.7 d
N3	2.9 b	3.1 b	23.0 b	23.6 b	12.2 e	12.8 e
N2c	1.2 d	1.3 d	9.6 d	9.7 d	13.8 c	14.4 c
N1	2.0 c	1.6 c	13.6 c	10.7 c	20.6 a	20.9 a
N2d	0.4 e	0.6 e	7.2 e	8.5 e	13.1 d	13.8 d
N0	--	--	--	--	--	--

Notes: N2a, N2b, N3, N2c, N1, N2d and N0 represent the nitrogen conversion rate. Different lowercase letters in the same column indicate significant difference in nitrogen conversion rate among cotton with different nitrogen treatments ($p < 0.05$).

4. Discussion

A suitable nitrogen application ratio significantly improves the growth characteristics of cotton. The plant height, fruit branch number, and boll number of N2a in Ningjin were significantly higher than those of N2b by 7.3, 22.3, and 8.4%, respectively. Moreover, the plant height, fruit branch number, and boll number of N2a in Changyi were 16.4, 28.9, and 21.1% higher than those of N2b, respectively. We believed that the poor growth traits of N2b were attributed to the relative lack of nutrients in the early stage of cotton, which did not provide good nutritional conditions for the growth of vegetative organs [31]. Therefore, the reproductive organs (bolls) of cotton in the later period of growth lacked sufficient sources of nutrition, and one-time fertilization could not improve the growth characteristics of cotton. Similarly, Tang et al. [32] have also shown that low nitrogen treatment at the early growth stage of cotton can reduce the carbohydrate of cotton boll and leaf fiber, which is unfavorable to cotton growth and boll development.

There are significant differences in the nutrient requirements of cotton at various growth stages [11]. Therefore, an appropriate nitrogen application rate and nitrogen allocation ratio are beneficial to dry-matter accumulation in plants [20,22]. At the flowering stage, the quality of dry matter treated with N3 in the Ningjin and Changyi experimental areas was the highest, and its value in N3 was 47.9 and 50.0% higher than that in N2a, respectively. This finding indicated that a large supply of nitrogen fertilizer was needed during the flowering period [15]. In the late growth period, N2a treatment significantly increased the dry matter by 54.6 and 73.3% compared with N2b treatment in the Ningjin and Changyi experimental areas, respectively. In addition, the dry-matter weight of vegetative organs in the bud stage accounted for 94.5, 91.4, 95.1, 96.4, 94.3, 93.4, and 93.4% of the total dry weight, respectively. The dry-matter weight of vegetative organs in the flopping stage accounted for 64.8, 76.9, 64.4, 65.6, 73.7, 69.9, and 74.0% of the total dry weight, respectively. The change in dry-matter proportion in reproductive organs was caused by the gradual transfer of nitrogen to reproductive organs in the later growth period.

Nitrogen is a vital component of biomacromolecules in plants [13]. Nitrogen absorbed by crops is coordinated with protein metabolism and carbon metabolism through various physiological processes, such as reduction, transport, and metabolism, to form the basic process of plant activities [33]. In the bud stage, N3 treatment in the Ningjin and Changyi experimental areas was 15.6 and 12.5% higher than N1, respectively. It was 9.1 and 8.9% higher at the flowering stage and 11.0 and 10.5% higher in the flopping stage. According to the rules of nitrogen absorption and utilization during cotton growth, the plant growth accelerates at the bud stage and enters a stage of simultaneous vegetative growth and reproductive growth, the root system expands rapidly [7], and the fertilizer absorption capacity is significantly enhanced. The flowering and boll stage is the key period for yield [34]. The vegetative growth of cotton plants at the full flowering stage reaches its peak and then switches to reproductive growth. At the batting stage, the growth of cotton is weakened, the absorption capacity is reduced, and the absorption intensity is also significantly decreased [2].

Choosing the right fertilizer regime for a crop in a given location is crucial for yields, environmental protection, and sustainable development. An increase in boll biomass under nitrogen treatment (240 kg hm^{-2}) was associated with a significant increase in root systems, especially shallow roots, resulting in an increase in cotton seed yield [35]. Similarly, Luo et al. [36] have shown that a reasonable nitrogen application rate will improve cotton yield and NUE. Our study showed that the seed cotton yield of the N3 treatment in the Ningjin experimental area was 5.0 and 18.5% higher than that of the N2a and N1 treatments, respectively, and the seed cotton yield of the N3 treatment in the Changyi experimental area was 5.7 and 23.4% higher than that of N2a and N1 treatments, respectively. Therefore, increasing the nitrogen application rate could promote cotton yield [37]. Ensuring adequate nutrient supply is the key to obtaining higher yields and benefits from cotton [38]. The yield of seed cotton treated with N2a in the Ningjin and Changyi experimental areas was 21.9 and 21.6% higher than that treated with N2b, respectively. This finding suggested that a suitable nitrogen allocation ratio was beneficial to increasing cotton yield [12]. Therefore, it is a labor-saving method to apply nitrogen fertilizer on cotton at one time, while it is not suitable to apply it on medium-fertility soil with a similar ecological environment, such as the Yellow River Basin. This conclusion was also supported by Liu et al. [12].

Nitrogen use affects cotton yield and NUE [39]. Therefore, we analyzed the synergistic relationship between nitrogen uptake and yield by means of agronomic NUE, NPE, and PFPN. The study on NUE showed that the maximum NUE was obtained when the nitrogen application rate was 220 kg hm^{-2} and the nitrogen allocation ratio was 3:5:2. The PFPN of cotton was the highest at 150 kg hm^{-2} and the lowest at 300 kg hm^{-2}. The results showed that the yield and nitrogen accumulation of cotton were increased with the increase in nitrogen application rate, while the NUE was decreased. This finding was also consistent with a previous study [40,41]. The model of high yield under high fertilizer application will result in a low fertilizer-utilization rate, and to some extent, it will bring about farmland pollution [38]. Therefore, with the premise of maintaining cotton yield, reducing nitrogen application and adopting protective measures can improve cotton NUE and reduce the risk of nitrogen point source pollution [42,43].

In addition, we take into account the variety, planting density, local climate, soil fertility and other factors on the growth of cotton [44]. Therefore, similar tests should fully consider the above factors. Before planting cotton, we need to fully understand the planting environment and the law of cotton growth and development, so that the fertilizer supply conforms to the law of cotton growth and development [45]. At the same time, considering the influence of environmental factors, we adopt appropriate cultivation techniques to increase cotton production. Therefore, based on the accurate diagnosis and dynamic control of crop nitrogen nutrition, it is necessary to determine the accurate and reasonable application of nitrogen fertilizer, so as to prevent the abuse, waste or loss of nitrogen fertilizer, and effectively improve crop yield and crop quality. It also has positive effect on preventing nitrogen fertilizer pollution in the field environment. This is good for the environment and good for growers. Therefore, the economic and ecological benefits of cotton production in the Yellow River Basin can be created with an appropriate total nitrogen application rate and fertilizer ratio at different growth stages.

5. Conclusions

In the present study, we clearly demonstrated the effects of nitrogen application rate and nitrogen allocation ratio on cotton growth indices, biomass, nitrogen content, yield, and NUE. The most important finding was that the growth index, biomass, nitrogen content, and cotton yield were the highest when the nitrogen application rate was 300 kg hm^{-2}, while the PFPN was the lowest. When the nitrogen application rate was 220 kg hm^{-2} with a nitrogen allocation ratio of 3:5:2, cotton had the highest agricultural and physiological NUE and the second highest yield. Therefore, based on the rational use of nitrogen fertilizer and sustainable development of the environment, it is more beneficial to the cotton yield and use of nitrogen fertilizer in North China Plain when the nitrogen application rate is 220 kg hm^{-2} with a nitrogen allocation ratio of 3:5:2. The results provided a practical basis for nutrient demand, cotton yield and ecological protection in different growth stages of cotton in North China Plain. At the same time, in view of the nitrogen fertilizer use efficiency of cotton, the application amount of alternative organic fertilizers should be studied, and the organic fertilizers of different sources should be uniformly standardized. Under the concept of green agriculture development, soil testing and formulation technology should be actively applied to guide agricultural fertilization.

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