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The Yield-Forming Role of Nitrogen in Rice in the Growing Seasons with Variable Thermal Conditions

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Abstract: A reduced basal and increased topdressing fertilizer rate (RBIT) can usually increase rice yield, but whether this practice alleviates the impact of poor weather on rice production is unknown. Thus, the effect of three integrated RBIT treatments (RBITs, including RBIT alone, RBIT in combination with straw incorporation (RBITS) or a reduced fertilizer rate (RBITR)) on rice growth and nutritional status under different weathers was investigated in a 9-year experiment. Conventional fertilization (CF) was the control. We found that daytime temperature and light (DTL) after heading were the main meteorological factors limiting rice yield increases. RBITs did not affect rice yield under High-DTL, compared with CF, but RBITS significantly increased rice yield under Low-DTL. Compared with High-DTL, the positive effect of RBIT and RBITR on the N concentration and proportion in vegetative organs under Low-DTL was higher than the K concentration in vegetative organs, but RBITS showed the opposite trend. Regression analysis indicated that the harvest index had stronger correlations with the N concentration (negative), K concentration (positive), and N/K (negative) in vegetative organs under Low-DTL than under High-DTL. Our findings suggested that RBITS could improve rice adaptability to daytime temperature and light changes after heading by balancing crop nutritional status (N/K).

Keywords: thermal conditions; fertilization management; rice yield; nutritional balance; long-term experiment

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1. Introduction

Rice is the main staple food worldwide, covering an area of more than 140 million hectares and feeding more than half of the world's population [1–3]. Between 1961 and 2019, the world's rice production per unit area tripled due to variety renewal and chemical fertilizer application [1,4]. However, studies showed that rice production was stagnant in over 35% of the global rice planting areas and 22% of the rice–wheat rotation areas in Asia [5,6]. Climate change (e.g., extreme temperature, heavy precipitation, and low photosynthetically active radiation (PAR)) caused rice yield losses of over 10% [7–9], which was attributed to increasing maintenance energy demands and decreasing the number of photosynthetic products for yield formation. Therefore, how to adopt agricultural strategies to improve rice adaptation and reduce yield losses under poor weather conditions is essential.

Fertilization management plays an important role in rice production. Compared with farmer's conventional fertilization (CF), a reduced basal and increased topdressing fertilizer rate (RBIT) could generally increase N-use efficiency and rice yield [10–14]. This practice could provide a better synchronization of rice N demand with N supply, facilitate spikelet differentiation, and improve leaf photosynthetic capacity in the middle and late stages of growth [10–12]. However, these studies ignored the impact of weather factors (e.g., temperature, light) on rice growth, which might lead to weakening or even adverse effects on the yield-increasing effect of RBIT. The N cost of photosynthesis suggests that if this practice is still adopted under poor weather conditions (e.g., low temperature, low light) with weak photosynthesis, excess N may be retained in the vegetative organs [15–17]. There are imbalances in the growth of vegetative and reproductive parts of plants, leading to a reduction in the number of grains per unit area and the harvest index (HI) [18]. Therefore, it is necessary to assess the effect of RBIT on rice production under poor weather conditions and its underlying mechanisms.

Plant nutritional status plays a crucial role in crop tolerance or resistance to abiotic stresses [19–21]. Generally, the risk of cold damage was increased with high crop-N status [22]. Excess N could increase the lodging susceptibility of rice under shading stress, leading to yield losses [23]. Webster et al. showed that a high rate of N could increase the freezing stress of perennial ryegrass [24]. Some studies found that applying high N or K fertilizers could compensate for the weak photosynthesis of crops under low light conditions [19,25]. Long-term experiments observed that straw incorporation could reduce the interannual fluctuation of crop yields under weather changes by improving the soil nutrient (N, K) supply capacity [26–28], implying that changing the crop nutritional status could mitigate the effects of poor weather on crop growth and achieve stable yields. Taken together, regulation of plant nutrient status through optimal fertilization strategies may improve crop tolerance or resistance to weather changes.

Long-term experiments as a key research method can effectively assess the impact of fertilization management on crop production under different weather scenarios and help to select appropriate weather change adaptation strategies [16,26–28]. Therefore, we planted the same rice variety continuously over nine years, and the objective of this study was to identify the key meteorological factors affecting rice yield and analyze the impact of integrated RBIT treatments (RBITs, including RBIT alone, RBIT in combination with straw incorporation (RBITS) or reduced fertilizer rate (RBITR)) on rice yield, biomass accumulation and nutrient (N, K) status under different weather years.

2. Materials and Methods

2.1. Experimental Site and Design

The study was conducted in Zhenjiang city, Jiangsu province, China (119°10′ E, 34°36′ W). This area is a typical rice–wheat rotation area. The climate is subtropical humid. Air temperature, PAR, and precipitation during the 2010–2018 rice season were obtained from the weather station (2009ET, WatchDog, USA/Calif.), and the average value in each rice growth stage is summarized in Figure 1. Soil type was classified as waterloggogenic paddy soil (Chinese soil taxonomy). The soil chemical parameters at the start of the experiment (2009) were shown by Zhang et al. (2021) [27].

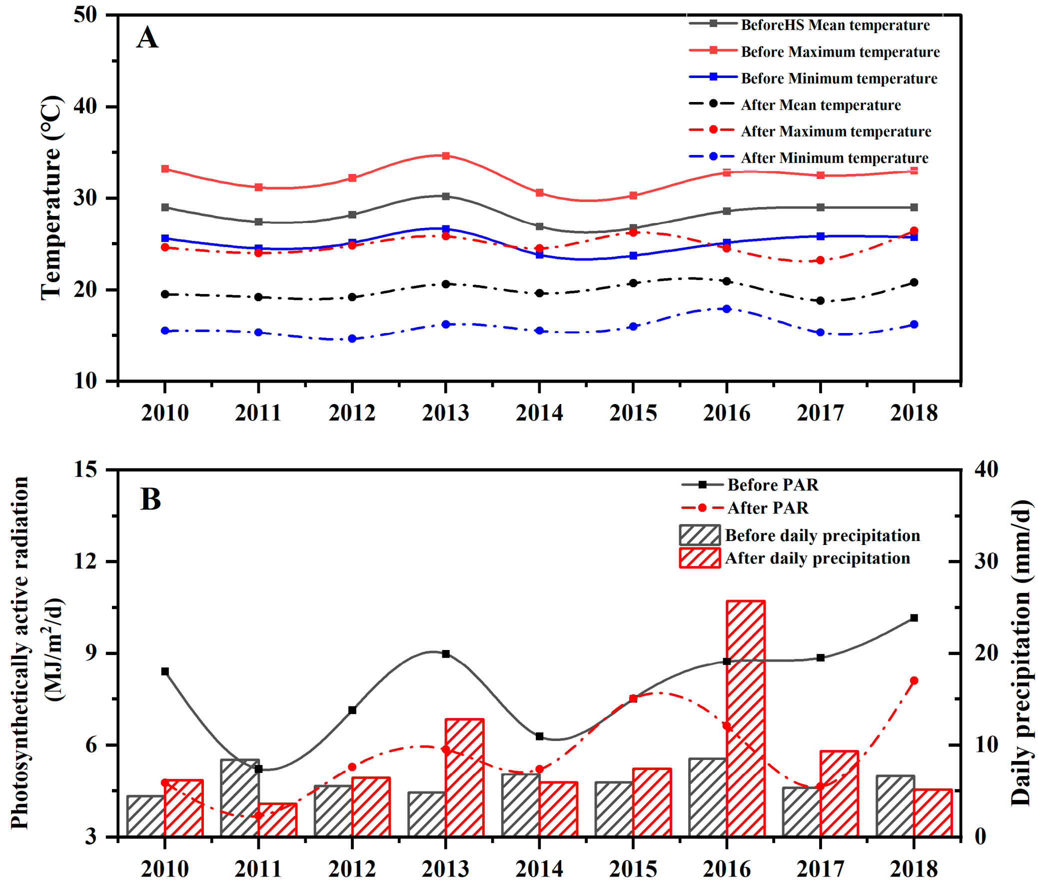

Figure 1. Air temperature (**A**), photosynthetically active radiation ((**B**), Line) and daily precipitation ((**B**), column) during the 2010–2018 rice season. Note: HS: heading stage.

2.2. Field Experiment

This study was based on a 9-year fertilization management experiment from 2010 to 2018. The same rice variety (Wuyun Geng 23#) was planted for nine years. The experiment was arranged in a completely randomized design and had four fertilization management with three replicates: CF as the control, RBIT, RBITS, and RBITR, respectively. The fertilization management for each treatment is shown in detail in Table 1. During the rice season, the total N, P and K fertilization rates were the same for CF, and RBIT at 300 kg N/ha, 150 kg P_2O_5/ha and 240 kg K_2O/ha, and 198 kg N/ha, 120 kg P_2O_5/ha and 180 kg K_2O/ha for RBITS. The N rates of the basal fertilizer, tillering fertilizer, spikelet-promoting fertilizer, and spikelet-protecting fertilizer for CF, RBIT and RBITR were 150–75–75–0, 120–60–60–60 and 79.2–39.6–39.6–39.6 kg N/ha, respectively. The P fertilizer rates of the basal fertilizer and joint fertilizers for CF, RBIT and RBITR were 150–0, 75–75 and 60–60 kg P_2O_5/ha, respectively. The K fertilizer rates of the basal fertilizer and joint fertilizers for CF, RBIT and RBITR were 240–0, 120–120 and 90–90 kg K_2O/ha, respectively. Basal fertilizers were applied once per day before ploughing at the time of rice transplantation and wheat sowing. Tiller fertilizers were applied seven days after rice transplantation and the wheat three-leaf stage. Spikelet-promoting fertilizers were applied in the rice and wheat jointing stage, and then spikelet-protecting fertilizers were applied at the appearance of the inverse 2nd leaf. For RBITS, all rice and wheat straws were returned to the subsequent crop. N, P and K fertilizers were in the form of urea, triple superphosphate, and potassium chloride, respectively. The area of each plot was 7.5 m × 4.2 m. The seeding and transplanting dates over the nine years were May 25–28 and June 18–25, respectively. Transplanting was conducted at a hill spacing of 13.3 cm × 30.0 cm with 2–3 seeding per hill. The basal fertilizers were applied one day before rice transplantation. The tilling fertilizers were applied on day 7 after transplantation. Weeds, pests and diseases were intensively controlled. Water management employed alternate dry and wet irrigation.

Table 1. Fertilizer application rates at different growth stages of rice under different fertilization management (kg/ha).

Fertilizer Period	CF	RBIT	RBITS	RBITR
Total nitrogen	300	300	300	198
Basal	150	120	120	79.2
Tilling	75	60	60	39.6
Panicle initiation	75	60	60	39.6
Spikelet differentiation	–	60	60	39.6
Total phosphorous (P_2O_5)	150	150	150	120
Basal	150	75	75	60
Jointing	–	75	75	60
Total potassium (K_2O)	240	240	240	180
Basal	240	120	120	90
Jointing	–	120	120	90

Note: CF: conventional fertilization; RBIT: reduced basal and increased topdressing fertilizer rate; RBITS: RBIT combined with straw incorporation; RBITR: RBIT combined with reduced fertilizer rate. –: no data.

2.3. Measurements and Data Analysis

At harvest, a 5 m^2 area in the middle of each plot was harvested manually to determine grain yields based on the standard moisture concentration of 13.5%. At the mature stage, the number of panicles was counted in 60 hills, and three representative hills for each plot were divided into their stem + leaf and panicle to measure the total biomass and yield components.

Plant samples were over-dried at 105 °C for 30 min and then at 80 °C; for three days. The samples were finely ground, passed through a 0.5 mm sieve, and then digested with H_2SO_4–H_2O_2 at 250–300 °C. The concentration of N and K was determined using the Kjeldahl method and flame photometry, respectively.

Soil samples (0–20 cm) were gathered using a 5-point sampling method after the rice harvest in 2018. Soil organic matter and total N were measured by the potassium dichromate oxidation method and the Kjeldahl method. Total K and available K were determined by flame photometry after being digested with H_2SO_4–H_2O_2 and extracted with 1 M NH_4OAc (pH 7.0), respectively.

2.4. Statistical Analysis

The classification of weather types was based on a cluster analysis of meteorological factors that were significantly related to rice yield. We used an independent sample *t*-test to examine the effect of weather types on meteorological factors (PAR; DMT: daytime mean temperature; NMT: night mean temperature; MT: mean temperature; MAXT: maximum temperature; MINT: minimum temperature; DMP: daily mean precipitation) using SPSS 22.0. Two-way analysis of variance (ANOVA) was used to determine rice yield, yield components, biomass, and the concentration, absorption and proportion of nutrients (i.e., weather types and treatments). Duncan's multiple range test was used to compare differences among treatments during the same weather years and soil fertility parameters at $p < 0.05$. Correlation analysis, cluster analysis, and fitting analysis were used by Origin 2017 software.

3. Results

3.1. Relationship between Rice Yield and Meteorological Factors

There were significant differences in rice yield from year to year (Figure 2A). In order to clarify the meteorological factors affecting rice yield, we found a significant positive correlation between rice yield and meteorological parameters, such as PAR (R = 0.61), DMT (R = 0.67), MT (R = 0.55), MAXT (R = 0.68), after the heading stage, and NMT (R = 0.34) during the entire growing season (Figure 2B). Therefore, we chose PAR, DMT, MT, and MAXT after heading as the classification basis and clustered the experiment years into two groups: high daytime temperament and light (High-DTL) years (2013, 2015, 2016, and 2018); low daytime temperament and light (Low-DTL) years (2010–2012, 2014 and 2017) (Figure 2C). There were significant differences in PAR, DMT, MT, and MAXT after heading between High-DTL (7.0 $MJ/m^2/d$, 20.8 °C, 22.9 °C, and 25.7 °C) and Low-DTL (4.7 $MJ/m^2/d$, 19.3 °C, 21.3 °C, and 24.2 °C) (Figure 2D).

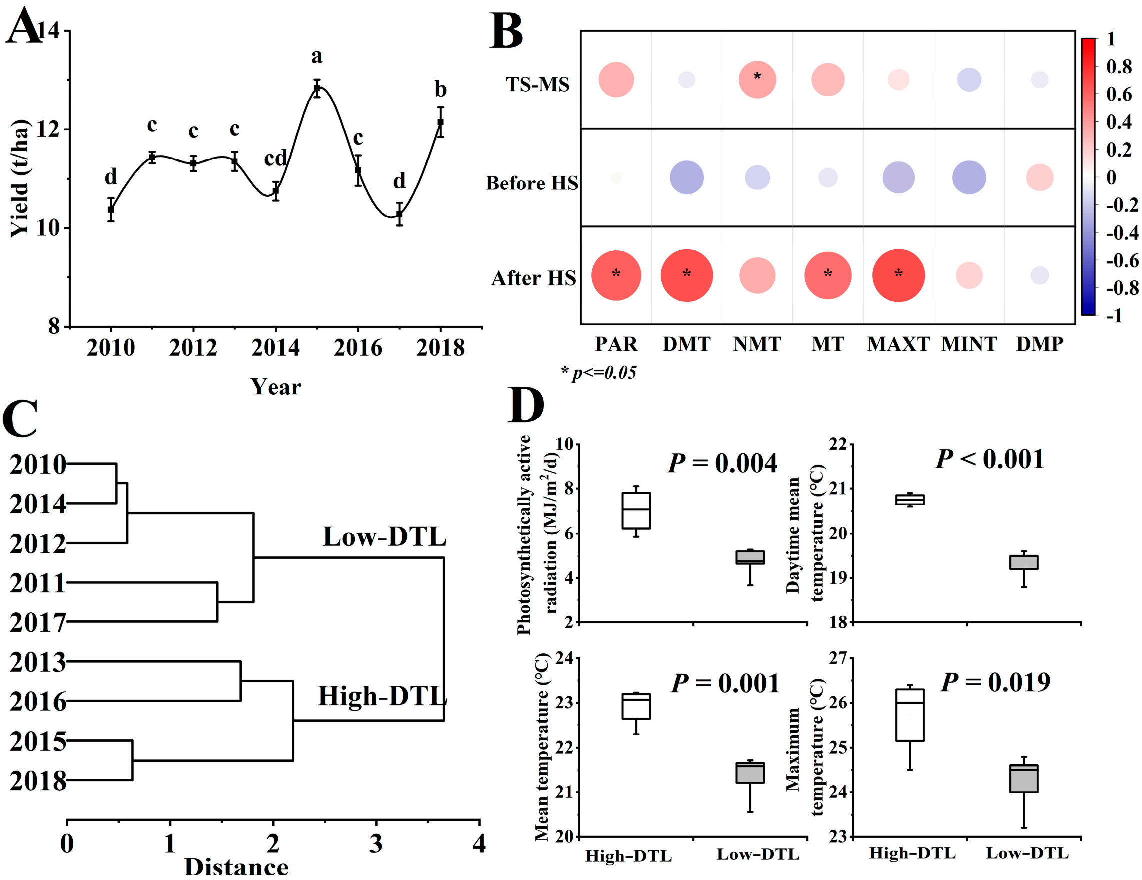

Figure 2. Annual average rice yield (**A**), the relationship between yield and meteorological parameters (**B**), the cluster analysis of temperature and light parameters after heading that were significantly related to yield (**C**), and meteorological parameters after heading (PAR, DMT, MT, MAXT) between the High-DTL and Low-DTL (**D**). The different lowercase letters indicate the difference in nutrient absorption among treatments at the $p < 0.05$ level under High-DTL and Low-DTL, respectively. Note: PAR: Photosynthetically active radiation; DMT: Daytime mean temperature; NMT: Night mean temperature; MT: Mean temperature; MAXT: Maximum temperature; MINT: Minimum temperature; DMP: Daily precipitation; TP: transplanting stage; HS: heading stage; High-DTL: High daytime temperature and light after heading; Low-DTL: Low daytime temperature and light after heading.

3.2. Effect of Fertilization Management on Rice Yield and Yield Components under Two Weather Types

Rice yield was significantly lower under Low-DTL (10.5 t/ha) than under High-DTL (11.9 t/ha) (Table 2). Compared with High-DTL, only the number of panicles and grain weight was markedly decreased under Low-DTL, while the response of grain weight (*F-value*, 66.3) to weather types was stronger than the number of panicles (*F-value*, 9.9).

Table 2. Effect of fertilization management under High-DTL and Low-DTL on rice yield and yield components.

Type	Treatment	Yield (t/ha)	No. of Panicles (/m^2)	No. of Spikelets Per Panicle	Grain Weight (mg)	Seed Setting Rate (%)
High-DTL	CF	11.6 ab	337.7 ab	123.4 c	31.2 b	90.0 a
	RBIT	12.4 a	360.7 a	130.9 b	31.4 ab	84.3 bc
	RBITS	12.2 ab	344.4 ab	138.9 a	31.2 b	82.9 c
	RBITR	11.4 b	313.1 b	126.8 bc	32.6 a	89.7 ab
	Mean	11.9	339.6	130.1	31.6	86.6
Low-DTL	CF	10.5 B	319.2 A	123.4 C	29.9 AB	89.9 A
	RBIT	10.8 B	331.6 A	129.8 BC	29.3 B	86.2 A
	RBITS	11.4 A	331.9 A	138.5 A	29.4 AB	85.3 A
	RBITR	10.6 B	304.2 B	130.8 B	30.1 A	88.7 A
	Mean	10.5	321.7	130.6	29.7	87.5
Type (TP)		59.2 **	9.9 **	0.0 ns	66.3 **	1.0 ns
Treatment (T)		3.9 *	3.9 *	11.1 **	3.8 *	3.0 *
TP × T		1.0 ns	0.2 ns	0.5 ns	1.0 ns	0.3 ns

Note: High-DTL: High daytime temperature and light after heading; Low-DTL: Low daytime temperature and light after heading; CF: conventional fertilization; RBIT: reduced basal and increased topdressing fertilizer rate; RBITS: RBIT combined with straw incorporation; RBITR: RBIT combined with reduced fertilizer rate. The different lowercase and uppercase letters indicate the difference among treatments at the $p < 0.05$ level under High-DTL and Low-DTL, respectively. *: $p < 0.05$; **: $p < 0.01$; ns: non-significance.

Compared with the CF treatment, three integrated RBITs did not markedly change rice yield under High-DTL, showing RBIT > RBITS, CF > RBITR, but only RBITS under Low-DTL significantly increased rice yield (Table 2). In terms of yield components, fertilization management significantly impacted the yield components under two weather types, except seed setting under Low-DTL. Compared with CF, RBIT, RBITS and RBITR under High-DTL increased the number of panicles by 6.8%, 2.0% and −7.3%, the number. of spikelets per panicle by 6.1%, 12.6% and 2.8% and grain weight by 0.6%, 0.1% and 4.5%, respectively, but decreased the seed setting rate by 6.3%, 7.9% and 3.3%, respectively. Under Low-DTL, RBIT, RBITS and RBITR increased the number of panicles by 3.9%, 4.0% and −4.5%, and number of spikelets per panicle by 5.2%, 12.2% and 6.0%, respectively, but decreased the grain weight by 2.0%, 1.7% and −0.7%, and seed setting rate by 4.1%, 5.1% and 1.3%, respectively.

3.3. Effect of Fertilization Management on Biomass and HI under Two Weather Types

Table 3 shows that biomass at HS (10.9 t/ha) and MS (19.0 t/ha), and HI (0.49) under Low-DTL was lower than High-DTL (12.0 t/ha, 20.4 t/ha and 0.52) (Table 3). Fertilization management under two weather types significantly affected biomass after heading and at MS but did not change biomass before HS and HI. Compared with the CF treatment, three integrated RBITs increased biomass accumulation after HS by 14.8%, 12.7% and −9.5% under High-DTL, and 18.2%, 21.9% and 7.9% under Low-DTL, respectively. This resulted in the RBITR treatment having the lowest final biomass under High-DTL and the RBITS treatment having the highest final biomass under Low-DTL among all treatments. Furthermore, compared with High-DTL, the reduction of HI in the RBITS treatment (2.3%) under Low-DTL was less than that in the CF (3.9%), RBIT (6.0%) and RBITR (7.1%) treatments, implying that RBITS could contribute to stabilizing the distribution of photosynthetic products.

Table 3. Effect of fertilization management on biomass and HI at different growth stages and harvest index under High-DTL and Low-DTL.

Type	Treatment	Biomass (t/ha)			Harvest Index
		HS	HS–MS	MS	
High-DTL	CF	12.2 a	8.0 ab	20.7 a	0.509 a
	RBIT	12.2 a	9.2 a	21.0 a	0.515 a
	RBITS	12.0 a	9.1 a	21.1 a	0.509 a
	RBITR	11.5 a	7.2 b	18.7 b	0.534 a
	Mean	12.0	8.4	20.4	0.517
Low-DTL	CF	11.3 A	7.3 B	18.5 B	0.489 A
	RBIT	10.4 A	8.7 A	19.1 B	0.484 A
	RBITS	11.2 A	8.9 A	20.4 A	0.497 A
	RBITR	10.6 A	7.9 B	18.1 B	0.496 A
	Mean	10.9	8.2	19.0	0.491
Type (TP)		18.5 **	0.6 ns	15.1 **	12.1 **
Treatment (T)		1.5 ns	8.8 **	7.7 **	1.1 ns
TP × T		0.8ns	1.0 ns	1.5 ns	0.6 ns

Note: High-DTL: High daytime temperature and light after heading; Low-DTL: Low daytime temperature and light after heading; CF: conventional fertilization; RBIT: reduced basal and increased topdressing fertilizer rate; RBITS: RBIT combined with straw incorporation; RBITR: RBIT combined with reduced fertilizer rate. HS: heading stage; MS: mature stage. The different lowercase and uppercase letters indicate the difference among treatments at the $p < 0.05$ level under High-DTL and Low-DTL, respectively. **: $p < 0.01$; ns: non-significance.

3.4. Effect of Fertilization Management on Nutrient Uptake under Two Weather Types

3.4.1. Absorption and Proportion of N and K in Rice

Weather types significantly influenced N uptake and the distribution of nutrients (N, K), showing a higher N absorption and proportion of N, K in the stem + leaf under Low-DTL than under High-DTL (Figure 3).

Fertilization management under two weather types had a significant effect on N and K uptake and N distribution but not K distribution (Figure 3). Compared with the CF treatment, the RBIT and RBITS treatments increased the total N and K absorption by 25.7%, 32.0%, 5.5% and 25.6%, respectively, under High-DTL, and 18.7%, 23.2%, 25.6% and 45.2%, respectively, under Low-DTL. However, there was no statistical difference in nutrient uptake between the RBITR and CF treatments under two weather years. Furthermore, the proportion of N in the stem + leaf was significantly increased in the RBITS treatment under High-DTL, and there was no change in the RBIT and RBITR treatments compared with the CF treatment. Notable, the proportion of N in the stem + leaf was higher in the RBIT treatment under Low-DTL than in the other treatments. These results implied that excess N in the vegetative organs of RBIT might be retained under unfavorable weather.

3.4.2. Nutrient Concentrations and N/K in Different Rice Parts

The N concentration and N/K in the stem + leaf (1.16% and 0.46) and panicle (1.41% and 2.50) were significantly higher under Low-DTL than under High-DTL (0.97% and 0.39 in the stem + leaf; 1.31% and 2.17 in the panicle), but the K concentration in the panicle was significantly lower under Low-DTL than under High-DTL (Table 4).

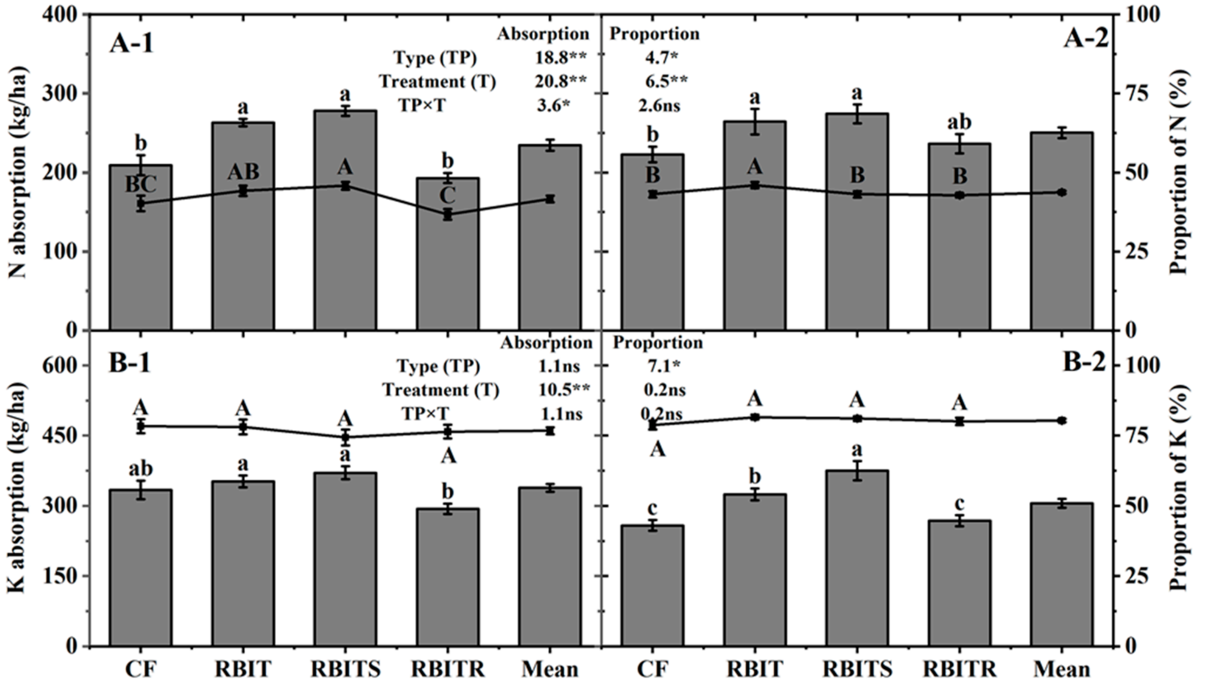

Figure 3. Effect of fertilization management on the nutrition absorption and the proportion of N and K in the stem + leaf under High-DTL (**A-1**,**B-1**) and Low-DTL (**A-2**,**B-2**). Note: High-DTL: High daytime temperature and light after heading; Low-DTL: Low daytime temperature and light after heading; CF: conventional fertilization; RBIT: reduced basal and increased topdressing fertilizer rate; RBITS: RBIT combined with straw incorporation; RBITR: RBIT combined with reduced fertilizer rate. The different lowercase letters indicate the difference in nutrient absorption among treatments at the $p < 0.05$ level under High-DTL and Low-DTL, respectively. The different uppercase letters show the difference in nutrient proportion among treatments at the $p < 0.05$ level under High-DTL and Low-DTL, respectively. *: $p < 0.05$; **: $p < 0.01$; ns: non-significance.

Table 4. Effect of fertilization management on the nutrient concentrations and N/K in different rice parts under High-DTL and Low-DTL.

Type	Treatment	N Concentration (%)		K Concentration (%)		N/K	
		Stem + Leaf	Panicle	Stem + Leaf	Panicle	Stem + Leaf	Panicle
High-DTL	CF	0.81 a	1.18 c	2.47a	0.64 a	0.33b	2.18 a
	RBIT	1.17 a	1.36 a	2.70 a	0.71 a	0.45 a	2.20 a
	RBITS	1.19 a	1.41 a	2.75 a	0.73 a	0.45 a	2.24 a
	RBITR	0.78 a	1.28 b	2.49a	0.69 a	0.33 b	2.06 a
	Mean	0.97	1.31	2.60	0.69	0.39	2.17
Low-DTL	CF	1.08 B	1.34 A	2.30 C	0.56 AB	0.49 A	2.49 A
	RBIT	1.27 A	1.43 A	2.83 B	0.61 AB	0.47 A	2.43 A
	RBITS	1.18 A	1.47 A	3.13 A	0.67 A	0.40 A	2.37 A
	RBITR	1.12 B	1.40 A	2.43 BC	0.55 B	0.47 A	2.74 A
	Mean	1.16	1.41	2.65	0.60	0.46	2.50
Type (TP)		50.7 **	27.1 **	0.9 ns	7.4 **	9.2 **	9.4 **
Treatment (T)		27.1 **	4.9 **	4.2 **	0.8 ns	1.3 ns	0.1 ns
TP × T		5.9 **	0.8 ns	1.7 ns	0.2 ns	3.8 *	0.7 ns

Note: High-DTL: High daytime temperature and light after heading; Low-DTL: Low daytime temperature and light after heading; CF: conventional fertilization; RBIT: reduced basal and increased topdressing fertilizer rate; RBITS: RBIT combined with straw incorporation; RBITR: RBIT combined with reduced fertilizer rate. The different lowercase and uppercase letters indicate the difference among treatments at the $p < 0.05$ level under High-DTL and Low-DTL, respectively. *: $p < 0.05$; **: $p < 0.01$; ns: non-significance.

Fertilization management significantly affected the nutritional status (N, K) of the different parts of rice, except for the K concentration in the panicle (Table 4). Compared with the CF treatment, three integrated RBITs (RBIT, RBITS, and RBITR) under High-DTL did not change the N concentration in the stem + leaf but markedly increased the N concentration in the panicle by 14.9%, 19.9% and 8.1%, respectively; under Low-DTL, the RBIT, RBITS and RBITR treatments enhanced the N concentration by 17.4%, 9.5% and 3.8% in the stem + leaf, and 6.6%, 9.3% and 4.6% in the panicle, respectively. For the K concentration in the stem + leaf, the increase rate of three integrated RBITs under Low-DTL (22.9%, 35.8% and 5.5% in the RBIT, RBITS and RBITR treatments, respectively) was higher than under High-DTL (9.0%, 11.0% and 0.5% in the RBIT, RBITS and RBITR treatments, respectively). Among them, the K concentration in the stem + leaf in the RBITS was the most sensitive to weather changes. Compared with High-DTL (0.45, 0.45, 0.33 and 0.33), the stem + leaf N/K value in the RBITR treatment (0.40) under Low-DTL showed a decreasing trend, while the RBIT (0.45), CF (0.49) and RBITR (0.47) treatments showed increasing trends. Furthermore, the two-way analysis showed a significant interaction between the weather year types and fertilization management on the N concentration and N/K value in the stem + leaf.

3.4.3. Regression Analysis

The harvest index refers to the ability of biomass to generate economic yield. Therefore, we analyzed the relationship between the nutritional status in the vegetative organs of rice and harvest index and found that there were negative linear correlations under the two weather types between the N concentration (R^2 = 0.04, p = 0.42 under High-DTL; R^2 = 0.39, p < 0.01 under Low-DTL) and N/K (R^2 = 0.18, p = 0.10 under High-DTL; R^2 = 0.34, p = 0.01 under Low-DTL) in the vegetative organs (stem + leaf) and harvest index (Figure 4A,B). With an increasing K concentration, the harvest index linearly increased under High-DTL (R^2 = 0.14, p = 0.15), and exponentially increased under Low-DTL (R^2 = 0.29, p < 0.01) (Figure 4C).

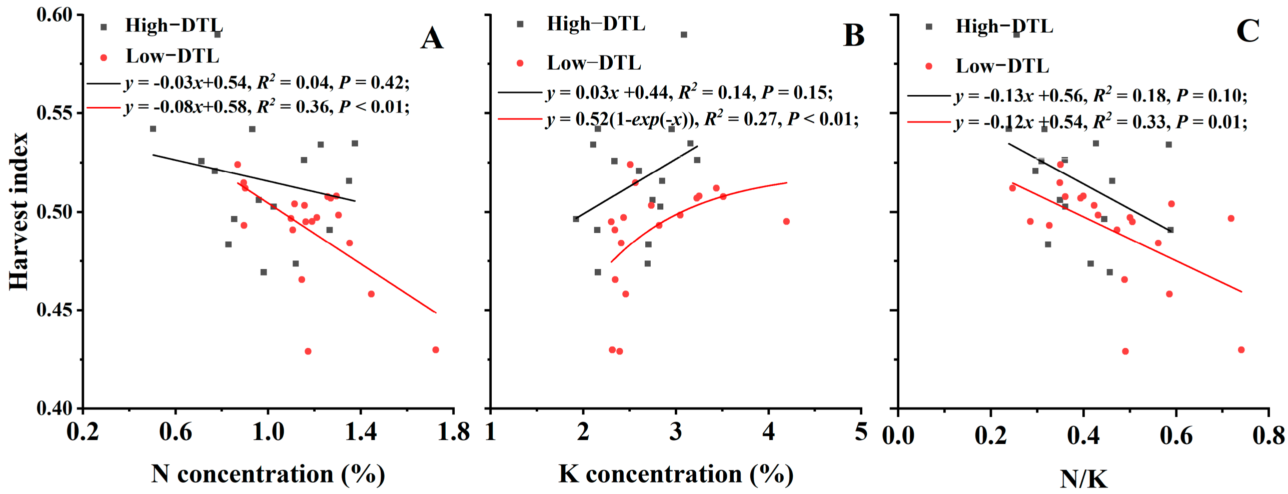

Figure 4. Regression analysis between the harvest index and the concentrations of N (**A**) and K (**B**), and N/K (**C**) in vegetative organs. Note: High-DTL: High daytime temperature and light after heading; Low-DTL: Low daytime temperature and light after heading.

4. Discussion

4.1. Effect of Daytime Temperature and Light Change after Heading on Rice Production

In subtropical and tropical rice systems, point stresses during the reproductive stage rather than warming seasonal temperatures determine yield [2,3]. Similar results were observed in our study that the response of rice yield to daytime temperature and light after heading was stronger than before heading. MT after heading was 19.5–20.9 °C over the nine years, which was within the temperature thresholds of japonica rice (17.9 °C and 29.8 °C for MINT and MAXT, respectively) [29]), implying that temperature stress did not occur in our study, while low light might be an underlying stress factor. Indeed, Stanhill and Cohen observed a global average solar radiation reduction of 0.51 W/m^2 per year [8]. The same scenario was observed in the same watersheds as in the present study [9]. Model simulation indicated a decrease in solar radiation by 12–26% in Indo-Gangetic Plains, leading to a 2–8% reduction in the potential yields of wheat and rice [30]. Therefore, dimming weather by haze, aerosol and cloudy weather should be worthy of attention in estimating the damage of climate change on future agricultural production.

Sunlight is the primary source of energy for crop growth and physiological metabolism. Shading experiments showed that the reduction in radiation and thermal energy during the grain filling stage directly damaged the leaf photosynthetic system, decreased the yields of ATP, delayed plant flowering, and hampered pollen germination and pollen tube growth, thereby causing an abortion in embryos and a grain weight decrease [19,30–33]. Some studies have shown that cold stress during the reproductive stage causes the degeneration of spikelets and an increase in spikelet sterility, affecting seed filling, which leads to a low seed set and low grain weight [18,21]. Indeed, in our study, the response of rice grain weight reduction to Low-DTL was higher than other yield components, implying that insufficient grain filling was a major contributor to rice yield losses under poor weather after heading [32,33].

Our experiment observed that rice yield losses under Low-DTL was attributed to a low final biomass (*F-value* 15.1) and HI (*F-value* 12.1) rather than a low post-heading biomass (*F-value* 0.6) (Table 3). These findings differed from those of previous shading experiments [17,34]. The possible reasons were as follows: (1) the difference between this study and artificial shading stress was that low light under natural conditions was temporary and intermittent [17], whereas the positive priming effect on the photosynthetic rate after removing the low light was attributed to a high chlorophyll content [17,34]; (2) inhibiting proteins related to the Calvin cycle and protein synthesis under shade stress resulted in a high concentration of leaf-soluble N-containing substances (such as proline), which could enhance crop tolerance or resistance via osmotic regulation [35,36]. Indeed, the N concentration in the vegetative organs under Low-DTL was higher than under High-DTL, and the negative relationship between the N concentration in the vegetative organs and HI under Low-DTL (R^2 = 0.39, p < 0.01) was stronger than High-DTL (R^2 = 0.04, p = 0.42). These results suggested that the transfer of carbohydrates to the sink (panicles) under poor weather was regulated by the N concentration in vegetative organs. Taken together, under poor weather conditions, regulating the nutrient status of crops by fertilization management could help alleviate the inhibition of assimilative transport by excess N.

4.2. Adaptation Strategies of Fertilization Management under Weather Changes

In our study, RBIT under High-DTL did not affect rice yield, attributed to a strong mutual compensation effect between a high number of spikelets and low grain filling [11–13]. However, RBIT had a higher rice yield under High-DTL than RBITR, but no difference was found under Low-DTL. So we speculated that 300 kg N/ha of RBIT under Low-DTL was excessive, resulting in excessive retention of N in vegetative organs and thereby inhibiting the transport of carbohydrates to the grain [11,37]. Our results confirmed this conjecture (Figure 3). Indeed, in poor weather, high doses of N could cause an imbalance in the carbon and N metabolism of plants [23,35,36]. Excess N could promote the occurrence of ineffective tillers and high-node tillers in rice, leading to a reduction in the number of panicles per unit area and HI [10]. Danso et al. indicated that there was no yield benefit from applying more fertilizer under drought conditions [16]. Kyverga et al. showed that in years with poor growing conditions, reducing the N fertilizer rate could improve the environmental adaptability and reduce the risk of yield loss [37]. Taken together, adjusting reasonable N fertilizer rates according to future weather conditions is crucial to reduce the risk of rice yield losses while saving fertilizer.

However, current technology makes it difficult to obtain accurate future weather data. Luckily, in our study, RBITS could still obtain a greater rice yield under Low-DTL, suggesting that this strategy could alleviate the negative effect of poor weather conditions after heading on rice growth. This finding is consistent with previous studies on straw incorporation and yield stability [16,27,28]. This result might be because straw incorporation could improve soil fertility, increase root bacterial communities, and promote rice root growth and nutrient absorption [16,25,38–40]. In our experiment, RBITS increased the content of soil organic matter, total N and available K (data not shown), and had a higher positive effect on K concentration and absorption under Low-DTL than under High-DTL. This implies that RBITS could help to promote K uptake in rice under poor weather conditions. Microbiota and light manipulation experiments indicated that a microbiota–root–shoot circuit alleviated plant growth deficiencies under low light [41]. Haro and Benito reviewed that soil microorganisms form mutualistic associations with roots that could influence the availability of mineral nutrients (e.g., K) for plants [42]. Therefore, we speculate that RBITS may improve the soil K supply under Low-DTL by modulating microbial root commensals, but its mechanism needs further verification.

Under low temperature and light conditions, weakened rice transpiration might inhibit K uptake by the pathway of mass flow (depending on transpiration pull). Huge root systems and strong root vitality in straw incorporation [39,40,43] might cause the dominance of root interception of K under poor weather conditions, promoting K uptake and enhancing the resistance of crops to abiotic stresses. Increasing crop K concentrations could promote the development of vascular bundles in stems, and then promote the transportation of substances and N to the panicle [16,18,19]. The positive effect of K might mitigate the negative effects of excess N in vegetative organs on blocked assimilate transport, thereby reducing yield losses. Hou et al. suggested that N and K had significant synergistic effects on photosynthesis and assimilation transport [44]. In our study, stronger correlations between the K concentration (positive) and N/K (negative) in vegetative organs and HI under Low-DTL than under High-DTL suggested that K or N/K in crops played an important role in promoting rice assimilate transport to grains under poor weather conditions. However, its physiological mechanism needs further research.

In China, delaying rice harvest to obtain higher yields is common [45], indicating that the risk of rice suffering from low temperatures and light may be increased. The strong resistance to Low-DTL in RBITS suggested that this practice could enhance rice adaptability to poor weather conditions and a stable rice yield. Furthermore, N_2O emissions and NO_3^- leaching and runoff were closely related to high reactive N levels in the environment [46]. As a result of the high absorption and utilization of the N fertilizer in RBITS, this strategy may be an effective way to reduce soil reactive N levels and mitigate the risk of environmental pollution [26]. In addition, aerobic paddy irrigation should be used to reduce the negative effect of reduction substances released by returning straw on rice growth at the early stage, promote root growth, and provide adaptability to weather changes [38].

5. Conclusions

This study clarified that rice yield was affected by daytime temperatures and light after heading. Under Low-DTL, rice yield losses were due to inhibition of assimilate accumulation and distribution caused by excessive N concentrations in vegetative organs, leading to poor grain filling. Integrated RBITs had no change in rice yield under High-DTL because its positive effect on spikelets was offset by its negative effect on grain filling. Interestingly, compared with other RBITs, RBITS could mitigate the negative effect of poor weather on assimilate accumulation and distribution, reducing grain filling deficiencies and yield losses. This was due to the increased K concentration and decreased N/K in the vegetative organs. Correlation analysis indicated that rice assimilate transportation under poor weather conditions was more dependent on the nutritional status of the vegetative organs. In conclusion, integrated fertilizer postponing combined with straw incorporation could enhance rice adaptability to poor weather conditions by balancing N/K in vegetative organs.

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