Improving Rice Yields and Nitrogen Use Efficiency by Optimizing Nitrogen Management and Applications to Rapeseed in Rapeseed-Rice Rotation System

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Abstract: This investigation aims to provide theoretical and practical evidence for the efficient utilization of nitrogen (N) in paddy-upland rapeseed-rice rotation systems because a lack of previous research on such rotation systems leads to inefficient management practices. The effects of the N application rates and the N fertilizer management strategies for rapeseed and rice were examined, respectively, in relation to the photosynthetic productivity and yields of hybrid rice. The results indicated that the leaf area, Pn, with 40% as basal fertilizer, 40% as tillering fertilize, and 20% as panicle fertilizer and a reduced N rate (30 kg/ha) during the rape season, were higher than other nitrogen management strategies trialed, with conventional N rates in the rape season. The average rice grain yield (9545.15 kg/ha) over the two years with 40% as basal fertilizer, 40% as tillering fertilizer, and 20% as panicle fertilizer was higher than other N treatments with the reduced N rates during the rape season. The reduced N rate during the rapeseed season and 40% as basal fertilizer, 40% as tillering fertilizer, and 20% as panicle fertilizer management during the rice season for the rape-rice rotation system exhibited the highest rice yields. Our findings indicated that the N fertilizer management model was a high-yielding, N-saving, and environmentally friendly measure for rape–rice rotation systems in southern China.

Keywords: photosynthetic production; yield; rapeseed-rice; nitrogen management

1. Introduction

China has the world's largest population, but insufficient cultivated land resources to meet the required needs of its people. Furthermore, according to reports, China's population is set to increase and will reach 1.4 billion by 2030 [1]. Increasing grain crop yields in China is a central strategy being utilized to address this problem. Diversified crop rotations regularly enhance grain crop yields by 10% or more, relative to simple rotations, and they have previously been widely utilized in agricultural systems [2]. Rice is a staple food in China as it is the major grain crop, and its per unit yield is more than 65% higher than the world average level. However, it still ranks seventh after Australia, Egypt, the United States, Spain, Japan, and South Korea. Ensuring high and stable rice yields is important for food security, both in China and globally [3,4]. Reasonable applications of N are one of the cultivation techniques used to ensure stable and high rice yields [5,6]. Nitrogen (N) is extremely important for maintaining crop yields and improving grain qualities [7,8]. Excessive

applications of N fertilizer have led to a series of environmental problems, such as eutrophication and groundwater pollution [9]. Nitrogen (N) is one of the most important plant available nutrients and the most limiting factor for crop yields in agricultural fields [10,11], as it is an important component of nucleic acids, coenzymes, and photosynthetic pigment molecules. The photosynthetic function of the leaves determines the carbon transformation efficiency, and this exerts large impacts on the growth, development, and productivity of plants. In addition, as an indispensable inorganic nutrient, N input levels play a critical role in regulating the photosynthesis values in cereal crops [12,13].

The N content of a plant is closely related to its photosynthetic rate, as some studies have shown that in a certain range of N applications, the nitrogen content and net photosynthetic rates of rice leaves have increased with increased nitrogen applications [14]. The paddy-upland rotation is the main planting model in Sichuan Province, China. Previous studies have concentrated on the effects of N management on the photosynthetic characteristics of the rice in the rice season [15]. There have only been a few previous studies on the effects of the N fertilizer inputs on the crops rotated prior to the rice, and the N fertilizer management on the photosynthetic productivity and yields of the rice. The objective of this investigation was to explore the optimal N fertilizer application rates, and the management between different crop rotations, for maintaining N fertilizer efficiency and high rice yields. F-you 498, a widely planted high-yield hybrid rice/cultivar, was utilized to explore the effects of the N fertilizer inputs form previous crops, and the N fertilizer management during the rice season, on the photosynthetic characteristics, matter production and transfer, and yield of the rice, to provide the optimal N fertilizer management methods for rape-rice rotations in China.

2. Materials and Methods

2.1. Experimental Site Information

Field experiments were conducted at the farm of the Rice Research Institute, Sichuan Agricultural University, Wenjiang, Sichuan Province, China (30.70° N, 103.83° E) from October, 2017 to early September, 2019. Right before the long-term field experiment (2017), soil samples from the top 0.20 m of surface soil contained 1.52 g kg^{-1} of total nitrogen (Kjeldahl method, UDK-169, ITA), 23.89 mg kg^{-1} of available phosphorus (Mo–Sb colorimetry after digested by H_2SO_4 and $HClO_4$), 2.421% of organic matter ($K_2Cr_2O_7$–volumetric method), 52.61 mg kg^{-1} of available K (Flame spectrometry after NH_4OAc extraction), and had a pH of 6.19 (tested in a sample containing a 1:2.5 ratio of soil to water). The average air temperature and precipitation during the previous crop and rice growing season, measured at the weather station close to the experimental site, are detailed in Figure 1.
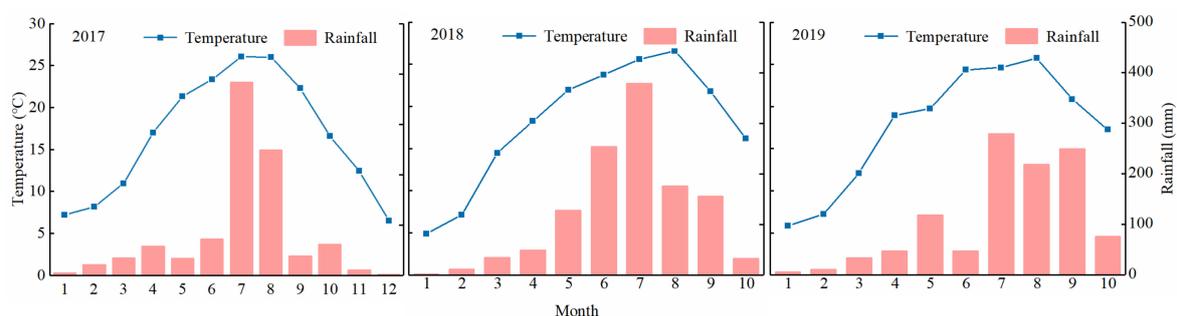
Figure 1. Meteorological data of the experimental area, including temperature and rain full in 2017–2019.

2.2. Field Experiments

From October 2017 to September 2019, treatments were established annually in the same area, and were arranged in a split plot design with three replicates. Conventional nitrogen rates (Nc: 180 kg ha^{-1}) and reduced N rates (Nr: 150 kg ha^{-1}) were utilized in the rape seasons. A 150 kg ha^{-1} N application rate in the rice seasons, using 3 different management models, named M1, M2, and M3

were also prepared. The N application rates for the base fertilizer, tiller fertilizer, and panicle fertilizer were set at 20%:20%:60%, 30%:30%:40%, and 40%:40%:20%, for M1, M2, and M3, respectively. The M0 (0 N) model was used as a control. Furthermore, 75 $P_2 O_5$ kg/ha and 150 $K_2 O$ kg/ha, were applied as basal fertilizers in the rape and rice seasons, respectively. Each experimental plot was 15.75 m^2 in area with a 30 cm-wide ridge, covered with a plastic film, to prevent water and nutrient penetration from the contiguous plots.

2.3. Crop Management

The oilseed rape variety, Mianyou15, was provided by the national super seed industry. Oilseed rape seeds were sown in a seedbed on September 13, 2017 and on September 14, 2018 and seedlings were transplanted to the field on 12 October 2017 and on 13 October 2018, spaced at 50×35 cm 57,171 plants ha^{-1}) in both 2017 and 2018. F-you 498, the widely planted high-yield hybrid rice cultivar in Chengdu plain in Sichuan, was grown in the paddy fields. In each year, pre-germinated rice seeds were sown in a seedbed on April 17, and the seedlings were transplanted to the field on May 23. The rice seedlings were transplanted and spaced at 33.3×16.7 cm, in both 2018 and 2019, respectively, with one plant per hill^{-1}. The weeds were controlled in the oilseed rape and rice with pretilachlor (Jiangsu Changlong agrochemicals Co.,Ltd., Jiangsu, China). The herbicide was applied once at the seedling stage of rapeseed and the tillering stage of rice. Pests and diseases were controlled by imidacloprid (Hubei Xinhe Chemical Co., Ltd., Hubei, China.) and kasugamycin (Hubei Dibai Chemical Co., Ltd., Hubei, China) to avoid yield loss. The herbicide was applied twice at the jointing stage of rice. The straw of the oilseed rape after harvest, was chopped to lengths of 5–10 cm and embedded into the soils in early May. The straw of the oilseed rape were then ground into powder for N determination (Kjeldahl method). Nitrogen nutrients brought into the field by returning rape straw are 19.19–22.36 kg/ha.

2.4. Photosynthetic Characteristics and Leaf Area Measurements

The rice flag leaf net photosynthetic rate (Pn), stomatal conductance (gs), and transpiration rate (Tr) were measured from the main stems, with a LI-6400 photosynthetic analyzer (LI-6400, American LI-COR, Lincoln, NE, USA).The measurements were conducted from 09:00 to 11:00 during the full heading stage, as well as 15 and 30 days after the full heading stage. The flow rate of the air in the leaf chamber was adjusted to 1200 μmol/s, and the CO_2 concentration was 0.55 mg/L. Three rice plant leaf areas were measured with a LI-3100C leaf area analyzer (LI-3100C, American LI-COR, Lincoln, NE, USA) during the full heading stage in 2018 and 2019.

2.5. Dry Matter Accumulation and Transport of Rice Plants

Three physically similar plants with generally the same growth in the field were taken at the jointing, panicle, and mature stages in 2018 and 2019, respectively. They were then divided into stem, leaf, and spike. The rice plants were treated at 105 °C for 30 min and then dried at 75 °C for 72 h, to a constant mass, before the dry mass of each part was weighed.

2.6. Rice Yield Measurements

The rice yield was determined using 5 mature sample plants from each plot. Unhulled (rough) rice kernels were obtained after reaping, threshing, and winnowing. The weight of the rough rice kernels was adjusted to a moisture content of 13.5%.

2.7. Statistical Calculations and Analysis

$$\text{EPSS (\%)}\frac{\text{Stem or sheath mass at heading stage} - \text{Stem or sheath mass at maturing stage}}{\text{Stem or sheath mass at heading stage}} \times 100\ \% \quad (1)$$

$$\text{TPSS (\%)}\frac{\text{Stem or sheath mass at heading stage} - \text{Stem or sheath mass at matureing stage}}{\text{Grain dry mass}} \times 100\ \% \quad (2)$$

where EPSS is the export percentage of stem-sheaths and TPSS is the translocation percentage of stem-sheaths. The data were analyzed using analysis of variance (ANOVA), and means were compared based on the least significant difference (LSD) test at the 0.05 probability level using SPSS 23 (Statistical Product and Service Solutions Inc., Chicago, IL, USA). Origin Pro 2017 (OriginLab, USA) was used to draw the figures.

3. Results

3.1. Effects of N Application on Rice LeafAreas

The effects of the N application rates during the rape season and the N management during the rice season on the average rice leaf area over the two years are shown in Figure 2. Compared with conventional N treatments, the rice leaf area with the reduced N treatments was higher. The other effective leaf excluded three leaves on top of the main stem of the hybrid rice. The higher effective leaf was the three leaves on top of the main stem of the hybrid rice. Higher effective leaves with different N management models in the rice season showed significant differences with the different models, as M3 > M2 > M1 > M0, with conventional nitrogen applications and reduced N applications in the rapeseed season. The M3 management model during the rice season and the reduced N applications during the rapeseed season resulted in the leaf area being higher than with the M3 management model and conventional N application rates. The two years of data utilized in this investigation, from the rape–rice rotation system, further showed that the optimal treatment to increase the rice leaf area was reduced N applications during the rape season combined with the M3 nitrogen management model for the rice.
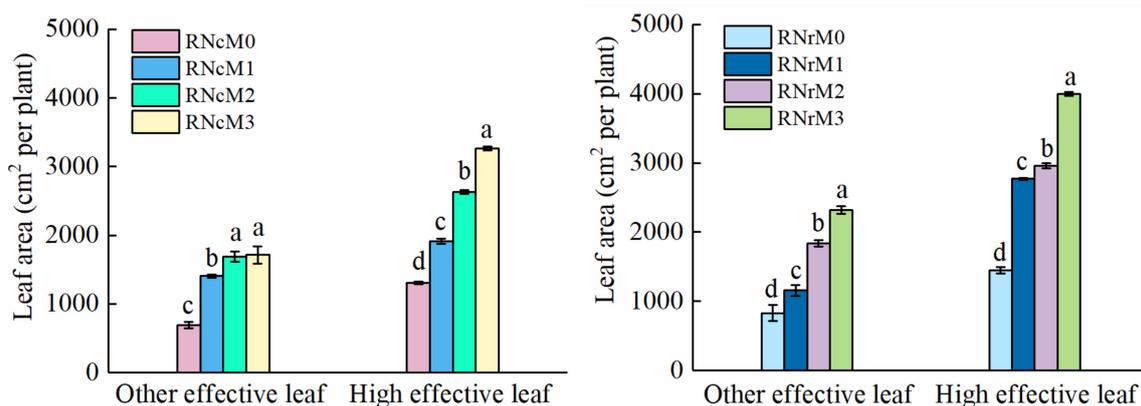
Figure 2. Effects of nitrogen fertilizer applications during the rapeseed season and nitrogen management during the rice season, on the leaf area of hybrid rice. R represents rapeseed; Nc and Nr represent the nitrogen fertilizer input of the rape season; M0, M1, M2 and M3 represent the nitrogen fertilizer operation in the rice season (0 kg N/hm^2) and conventional nitrogen application (150 kg N/hm^2), respectively **.** Lower case letters indicate that the photosynthetic characteristics of the hybrid rice are significantly different with the different treatments ($p < 0.05$, LSD method).

3.2. Effects of N Application on the Photosynthetic Characteristics of Rice

The average values over the two years, for the effects of the N application rates during the rape seasons and the N management models in the rice seasons, on the photosynthetic characteristics of the hybrid rice are shown in Figure 3. The photosynthetic characteristics of the rice flag leaves receded with the growth process. The effects of the N application rates during the rape season on the photosynthetic and transpiration rates of the hybrid rice during the heading stage and 15 days after the heading stage were not significant. The effects of the N management during the rice season, on the photosynthetic rate of the hybrid rice during the heading stage, and 15 and 30 days after the heading stage, were significant. Compared with conventional N applications, the photosynthetic rate and transpiration rate of the hybrid rice were reduced when the nitrogen in the rape season was reduced during the heading stage, but the differences were not significant. Compared with the M0 model during the rice season, the M1, M2, and M3 models increased the photosynthetic characteristics of the hybrid rice during the heading stage, and 15 and 30 days after the heading stage, with conventional N and reduced N application rates during the rape seasons. The photosynthetic rate was the highest with the M3 model. From the two years of data gathered, the optimal treatment for the rice photosynthetic rate was found to be the reduced nitrogen applications in the rape season combined with the M3 management model for the rice, in the rape-rice rotation system. The M3 management model for the rice season with the reduced N application rates in the rape season also resulted in improved photosynthetic rates of the flag leaves of the hybrid rice.

3.3. Effects of N Application on the Matter Accumulations and Transport of Rice

The effects of the N application rates in the rape season, N fertilizer management in rice season, and their interactions on the accumulation and transport of the hybrid-rice generally resulted in significant or extremely significant differences over the two-year analysis period (Table 1). Compared with conventional N applications, the stem-sheath mass at the heading stage, stem-sheath mass at the maturing stage, and translocation percentage of the stem-sheaths of the hybrid rice with the reduced-nitrogen applications, increased by 7.98%, 8.60%, and 10.29%, and 8.27%, 5.91%, and 14.13% over the two years, respectively. Compared with the M0 model during the rice season, the M1, M2, and M3 models increased the stem-sheath mass at the heading stage and the stem-sheath mass at the maturing stage with conventional nitrogen rates, and reduced the nitrogen rate during the rape season. The stem-sheath mass was the greatest with the M3 management model. This suggested that the post-nitrogen forward shift could increase the accumulation and transport of the hybrid-rice in this study. The stem-sheath mass at the heading stage, stem-sheath mass at the maturing stage, and the export percentage of the stem-sheaths were higher with the M3 management model, in comparison with the M0, M1, and M2 models, with both the conventional and reduced N application rates during the rape season. The average export percentage of the stem-sheaths (32.07%) over the two years for the M3 management model, was 38.45%, 51.36%, and 7.45% higher than with the M0, M1, and M2 models, respectively, with conventional N rates during the rape season. The average export percentage of the stem-sheaths (34.13%) over the two years with the M3 management model was 53.52%, 59.56%, and 0.37% higher than with the M0, M1, and M2 models, respectively, with reduced N rates during the rape season. From the two years of experimental data, the optimal treatment of the reduced nitrogen applications during the rape season and the M3 management model for rice, increased the rice dry matter in the rape-rice rotation system. This indicated that the M3 management model combined with reduced nitrogen applications during the rape season was the most beneficial strategy for improving the accumulation and transport of the dry matter of rice.
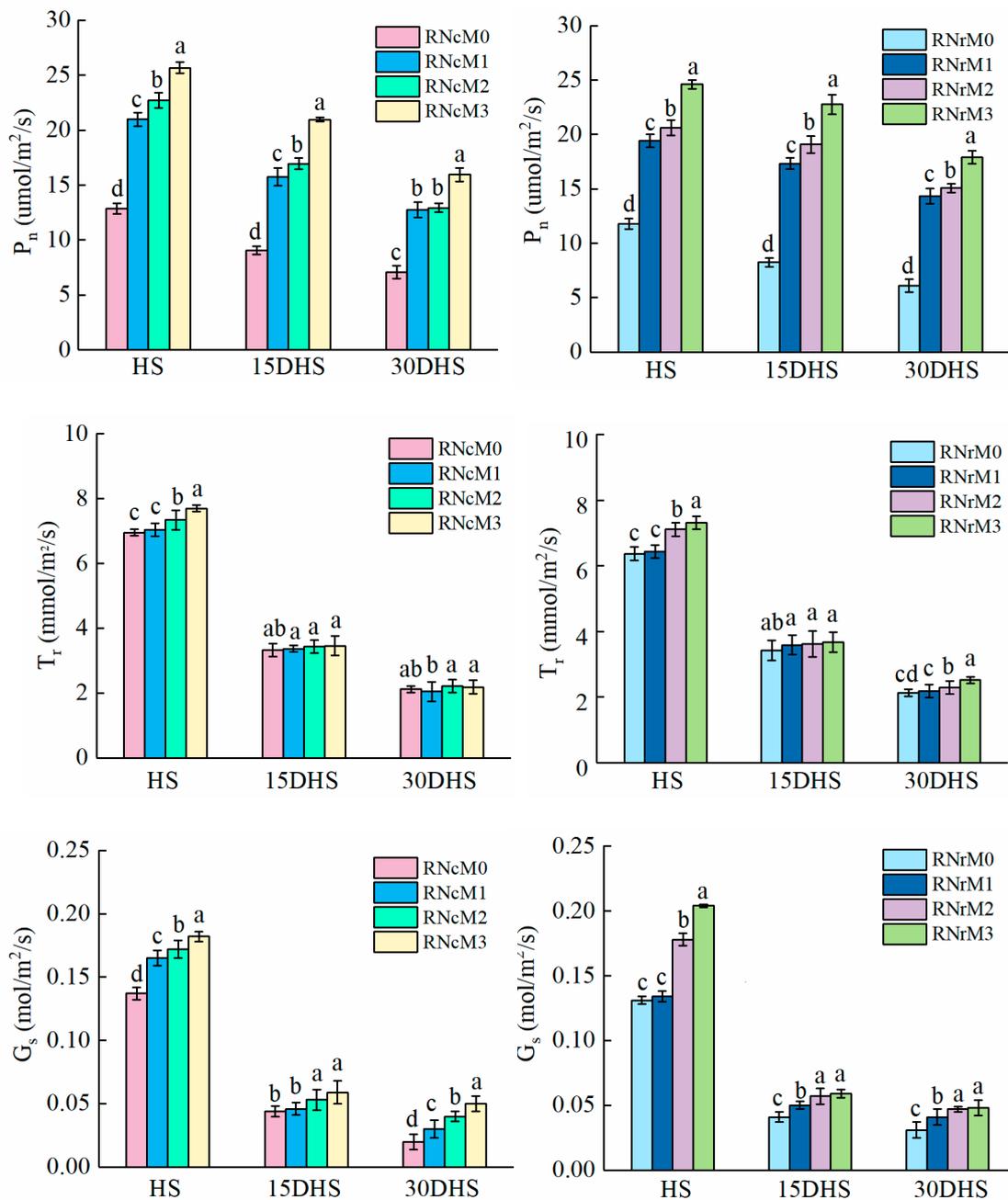
Figure 3. Effects of the N application rate during rapeseed season and N management during the rice season on the photosynthetic characteristics of the hybrid rice. Pn represents photosynthesis; Tr represents transpiration; GS represents stomatal conductance; R represents rapeseed; Nc and Nr represent the nitrogen fertilizer input of the rape season; M0, M1, M2 and M3 represent the nitrogen fertilizer operation in the rice season (0 kg N/hm^2) and conventional nitrogen applications (150 kg N/hm^2), respectively. HS represents heading stage; 15DHS represents 15 days after heading stage; 30DHS represents 30 days after heading stage. Lower case letters indicate that the photosynthetic characteristics of the hybrid rice are significantly different with the different treatments ($p < 0.05$, LSD method).

Table 1. Effect of N Rate in Rapeseed Season and N Management in Rice Season on the Accumulation and Transport of Hybrid Rice.

Year (Crop)	Treatment (kg/ha)		Stem-sheath Mass at the Heading Stage (kg/ha)	Stem-sheath Mass at the Maturing Stage (kg/ha)	Export Percentage of Stem-sheaths (%)	Translocation Percentage of Stem-sheaths (%)
2017–2018 (Rapeseed)	Nc	M0	5340.46 c	4034.71 d	24.45 ab	19.71 ab
		M1	5378.51 c	4166.68 c	22.53 b	13.48 b
		M2	6575.03 b	4556.74 b	30.73 ab	22.30 a
		M3	7001.52 a	4702.05 a	32.84 a	23.76 a
	Average		6073.88	4365.05	27.64	19.81
	Nr	M0	5604.60 d	4286.55 c	23.54 ab	18.46 bc
		M1	5637.07 c	4357.23 d	22.70 ab	14.38 c
		M2	7452.83 b	4865.72 b	34.71 a	27.92 a
		M3	7540.67 a	4913.19 a	34.84 a	26.65 ab
	Average		6558.79	4740.25	28.15	21.85
2018–2019 (Rapeseed)	Nc	M0	5066.64 d	3957.13 d	21.95 c	17.31 c
		M1	5104.33 c	4089.45 c	19.94 d	11.30 d
		M2	6301.02 b	4479.49 b	28.97 b	20.07 b
		M3	6727.34 a	4624.69 a	31.30 a	22.93 a
	Average		5799.83	4287.69	25.54	17.90
	Nr	M0	5329.39 c	4212.03 c	21.02 c	17.89 c
		M1	5348.04 c	4282.48 c	20.18 d	12.11 d
		M2	7177.55 b	4791.14 b	33.32 a	26.30 a
		M3	7269.43 a	4838.79 a	33.43 a	25.44 b
	Average		6279.85	4541.11	26.85	20.43
p— value	N		0.0453	0.0019	0.1006	0.0084
	M		0.0058	0.0272	0.0054	0.0238
	N × M		0.0001	0.0001	0.0003	0.0001

Nc and Nr represent the nitrogen fertilizer input of the former crops; M0, M1, M2 and M3 represent the nitrogen fertilizer operation in the rice season (0 kg N/hm^2) and conventional nitrogen application (150 kg N/hm^2), respectively, Lower case letters indicate that the hybrid rice material accumulation and transport was significantly difference under different treatments ($p < 0.05$, LSD method).

3.4. Effects of N Application on Rice Yield and its Components

The effects of the reduced N applications and the nitrogen management during the rice season, on the rice yield components over the two-year analysis period, are shown in Table 2. Significant effects from the nitrogen management during the rice season were observed on the rice yield components and yield. Compared with the M0 model, the M1, M2, and M3 models increased the rice yield components with the conventional N rates, and the reduced the nitrogen rates in the rape season. The 1000-GW (1000-grain weight and Grain yield) was higher than with the other nitrogen management model and thus the rice yields with the conventional N application rates during the rape season and the M3 model, were improved. The average rice yield (9410.16 kg/ha) over the two years with the M3 model was 38.69%, 4.65%, and 3.65% higher than with the M0, M1, and M2 models. The higher yield was due to the more productive 1000-GW under conventional N rates, in the rape-rice rotation system. The PN(No. of productive panicle), SPN(No. of spikelet per panicle), and 1000-GW were higher than with the other nitrogen treatments model during the rice season, and thus improved the rice yields when reduced N rates were applied during the rape season and the M3 management model applied to the rice. The average rice yield (9545.15 kg/ha) over the two years period for the M3 management model was 48.27%, 6.11%, and 10.14% higher than with the M0, M1, and M2 models, respectively. The higher rice yields were due to the more productive PN, SPN, and 1000-GW, with the reduced N application rates during the rape-rice rotation system. The data from the two years of analysis, showed that the optimal treatments for increased rice yield and efficiency were the reduced N application rates on the previous crops and the M3 nitrogen management model for the rice, in the rape-rotation system. This indicated that the M3 management model for the rice season under the reduced nitrogen rates during the rape season was the most conducive for improving the rice yield components and increasing yields.

Table 2. Effect of N Rate in Rapeseed Season and N Management in Rice Season on the Hybrid Rice.

Year (Crop)	Treatment (kg/ha)		PN (m^{-2})	SPN (Panicle^{-1})	SSR (%)	1000-GW (g)	GY (kg/ha)
2017–2018 (Rapeseed)	Nc	M0	133.20 b	193.61b	89.86 b	30.76 c	7140.01 d
		M1	154.86 a	207.63 b	90.86 ab	31.19 bc	8900.12 c
		M2	160.74 a	203.66 b	91.51 a	31.78 ab	9360.24 b
		M3	152.82 a	226.36 a	91.58 a	32.16 a	9600.15 a
	Average		150.41	207.82	90.95	31.47	8750.13
	Nr	M0	128.69 b	205.71 b	89.93 b	30.25 c	6620.06 c
		M1	153.72 a	218.64 a	90.83 ab	31.61 ab	8980.11 b
		M2	149.64 a	211.63 a	90.27 ab	31.33 b	9050.06 b
		M3	155.88 a	218.68 a	92.94 a	32.25 a	9670.14 a
	Average		146.98	213.67	90.99	31.36	8580.09
2018–2019 (Rapeseed)	Nc	M0	129.68f	179.49 e	83.87 c	29.92 b	6450.03 e
		M1	145.11 d	208.02 a	90.71 b	30.97 b	9090.21 cd
		M2	150.96 c	201.69 c	90.32 b	30.08b	9120.08bc
		M3	142.94 e	201.09 c	92.52 a	31.68 a	9220.17 b
	Average		142.17	197.57	88.46	30.66	8470.12
	Nr	M0	127.91 g	168.76 f	82.16 d	30.11 b	6260.15 f
		M1	156.96 b	205.76 b	87.21 c	30.09 b	9010.08 d
		M2	150.88 c	198.88 d	89.42 b	30.54 b	9120.14 bc
		M3	160.69 a	208.69 a	89.06 b	31.12 a	9420.17 a
	Average		149.11	195.52	86.96	30.46	8452.63

PN, SPN, SSR, 1000-GW, and GY represent the No. of productive panicle, No. of spikelet per panicle, Seed setting rate, 1000-grain weight and Grain yield, respectively. Nc and Nr represent the nitrogen fertilizer input of the former crops; M0, M1, M2 and M3 represent the nitrogen fertilizer operation in the rice season (0 kg N/hm^2) and conventional nitrogen application (150 kg N/hm^2), respectively, Lower case letters indicate that the hybrid rice yield was significantly difference under different treatments ($p < 0.05$, LSD method).

4. Discussion

4.1. Optimal N Management During the Rice Season and N Application Rates During the Rapeseed Season of Rapeseed-rice Rotation Systems, Increased the Photosynthetic Productivity of Rice

Photosynthetic capacity largely impacts on the potential biomass accumulations and production of crop plants [16,17]. In cereals, over 90% of the plant biomass is derived from photosynthetic assimilations, which control the plant yield characteristics [18]. Furthermore, in the late growth stage of cereals, grain filling is the central biological process. Similar to other external factors, such as light intensity, plant density, temperature, and CO2 conditions, that drastically affect the physiological processes in plants, due to their roles in regulating the carboxylation efficiency and electron transport capacity in photosynthesis [19,20], the nitrogen supply levels act as a critical factor in the regulation of leaf area expansion, photosynthesis efficiency, and leaf senescence [21,22].

In this study, the M3 management model for rice, with conventional and reduced N application rates in the rape seasons, could improve the photosynthetic productivity of the hybrid rice and leaf areas, in the rape-rice rotation system. The main reason for this may be that the development of the root system of the rapeseed could improve the ability to absorb and enrich more nutrient, and organic acids secreted by rape roots could dissolve the insoluble nutrients in the soil, and improve its effectiveness.N in the soils from the residues of the rape season caused high nitrogen levels in the paddy fields. Reasonable nitrogen fertilizer management (M3) in the rice season increased the supply of nitrogen fertilizer in the early stage, made up for the lack of soil fertility in the early stage, and created a better early population, which increased the leaf area index and high-efficiency leaf area index in the middle and later stages of growth, with strong light-capturing abilities to improve the photosynthetic performance of the rice, and slow the decline of its photosynthetic rate [23]. Optimized N fertilizer management could coordinate the nitrogen absorption characteristics of the rice during the growth period and increase the conversion of the assimilating substances. In addition, a reasonable

nitrogen fertilizer management strategy could increase the chlorophyll content, enhance the electron transfer ability of the photosystem, delay the senescence of the rice plants, and effectively regulate the photosynthetic performance [24]. At the same time, optimized nitrogen fertilizer management extended the duration of the high value of the rice leaf area index and maintained a high photosynthetic area. Overall, suitable N applications were effective at improving the photosynthetic rate of the flag leaves of rice in the Chengdu Plain.

4.2. Optimal N Management During the Rice Season and N Application Rates During the Rapeseed Season for Rapeseed-Rice Rotation Systems, Increased Rice Grain Yield

Recent research has revealed that high-yield populations of rice must be high-efficiency populations after flowering, and that the photosynthetic productivity of the rice was the primary factor affecting its yield [25–27]. The Sichuan Basin has low-sunlight levels and high humidity, and the post-anthesis populations are often shaded, poorly ventilated, and light-transmissive, which leads to reduced accumulations of photosynthetic products after anthesis and accumulations of post-anthesis photosynthetic products among the rice groups with different yield levels. Pre-flowering material transport was previously found to be a decisive factor for yield changes [28]. Reasonable supporting cultivation measures could also increase dry matter accumulations after anthesis in rice areas with poor light, and these are key to stimulating synergistic effects to improve the varieties and methods at a higher level. In this study, the highest rice yields (9670.14 and 9420.17 kg/ha), were achieved with reduced nitrogen applications in the rapeseed season, and the M3 nitrogen management model during the rice season, for the rapeseed–rice rotation system, in both 2018 and 2019. Previously, [15] N tracers showed that the nitrogen content of the rapeseed plants and residual nitrogen under the reduced N application rates, were higher than those with the conventional N application rates. The nitrogen concentrations in the paddy soils were relatively high after the rape straw was returned to the field. The M3 management model for rice resulted in high-quality rice populations. Although the amount of material transported before flowering was low, its photosynthetic production performance was strong after flowering. After compensating for the loss of pre-anthesis material transport, the remainder could remain flat or lead to the accumulation of the post-anthesis photosynthetic products in the rice populations, using other nitrogen fertilizer management models. This supported the theory that strong photosynthetic productivity after flowering was a prominent feature of reduced nitrogen applications during the rapeseed season and the M3 management model for rice, under the rapeseed-rice rotation system. The PN slowly rises and declines in rice populations, but the highest SPN was achieved with reduced nitrogen applications in the rapeseed season and the M3 nitrogen management model in rice, with the rapeseed-rice rotation system. Our research results were a little bit similar to previous studies [29]. It is generally accepted that peak seedlings in high-yield rice populations should appear at the jointing stage [30]. The emergence of peak seedlings is critical for rice fields in the Sichuan Basin. If the peak seedlings appear too early, the rice population at the booting stage would contain more ineffective tillers. The nutrition required for effective tillering and ear differentiation could not be guaranteed, due to increased competition, and large panicles are difficult to form. If the peak seedlings appear too late, the nutrient supply of rice plants is inclined to panicle differentiation after jointing, and if there is late tillering it is difficult to form panicles due to an insufficient nutrient supply, and this results in an insufficient number of effective spikes in the rice population. A reduction in effective panicles would consequently lead to greater yield losses in this region. Comparatively, reduced nitrogen applications during the rapeseed season and the M3 nitrogen management model in rice resulted in fewer nitrogen fertilizer inputs and the post-anthesis photosynthetic production performance was a greater advantage, and was more advantageous in terms of the efficient use of nutrients and technical versatility.

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