

## Article

# Nitrogen Fate and Efficiency of Fertilizer Application under a Rapeseed–Wheat–Rice Rotation System in Southwest China

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**Abstract:** To evaluate the efficient use of nitrogen (N) for rice in a rapeseed–wheat–rice rotation system, a pot experiment was conducted. The results indicated that in the conventional <sup>15</sup>N-labeled (Nc) and reduced <sup>15</sup>N-labeled (Nr) urea applications, absorbed N and soil residual N was higher in rapeseed than in wheat. In the rice season, the higher accumulation of <sup>15</sup>N was achieved with an Nr application rate during the rapeseed season and an N fertilizer management model (40% as basal fertilizer, 40% as tillering fertilizer, and 20% as panicle fertilizer) during the rice season (PrNrM3). A high <sup>15</sup>N accumulation was also achieved under the Nc application rate during the wheat season and the N fertilizer management model during the rice season (PwNcM3). The accumulation of <sup>15</sup>N in PrNrM3 and PwNcM3 accounted for 21.35% and 36.72% of the residual N under the Nr application rate in the rapeseed season and the Nc application rate in the wheat season, respectively. Compared with the Nc application rate in the rapeseed season and M3 N management in the rice season (PrNcM3), the N agronomy efficiency (NAE) and the N partial factor efficiency (NPFP) of rice were increased by 23.85% and 1.59%, respectively, in PrNrM3. The annual crop yield was 3.95% lower in PrNrM3, which was not significant. PrNrM3 was a stable yield, N-saving application rate for rapeseed-rice rotation systems in southern China.

**Keywords:** rapeseed-wheat-rice rotation system; <sup>15</sup>N tracer; nitrogen management; crop yield; N efficiency



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## 1. Introduction

Nitrogen (N) fertilizer input is an effective way of increasing crop yield [1]. China is the largest consumer of N fertilizer in the world [2]. However, many farmers apply more N fertilizer than necessary to promote higher rice production in China [3]. Excessive application of N fertilizer leads to a series of environmental problems, such as groundwater pollution [4], air pollution from ammonia [5], and significant soil acidification [6]. Excessive N fertilizer and improper application methods not only increase input costs but also result in lower N-use efficiency. The Ministry of Agriculture of the People's Republic of China has issued a new policy called "The action plan for zero growth fertilizer use by 2020," which aims to improve the utilization of fertilizers [7]. The main reason for the low N-use efficiency is the neglect of the environment and soil nutrient use during rice production. Many fertilizer losses are through nitrate leaching and surface runoff and atmosphere breakup through ammonia (NH<sub>3</sub>) volatilization and nitrous oxide (N<sub>2</sub>O) emission [8]. Therefore, both economic and environmental factors must be considered to ensure the efficient utilization of N fertilizers for sustainable crop production. In general, residual N in the soil from the previous season's crop contributes to the following season's crop yield and N-use efficiency [9]. The residual N in the soil from the previous crop is easily absorbed by the following season's crop. It exists mainly in the form of inorganic and fixed N, and it is more effective for the plant than intrinsic soil N.

The wheat and rapeseed seasons extend from November to May of the following year. Rice is the predominant crop of southwest China and is grown from May to September. The wheat–rice rotation and rapeseed–rice rotation systems are the most common planting systems in this region. N fertilizer is applied to wheat and rapeseed at a rate of 90 to 360 kg N·ha<sup>-1</sup> in Sichuan and Chongqing [10]. The application rate to the rice crop in Hubei province is 84 to 301 kg N·ha<sup>-1</sup> [11]. In Chongqing province, it ranges from 150 to 270 kg N·ha<sup>-1</sup> [12], and peaks at an application of 374 kg N·ha<sup>-1</sup> in the Hunan province [13]. Recent research has investigated whether reducing fertilizer inputs in the current season can maintain or even increase yields while reducing environmental impact. Some studies have shown that a reduced N application can maintain rapeseed yield and increase N-use efficiency [14]. Ju et al. [15] found that a 30 to 60% reduction of N input can maintain rice yield in the Taihu region, wheat and maize yields in the North China Plain (NCP), and reduce the N loss by half. It is possible to reduce N fertilizer input and maintain crop yields in single-season crops, but that does not necessarily ensure food security in China. Thus, rotational cropping systems play an important role in sustainable agricultural production. Wheat, vegetables, and rapeseed are used in multiple-cropping systems together with summer rice and maize in traditional lowland rice and maize cropping systems in the Chengdu plain. However, research is mainly aimed at regulating N fertilizer in single-season rice or pre-season crops and does not fully consider the effect of the former N fertilizer application and its utilization in the same year. The residual N in the soil from the previous crop has a great impact on the yield of successive crops. The objectives of this experiment were to quantify the fate of <sup>15</sup>N-labeled fertilizer in terms of plant accumulation, residue in the soil, and loss to the ecosystem, to understand the annual utilization of N fertilizer, and to determine if N utilization and recovery could be improved under the rapeseed–wheat–rice rotation. This study also aims to recommend an optimal N management protocol for multiple-cropping systems, considering both the yield and the environmental risk of N application. This study will provide a theoretical basis for the application of N fertilizers in seasonal crop rotations while reducing losses in yield and improving fertilizer utilization rate.

## 2. Materials and Methods

### 2.1. Experimental Site Information

The pot experiments were conducted at the Rice Research Institute farm, Sichuan Agricultural University, Wenjiang, Sichuan Province, China (30.70° N, 103.83° E) from October 2017 to early September 2019. The soil track was sandy loam and analyzed for selected physical and chemical characteristics before conducting the experiment (Table 1). The average air temperature and precipitation during the previous crop and rice-growing season were measured at the weather station close to the experimental site (Figure 1).

**Table 1.** Physicochemical characteristics of soil (0–20 cm) in the experiments.

Year	Total N (g kg <sup>-1</sup> )	Organic Matter (g kg <sup>-1</sup> )	Available Nutrient (mg·kg <sup>-1</sup> )			pH	Bulk Density (g cm <sup>-3</sup> )
			N	P	K		
2017	1.52	24.21	114.93	23.89	52.61	6.19	1.31
2019	1.57	26.89	117.73	21.32	55.76	6.21	1.34

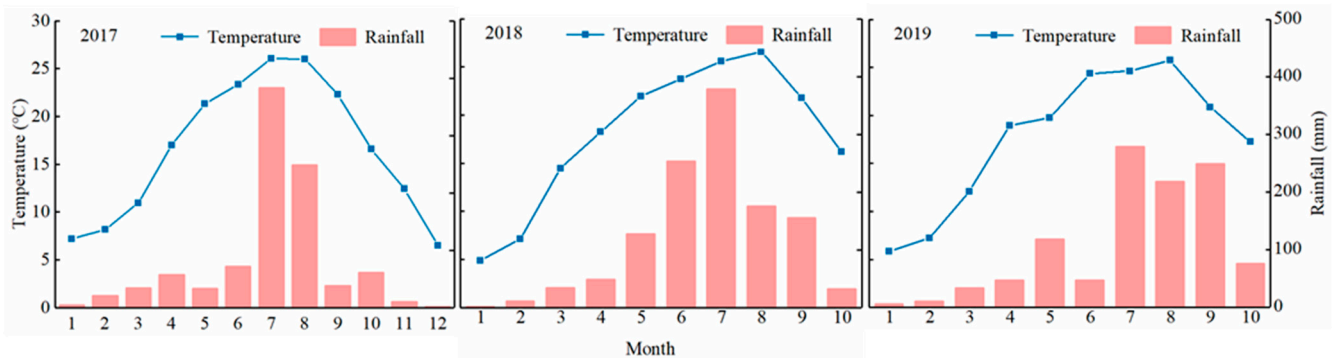


Figure 1. Meteorological data of the experimental area, including temperature and rain full in 2017–2019.

## 2.2. Experiment Design

The experiment adopted a three-factor design. The first factor (two levels) was the previous crop, which was either rapeseed or wheat. The second factor (two levels) was N application rate, with a conventional N application (Nc) ( $^{15}\text{N}$  3.14 g·plot $^{-1}$  in the rapeseed season or  $^{15}\text{N}$  1.66 g·plot $^{-1}$  in the wheat season), reduced N (Nr) ( $^{15}\text{N}$  2.62 g·plot $^{-1}$  in the rapeseed season or  $^{15}\text{N}$  1.28 g·plot $^{-1}$  in the wheat season), and N fertilizer as basal manure and topdressing 5:5 ( $^{15}\text{N}$ -labeled urea, Shanghai Institute of Chemical Industry, abundance 10.16%). The third factor (three levels) was N fertilizer management, with common urea as the N source. Based on an application rate of 1.66 g·pot $^{-1}$  N in rice season, three N management models were used, where the ratio of the application of base fertilizer, tiller fertilizer, and panicle fertilizer was 20%:20%:60% in treatment M1, 30%:30%:40% in treatment M2, and 40%:40%:20% in treatment M3, respectively. M0 (control) was defined as zero N. The 15 L pot (bottom diameter: 0.225 m, top diameter: 0.330 m, height: 0.250 m) contained 13.5 kg of soil, with 36 repetitions for each treatment in the rapeseed and wheat season, respectively, and nine repetitions for each treatment in the rice season, with each pot representing one repetition. The rapeseed variety used was ‘Mianyou No. 15’ (Mianyang Academy of Agricultural Sciences, Sichuan Province), and the wheat variety used was ‘Shumai 969’ (Wheat Research Institute of Sichuan Agricultural University). Rapeseed seedlings were transplanted (one plant per pot) into each pot on 12 October 2017, and 2018, and 20 wheat seeds were evenly seeded in each pot on 12 October 2017, and 2018. The rapeseed was harvested on 1 May 2018, and 2019, and the wheat was harvested on 8 May 2018, and 2019. Straw was cut into 5 cm pieces and returned to the corresponding pots after rapeseed and wheat harvest. The rapeseed and wheat straws contributed 0.26–0.35 g·pot $^{-1}$  and 0.14–0.17 g·pot $^{-1}$  N to the pots, respectively. Urea (N, 46.4%) was used as the N source, phosphorus pentoxide (P $_2$ O $_5$ , 12.0%) was used as the P source, and potassium chloride (K $_2$ O, 60.0%) was used as the K source. P and K were applied to the soil as a base fertilizer one day before sowing or transplanting.  $^{15}\text{N}$ -labeled urea ( $^{15}\text{NH}_2\text{CO}^{15}\text{NH}_2$ ) with an abundance of 10.16 atom %  $^{15}\text{N}$  excess was obtained from the Shanghai Research Institute of Chemical Industry (Shanghai, China). N, phosphorus, and potassium fertilizer was applied in the rapeseed season in the ratio of 2:1:2 and wheat season in the ratio of 2:1:1. ‘Fyou 498’, a commonly planted, high-yield, indica hybrid rice cultivar, was sown in a seedbed on 17 April 2018, and 2019, and seedlings were transplanted to the field on 23 May 2018, and 2019. Two rice plants were transplanted into each plot after rapeseeds and wheat were harvested. Ordinary urea was applied in rice season. NPK fertilizer was applied in the rapeseed season in a ratio of 2:1:2.  $^{15}\text{N}$  fertilizer was first dissolved in 500 mL of water and then poured into the pots to replenish water when the rapeseed, wheat, or rice showed slight wilting. Pests, diseases, birds, and grass were controlled to avoid any loss in rapeseed, wheat, or rice yield.

### 2.3. Plant and Soil Sampling and Measurements

For rapeseed, three plants in pots were taken at maturity. The plants were divided into capers, pods, and grains. The aerial biomass and harvest index were determined after oven-drying at 75 °C to a constant weight. Plant samples were then ground into powder for N determination (Kjeldahl method). Rapeseed yield ( $\text{g}\cdot\text{pot}^{-1}$ ) was measured in three plants within each pot, and the value was adjusted to 9.5% moisture. To determine the fate of  $^{15}\text{N}$ -labeled fertilizer, three pots of rapeseed were sampled at maturity. The aerial part of the plant was cut. Using a circular soil sampler with a 5 cm diameter, soil samples were taken from one point in the three pots. For wheat, three pots were sampled at maturity. The aboveground biomass was determined after oven-drying at 75 °C to a constant weight. Plant samples were then ground into a powder for N determination. Wheat yield ( $\text{g}\cdot\text{pot}^{-1}$ ) was determined from an average of three pots, and the value was adjusted to 12.5% moisture. To determine the fate of  $^{15}\text{N}$ -labeled fertilizer, three pots of wheat were chosen, based on the average panicle number per plot and the growth status. Their aerial parts were cut. For rice, three pots were sampled at full-heading and maturity. The aboveground biomass was determined after oven-drying at 75 °C to a constant weight. Plant samples were then ground into a powder for N determination and to calculate the total N accumulation at full-heading (FTNA); total N accumulation at maturity (MTNA); N dry matter production efficiency (NMPE); N grain production efficiency (NGPE); N agronomy efficiency (NAE); N partial factor productivity (NPFP) [16]. Rice yield ( $\text{g}\cdot\text{pot}^{-1}$ ) was determined from an average of three pots, and the value was adjusted to 13.5% moisture. Soil samples were taken from one point in each of the three pots with a 5 cm diameter, circular soil sampler. After air drying, soil samples were weighed and sifted through a 60-mesh sieve and stored in sealed bags for subsequent measurement. The  $^{15}\text{N}$ -labeled soil and plant samples were then analyzed for total soil N content and atom%  $^{15}\text{N}$  using a mass spectrometer (DELTAV Advantage, Chengdu Diversity Co., Ltd., Chengdu, China).

### 2.4. Calculations and Statistical Analysis

The following equations were used for the calculation of N accumulation and  $^{15}\text{N}$  fertilizer fate:

$$\text{NA (kg}\cdot\text{ha}^{-1}) = \text{WA} \times \text{N\%} \quad (1)$$

$$\text{Nsoil (kg}\cdot\text{ha}^{-1}) = \text{Wsoil} \times \text{N\%} \quad (2)$$

where NA and Nsoil are the N content ( $\text{kg}\cdot\text{ha}^{-1}$ ) of the aerial plant and soil, respectively; WA and Wsoil are the weight ( $\text{kg}\cdot\text{ha}^{-1}$ ) of the aerial plant and soil, respectively; N% is the N concentration in plant and soil samples.

$$\text{Ndff (\%)} = (\text{a} - \text{b}) / (\text{b} - \text{c}) \times 100\%, \quad (3)$$

$$\text{PNdff (kg}\cdot\text{ha}^{-1}) = \text{Ndff\%} \times \text{TN} \quad (4)$$

$$\text{PNdff (\%)} = \text{PNdff} / \text{TN} \times 100\% \quad (5)$$

$$\text{N residue (kg}\cdot\text{ha}^{-1}) = \text{Ndff soil} + \text{Ndff root} \quad (6)$$

$$\text{NRS (\%)} = \text{NRS} / \text{N rate} \times 100\% \quad (7)$$

$$\text{N loss (kg}\cdot\text{ha}^{-1}) = \text{N fertilizer rate} - \text{Ndff} - \text{N residue} \quad (8)$$

$$\text{Loss (\%)} = \text{N loss} / \text{N rate} \times 100\% \quad (9)$$

where Ndff % is the percentage of N derived from the fertilizer in the plant and soil samples; a is the abundance of  $^{15}\text{N}$  in plant and soil samples; b is the abundance of  $^{15}\text{N}$  in  $^{15}\text{N}$  fertilizer; c is the natural abundance of  $^{15}\text{N}$  (0.3664%) [17]; PNdff is the N accumulation derived from the fertilizer or plant; TN is the total N; N residue and N loss are the residual fertilizer N in the soil and the N loss of the fertilizer, respectively; NRS is the residual N.

The N accumulation and fate of  $^{15}\text{N}$  calculation methods were adapted from Li et al. [18]. The 2-year trends were consistent, and the difference of the main indicators of rice was not significantly different (Table 2); therefore, this paper uses the average value of the 2-year test data for analysis.

**Table 2.** Analysis of variance on rice yield and NDff of rice between 2018–2019 and previous crop and N rate and N fertilizer management (F values).

ANOVA	GY	HI	RNDff	NRR	NLR	NUE
Year	5.09 ns	0.73 ns	1.63 ns	1.71 ns	1.01 ns	0.76 ns
Year $\times$ P	2.55 ns	0.66 ns	2.44 ns	0.43 ns	1.67 ns	2.83 ns
Year $\times$ N	1.71 ns	0.05 ns	0.07 ns	1.23 ns	2.06 ns	2.31 ns
Year $\times$ M	0.95 ns	0.74 ns	0.26 ns	1.49 ns	2.33 ns	2.71 ns

P, N, M, GY, HI, RNDff, NRR, NLR, and NUE represent previous crop, N rate in previous, N management in rice, grain yield, harvest index, rice plant N uptake, N residue ratio, N loss ratio, and N-use efficiency, respectively. ns denote non-significance ( $p > 0.05$ ).

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, Northampton, MA, USA) was used to draw the figures.

### 3. Results

#### 3.1. The Effects of N Application Rate on Previous Crop Yield

Significant differences in the grain yield of rapeseed and wheat under the two different N management regimes were observed from 2017 to 2019 (Table 3). There was a significant loss in yield with the Nr application rate. For rapeseed, Nr reduced the yield by an average of 13.26% compared to the Nc application rate over two years. For wheat, Nr reduced the yield by an average of 13.61% compared to the Nc application rate over two years. The grain yield of rapeseed and wheat in the second year was higher than the first year. Although there were differences between years, the overall trend was similar in that an Nr application rate reduced the crop yield.

**Table 3.** Effects of N application rate on yield of rapeseed and wheat over two years.

Treatment (kg·ha <sup>-1</sup> )	2018		2019	
	Rapeseed (g·plot <sup>-1</sup> )	Wheat (g·plot <sup>-1</sup> )	Rapeseed (g·plot <sup>-1</sup> )	Wheat (g·plot <sup>-1</sup> )
Nc	45.44 a	472.96 a	62.10 a	505.07 a
Nr	43.89 b	400.30 b	47.75 b	445.21 b
Average	44.66	436.63	54.92	475.14
F value	11.03 *	53.82 **	33.53 **	37.20 **

Nc and Nr represent the conventional and reduced N fertilizer applications, respectively, for the two crops. Lowercase letters indicate that the yields are different under the different treatments ( $p < 0.05$ , LSD method). \* Significant at  $p < 0.05$ ; \*\* Significant at  $p < 0.01$ , respectively.

#### 3.2. Effects of N Application Rate in the Previous Season and N Management in Rice Season, on Rice Yield, Biomass, and Harvest Index

Table 4 shows the effects of Nr and N management on rice yield components and the harvest index under the wheat-rapeseed-rice rotation system. Previous crop N fertilizer input and N management in the rice season and their interactions were observed to significantly affect harvest index. The spikelet number.panicle<sup>-1</sup> (SPN), 1000-grain weight (1000-GW), seed-setting rate (SSR), harvest index (HI), and grain yield (GY) were the largest under the previous rapeseed crop (Pr) and smallest under the previous wheat crop (Pw). The rice components were the largest under Nc fertilizer input on the previous crop (Nc). The PN, SPN, SSR, HI, and GY were shown to vary in the treatments as follows: M3 > M2 > M1 > M0 under N management in the rice season. The highest GY



(106.41 g·pot<sup>-1</sup>) and HI (54.12%) were achieved with Nr in the rapeseed season and M3 N management in rice season (PrNrM3). The highest GY (105.44 g·pot<sup>-1</sup>) and HI (52.65%) were also achieved with an Nc application rate in the wheat season and M2 N management in the rice season (PwNcM2).

**Table 4.** Effects of N management on biomass, grain yield and its components, and the HI of rice.

Treatment		PN (plant <sup>-1</sup> )	SPN (NO.panicke <sup>-1</sup> )	SSR (%)	1000-GW (g)	GY (g·plot <sup>-1</sup> )	HI (%)	
Pr	Nc	M0	7.44 c	148.42 k	87.03 g	30.58 h	74.61 f	45.74 i
		M1	10.11 b	169.87 d	91.31 cd	31.34 cde	100.33 cd	51.05 f
		M2	10.49 ab	164.77 h	91.07 d	31.17 efg	102.68 abcd	50.81 g
		M3	10.40 ab	175.47 b	92.15 a	32.16 a	104.74 ab	51.41 e
		average	9.61	164.63	90.39	31.31	95.59	49.75
	Nr	M0	7.63 c	149.41 j	86.15 h	30.44 h	69.11 g	44.54 j
		M1	10.47 ab	174.33 c	89.14 f	31.22 defg	100.33 cd	51.66 d
		M2	10.19 b	167.37 f	90.05 e	31.24 defg	101.33 bcd	52.84 b
		M3	10.75 a	175.56 b	91.30 cd	32.06 a	106.41 a	54.12 a
		average	9.76	166.67	89.16	31.24	94.30	50.79
Pw	Nc	M0	7.65 c	147.92 k	85.64 i	29.94 i	71.04 fg	44.70 j
		M1	10.45 ab	169.10 e	88.91 f	31.06 fg	100.18 d	51.74 d
		M2	10.51 ab	178.32 a	91.80 ab	31.68 b	105.44 a	52.65 b
		M3	10.49 ab	165.64 g	91.63 bc	31.06 g	103.41 abcd	52.20 c
		average	9.78	165.25	89.50	30.94	95.02	50.32
	Nr	M0	7.60 c	151.01 i	86.12 h	29.22 j	68.81 g	44.52 j
		M1	10.44 ab	169.42 de	88.99 f	31.29 cdef	95.56 e	51.65 d
		M2	10.35 ab	168.70 e	91.02 d	31.41 cd	104.04 abc	51.80 d
		M3	10.23 ab	169.88 d	91.91 ab	31.49 bc	100.63 cd	50.38 h
		average	9.66	164.75	89.51	30.85	92.26	49.59
F value	P	0.95 ns	50.67 *	77.10 *	119.30 **	5.09 ns	208.49 **	
	N	0.10 ns	15.86 *	117.2 **	5.06 ns	19.70 *	33.94 **	
	M	6.49 ns	42.95 **	122.73 **	0.02 ns	2.55 ns	1156.98 **	
	P × N	199.39 **	2894.82 **	1218.18 **	556.03 **	789.56 **	10184.70 **	
	P × M	0.66 ns	2003.61 **	41.44 **	46.09 **	3.28 *	110.16 **	
	N × M	0.73 ns	401.02 **	7.72 **	18.80 **	1.71 ns	81.16 **	
	P × N × M	0.66 ns	664.95 **	7.76 **	11.01 **	4.60 *	340.68 **	

Pr and Pw represent the previous rapeseed and wheat, respectively. PN, SPN, SSR, 1000-GW, GY, and HI represent the productive panicle number, spikelet number panicle<sup>-1</sup>, 1000-grain weight, grain yield, and harvest index, respectively. Nc and Nr represent the N fertilizer input of the previous crops; M0, M1, M2, and M3 represent the N fertilizer operation in the rice season (0 kg N/hm<sup>2</sup>) and conventional N application (150 kg N/hm<sup>2</sup>), respectively. The data is the average across 2 years. Within each factor, data are the mean of three replications. Lowercase letters indicate that the yields are significantly different under different treatments ( $p < 0.05$ , LSD method). \* Significant at  $p < 0.05$ ; \*\* Significant at  $p < 0.01$ ; ns denote nonsignificance ( $p > 0.05$ ).

The previous crop N fertilizer input and N management in the rice season impacted almost all rice yield components (Table 4). The higher SSR and 1000-GW were achieved under PrNrM3. The higher productive panicle number (PN) was achieved with an Nc application rate in the wheat season and M2 N in the rice season (PwNcM2). The highest rice yields were achieved with M2 N management. The higher GY was due to a higher SSR and 1000-GW under PrNrM3. The highest rice yields were also achieved under PwNcM2, where the higher yield was due to a higher PN and SPN. In conclusion, a 2-year average data suggests that Nr application in the previous rapeseed and M3 N management in rice provides an optimal combination for rice yield and efficiency.

### 3.3. Effects of N Application Rate in the Previous Season and N Management in Rice Season, on N Accumulation and N-Use Efficiency (NUE) in Rice

The interaction effect of the previous crop, N application rate, N fertilizer management, and the previous crop and N application rate on the N accumulation in the mature period was significant. In contrast, the interaction effect of the previous crop and N fertilizer management was not significant (Table 5). Previous crops, N application rate, N fertilizer management, and the interaction of the three factors have significant impacts on

N dry matter production efficiency (NMPE), N grain production efficiency (NGPE), and N agronomy efficiency (NAE). NMPE and NGPE showed  $P_r > P_w$  under different previous crops, and  $N_c < N_r$  under the previous crop N application rate. NMPE under the treatment of N fertilizer management in the rice season showed the sequence of efficiencies to be  $M_0 > M_1 > M_2 > M_3$ , and NGPE sequence under the N fertilizer management in the rice season was  $M_0 > M_3 > M_2 > M_1$ . NAE and NPPFP under different previous crops showed  $P_r > P_w$ , and N agronomic use efficiency showed  $N_c < N_r$  under the previous crop N application, and  $M_3 > M_2 > M_1$  under rice season N management. A higher NAE and NPPFP were achieved under  $M_3$ . Compared with the  $N_c$  application rate in the rapeseed season and  $M_3$  N management in the rice season ( $P_r N_c M_3$ ), the NAE and NPPFP of rice were increased by 23.85% and 1.59% in  $P_r N_r M_3$ . Compared with  $P_w N_c M_2$ , the NAE and NPPFP of rice were decreased by 3.24% and 4.56%, with  $N_r$  application rate in the wheat season and  $M_2$  N management in rice season ( $P_w N_r M_2$ ). The interaction effect between the N application rate of the previous crop and the N fertilizer management on the N accumulation and utilization efficiency of rice is significantly higher than the interaction effect between the previous crop and the N fertilizer management and the three factors of the previous crop, the N application rate, and the N fertilizer management interaction effect. In this study, higher NPPFP and NAE of rice were achieved under  $P_r N_r M_3$  (NPPFP:  $63.84 \text{ kg} \cdot \text{kg}^{-1}$ ; NAE:  $22.38 \text{ kg} \cdot \text{kg}^{-1}$ ) and  $P_w N_c M_2$  (NPPFP:  $63.26 \text{ kg} \cdot \text{kg}^{-1}$ ; NAE:  $20.64 \text{ kg} \cdot \text{kg}^{-1}$ ), respectively. It shows that in the rapeseed–wheat–rice rotation system, reasonable N fertilizer management could improve N-use efficiency.

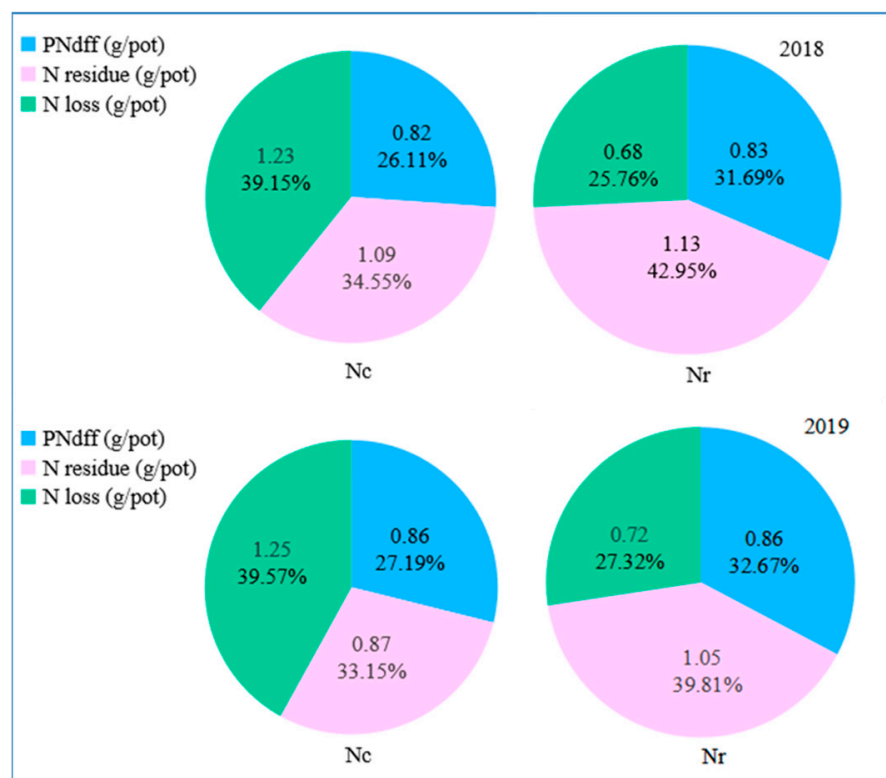
**Table 5.** Effects of N application in the previous season and N management in rice season, on N accumulation and N use efficiency (NUE) in rice.

Treatment		FTNA (g·pot <sup>-1</sup> )	MTNA (g·pot <sup>-1</sup> )	NMPE (kg·kg <sup>-1</sup> )	NGPE (kg·kg <sup>-1</sup> )	NAE (kg·kg <sup>-1</sup> )	NPPFP (kg·kg <sup>-1</sup> )	
$P_r$	Nc	M0	1.06 cd	1.27 g	127.44 ab	58.74 a	-	-
		M1	1.26 abc	1.90 bcde	103.38 d	52.81 h	15.43 j	60.20 abc
		M2	1.46 ab	1.95 ab	101.58 e	52.65 i	16.84 hi	61.60 ab
		M3	1.51 a	1.99 a	96.10 g	52.63 h	18.07 efg	62.84 a
	average	1.32	1.77	107.07	54.21	16.78	61.54	
	Nr	M0	1.02 de	1.21 g	128.23 a	57.12 b	-	-
		M1	1.18 bcd	1.81 f	107.35 c	55.43 d	18.76 def	60.19 abc
		M2	1.28 abc	1.86 ef	100.41 ef	55.07 e	19.33 cd	60.79 abc
		M3	1.36 abc	1.85 def	99.81 f	57.51 bc	22.38 a	63.84 a
	average	1.21	1.68	108.92	56.28	20.16	61.61	
$P_w$	Nc	M0	0.99 de	1.26 g	126.13 b	56.38 c	-	-
		M1	1.29 abc	1.92 abcd	100.84 ef	52.18 hi	17.48 gh	60.10 abc
		M2	0.93 e	1.93 abc	103.72 d	53.58 g	20.64 b	63.26 a
		M3	1.49 ab	1.95 ab	94.02 h	54.07 fg	19.42 cd	62.05 ab
	average	1.17	1.76	106.15	54.05	19.18	61.8	
	Nr	M0	1.11 cd	1.22 g	126.69 ab	56.4 c	-	-
		M1	1.27 abc	1.91 bcde	99.31 f	50.82 j	16.05 ij	57.33 c
		M2	1.17 bcd	1.88 cde	103.63 d	54.47 g	19.97 bc	60.42 abc
		M3	1.28 abc	1.92 bcd	95.64 gh	52.41 h	19.09 cde	60.37 abc
	average	1.20	1.73	106.28	53.52	18.37	59.37	
F value	P	2.31 ns	13.90 *	37.32 *	153.23 **	1.38 ns	2.81 ns	
	N	0.76 ns	31.60 **	11.24 *	44380.44 **	4.31 ns	7.65 *	
	M	10.70 **	855.91 **	6492.95 **	583.35 **	55.37 **	4.33 *	
	$P \times N$	2.71 ns	7.80 *	8.26 *	21103.99 **	43.19 **	88.28 **	
	$P \times M$	3.64 *	1.44 ns	99.43 **	68.40 **	158.64 **	39.66 **	
	$N \times M$	1.24 ns	0.49 ns	16.25 **	59.60 **	196.50 **	51.93 **	
	$P \times N \times M$	1.24 ns	0.62 ns	17.82 **	79.91 **	170.30 **	64.34 **	

$P_r$  and  $P_w$  represent the previous rapeseed and wheat, respectively. FTNA: total N accumulation at full-heading; MTNA: total N accumulation at maturity; NMPE: N dry matter production efficiency; NGPE: N grain production efficiency; NAE: N agronomy efficiency; NPPFP: N partial factor productivity. Nc and Nr represent the N fertilizer input of the previous crops; M0, M1, M2, and M3 represent the N fertilizer operation in the rice season ( $0 \text{ kg N/hm}^2$ ) and conventional N application ( $150 \text{ kg N/hm}^2$ ), respectively. The data is the average across 2 years. Within each factor, data are the mean of three replications. Lowercase letters indicate that the yields are significantly different under different treatments ( $p < 0.05$ , LSD method). \* Significant at  $p < 0.05$ ; \*\* Significant at  $p < 0.01$ ; ns denote nonsignificance ( $p > 0.05$ ).

### 3.4. Fate of $^{15}\text{N}$ -Labeled Urea in the Previous Season Crop

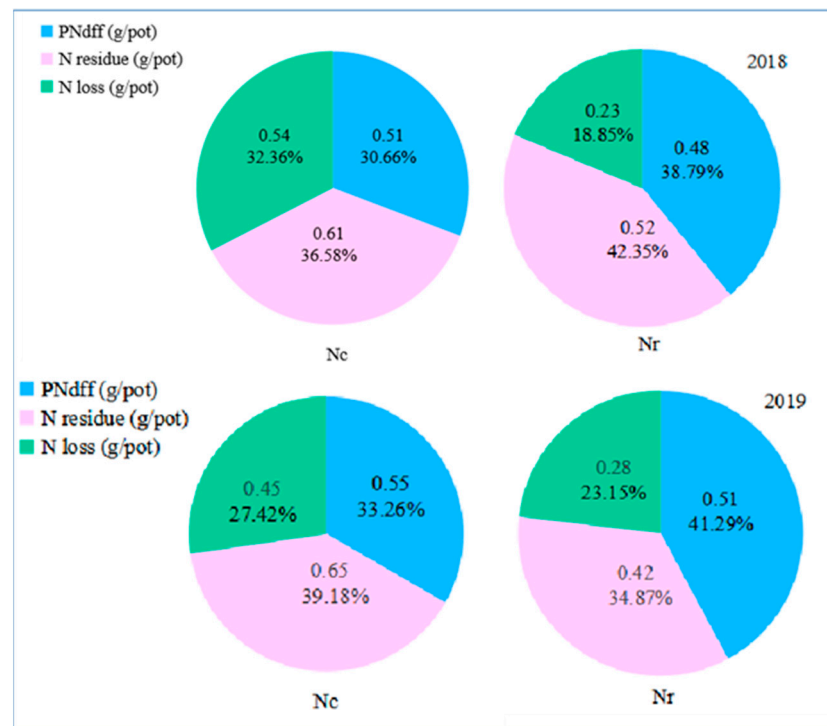
The N accumulation in the rapeseed plant derived from fertilizer (Ndff), the residual fertilizer N in the soil (N residue), and the fertilizer N loss (N loss) at the mature stage determined from  $^{15}\text{N}$  tracing showed a substantial variation across N applications (Figure 2). In the rapeseed season, with conventional  $^{15}\text{N}$ -labeled urea application over 2 years, rapeseed plants were shown to absorb an average of 0.84 g N/pot (26.65%), and 0.98 g N/pot (33.85%) was residual in the soil after harvesting, and the other 1.24 g N/pot (39.36%) was lost. Under the reduced  $^{15}\text{N}$ -labeled urea application over 2 years, rapeseed plants absorbed an average of 0.85 g N/pot (32.18%), 1.14 g N/pot (41.38%) was residual in the soil after harvesting, and the balance, 0.70 g N/pot (26.54%), was lost. This shows that the rapeseed plants absorbed  $^{15}\text{N}$ -labeled urea, and the residual soil N under reduced  $^{15}\text{N}$ -labeled urea application was more than that under the conventional  $^{15}\text{N}$ -labeled urea application.



**Figure 2.** The fate of nitrogen fertilizer in the rapeseed season.

In the wheat season, the trend over the two years was consistent (Figure 3). Wheat plants absorbed an average of 0.53 g N/pot (31.96%), 0.63 g N/pot (37.88%) was residual in the soil after harvesting wheat, and the balance, 0.49 g N/pot (29.89%), was lost under conventional  $^{15}\text{N}$ -labeled urea application over two years. The reduced application of  $^{15}\text{N}$ -labeled urea to wheat plants over two years showed that they absorbed an average of 0.50 g N/pot (40.04%), 0.47 g N/pot (38.61%) was residual in the soil after harvesting the wheat, and the other 0.25 g N/pot (21.00%) was lost. Wheat plants absorbed more  $^{15}\text{N}$ -labeled urea under a reduced  $^{15}\text{N}$ -labeled urea application.





**Figure 3.** The fate of nitrogen fertilizer in the wheat season.

### 3.5. Residual N Uptake and Use Regulated by N Management in Rice Season

The N accumulation in rice plants derived from fertilizer (Ndff), the residual fertilizer N in the soil (N residue), and the N fertilizer loss (N loss) from  $^{15}\text{N}$  application in the previous crop season are shown in Table 6. The N fertilizer input in the previous crop, the N management in the rice season, and their interaction were observed to significantly affect Ndff at the heading stage and on the N residue ratio and loss ratio. The Ndff in rice (RNdff) was largest under Pr and smallest under Pw. Pr increased by 2.83% relative to Pw. The RNdff was the largest under Nc, and it was shown that yields for the treatments were in the order of M3 > M2 > M1 > M0 under N management in the rice season. M3 increased by 2.25%, 3.63%, and 10.35% relative to M2, M1, and M0, respectively. The N residue ratio was largest under Pw and smallest under Pr. Pw increased by 22.92% relative to Pr. The N residue ratio was the largest under Nc, and it was shown that yields for the treatments were in the order of M1 > M0 > M2 > M3 under N management in the rice season. M1 increased by 0.25%, 2.05%, and 13.18% relative to M0, M2, and M3, respectively. The N loss rate was largest under Pr and smallest under Pw. The N loss rate was largest under Nc, and it is shown that yields for the treatments were in the order of M0 > M1 > M2 > M3 under N management in the rice season. In summary, in the rice season, the higher accumulation of  $^{15}\text{N}$  in plants was achieved with Nr in the rapeseed season and M3 N management in rice season (PrNrM3), and with an Nc application rate in the wheat season and M3 N management in the rice season (PwNcM3). The accumulation of  $^{15}\text{N}$  in plants of PrNrM3 and PwNcM3 accounted for 21.35% and 36.72% of the residual N in the previous crop, respectively. The residual soil  $^{15}\text{N}$  was higher under the Nc application rate in the wheat-rice rotation over two years. The rice plants used the residual N from the tillering to the mature stage under the M3 model in the rice season most with the Nr application rate for rapeseed and Nc application rate for wheat. The  $^{15}\text{N}$  not detected in plant and soil was considered to be lost (fertilizer N loss).

**Table 6.** Fate of residual nitrogen in previous crops in rice season under rapeseed–wheat–rice rotation system.

Treatment	<sup>15</sup> N Accumulation of Rice Plant (mg <sup>15</sup> N·pot <sup>-1</sup> )			<sup>15</sup> N-Residue Ratio (%)	<sup>15</sup> N Loss Ratio (%)		
	TS	HS	MS				
Pr	Nc	M0	13.48 de	95.54 k	97.57 lm	11.84 hi	68.78 b
		M1	16.22 bc	101.83 fgh	102.13 ij	14.21 bcdef	63.78 g
		M2	15.30 cd	99.72 hij	104.45 hij	14.62 bcde	63.32 h
	average	M3	15.55 cd	104.03 def	108.95 def	14.82 bcd	62.36 i
		average	15.14	100.28	103.28	13.87	64.18
		M0	12.07 ef	97.36 jk	101.70 j	12.13 ghi	67.28 c
	Nr	M1	13.77 de	108.02 abc	108.56 efg	13.02 efg	66.01 e
		M2	15.41 cd	103.55 ef	107.57 efg	13.56 defg	66.00 e
		M3	15.22 cd	105.58 cde	111.98 bc	12.93 fgh	66.04 e
	average	average	14.11	103.62	107.45	12.91	66.71
		M0	15.27 cd	100.59 ghi	106.28 fgh	18.94 a	46.10 l
		M1	16.60 bc	105.75 cde	110.51 cde	19.18 a	44.14 o
Nc	M2	17.08 ab	100.17 ghi	111.39 bc	18.70 a	45.24 m	
	M3	17.91 ab	101.61 fgh	111.84 bc	18.69 a	44.62 n	
	average	17.71	105.53	111.75	18.12	45.02	
Pw	M0	M0	9.27 h	85.53 m	89.24 n	18.91 a	44.89 mn
		M1	11.96 efg	89.50 l	94.62 m	15.40 bc	43.15 p
		M2	9.81 gh	91.28 l	102.17 ij	13.69 defg	43.27 p
	M3	M3	10.62 fgh	91.73 l	105.37 ghi	11.14 i	42.18 q
		average	10.41	89.51	97.85	14.78	43.37
		P	23.19 **	252.29 **	13.83 *	142.53 **	4740.04 **
	N	N	172.97 **	148.16 **	31.59 **	17.02 **	1669.33 **
		M	23.43 **	75.82 **	145.65 **	5.34 **	798.51 **
		P × N	78.07 **	636.83 **	335.89 **	42.49 **	529.82 **
	F value	P × M	0.19 ns	4.51 **	3.70 **	20.27 **	166.87 **
		N × M	0.11 ns	2.52 ns	1.47 ns	7.27 **	99.08 **
		P × N × M	5.11 **	1.82 ns	2.67 *	1.47 ns	18.61 **

TS, tillering; HS, heading stage; MS, maturation stage; Pr and Pw represent the previous rapeseed and wheat, respectively. Nc and Nr represent the N fertilizer input of the previous crops; M0, M1, M2, and M3 represent the N fertilizer operation in the rice season (0 kg N/hm<sup>2</sup>) and conventional N application (150 kg N/hm<sup>2</sup>), respectively. The data is the average across two years. Within each factor, data are the mean of three replications. Lowercase letters indicate that the yields are significantly different under different treatments ( $p < 0.05$ , LSD method). \* Significant at  $p < 0.05$ ; \*\* Significant at  $p < 0.01$ ; ns denote nonsignificance ( $p > 0.05$ ).

## 4. Discussion

### 4.1. The Fate of <sup>15</sup>N Fertilizer of the Previous Crop in Rapeseed/Wheat and Rice Crop Rotation

The fate of N fertilizer in a flooded soil-rice plant ecosystem has been extensively investigated using the <sup>15</sup>N tracing method [19]. It is a valuable tool for distinguishing fertilizer N from soil N. In this study, the <sup>15</sup>N tracing technology indicated that the <sup>15</sup>N-labeled urea utilization rate of rapeseed and wheat under the Nc application rate was less than that of reduced <sup>15</sup>N-labeled urea applications in the rapeseed and wheat seasons over 2 years (Figures 2 and 3). This study found that 26.65–32.18% of the N fertilizer in the rapeseed season was absorbed by the plant, 33.85–41.38% was residual in the soil, and 26.54–39.36% was lost through various means. In the wheat season, 31.96–40.04% was absorbed by the plants, 37.88–38.61% was residual in the soil, and 21.00–29.89% was lost through various ways. The <sup>15</sup>N residue in the soil is usually reported to increase with fertilizer application [20–23]. However, the present study indicates that the residual soil <sup>15</sup>N under the Nc application rate was less than that under the Nr application rate in the rapeseed-rice rotation over two years. The residual soil <sup>15</sup>N was higher under the Nc application rate in the wheat-rice rotation over two years. NH<sub>3</sub> volatilization and denitrification were previously reported as the dominant N loss pathways from flooded rice, which could have adverse environmental consequences such as air pollution, soil acidification, and water eutrophication [24]. The present study observed that the loss of fertilizer <sup>15</sup>N in paddy soil from the tillering stage to the mature stage in the M0 regime in the rapeseed season was lower than that in the Nc application rate over two years. It

was also observed that the loss of fertilizer  $^{15}\text{N}$  in paddy soil from the tillering stage to the mature stage in the M0 regime in the wheat season was lower than that under the Nc and Nr application rates in the wheat season in a wheat–rice rotation system. N loss was relatively high throughout the rapeseed–wheat rotation system. One possible reason is that soil organic N sources can be assimilated by plants more than inorganic N fertilizer [25]. The residual N fertilizer in the soil under the rapeseed–rice rotation was higher than that under the wheat–rice rotation. This is probably because rapeseed roots are relatively large, and therefore, the  $^{15}\text{N}$  absorbed is higher than that in wheat. The roots decompose more slowly in the paddy field; therefore, more  $^{15}\text{N}$  remains in the soil than in the rapeseed–rice rotation. Zhu et al. [26] reported that the dominant effect of plant growth is the reduction in loss of N, which means that the higher the N uptake, the lower the fertilizer N lost. N topdressing at vigorous growth stages when plant N uptake is higher could reduce uncounted N loss and  $\text{NH}_3$  volatilization [20]. This study found that the rice season follows rapeseed with a  $^{15}\text{N}$  content higher than wheat, mainly because the biological yield of rapeseed is relatively large, and the  $^{15}\text{N}$  content in rapeseed is higher than that in wheat. During the rice growth process, the N requirement is greater during the tillering period; increasing the N fertilizer during this period will promote the absorption of residual N from previous crops. Therefore, the full consideration of the effects of the previous crops can improve the N fertilizer utilization of annual crops.

#### 4.2. Crop Yield Influenced by N Rates and N Management in Rapeseed/Wheat and Rice Rotation System

The responses of rapeseed and wheat yields to N application have been widely studied in recent decades. In general, rapeseed and wheat yields increase with increasing N application, within a certain range [27]. A similar result was confirmed in the present study. The highest rapeseed and wheat yields were achieved at an N application rate of approximately  $3.14 \text{ g}\cdot\text{plot}^{-1}$  and  $1.66 \text{ g}\cdot\text{plot}^{-1}$  in 2018 and 2019, respectively (Table 3). It might be that the root system of the crop is improved so that the water and nutrients in the soil are more easily absorbed and utilized by the crop and converted into biomass. In general, rice grain yield increases and then plateaus, or even decreases, with increasing N application [28,29]. The rapeseed–rice, double-cropping system is an important mode of grain and oil planting, and the wheat–rice, double-cropping system is the largest grain-increment planting model in agricultural production. The latter system is a typical, modern, intensive, high input and output system, but also carries very high resource and environmental costs, due to the high N fertilizer inputs, especially over the last three decades [30]. Some studies have reported that N fertilizer can be used to satisfy the N demand of the crop, ensuring high and stable yields of crops under the rapeseed–rice and wheat–rapeseed rotation systems [31]. In this study, the higher rice yields were achieved under PrNrM3 ( $106.41 \text{ g}\cdot\text{pot}^{-1}$ ) and PwNcM2 ( $105.44 \text{ g}\cdot\text{pot}^{-1}$ ). The appropriate N fertilizer management could result in a reasonable use of rapeseed straw nutrients and residual N in the soil to promote early rice tillering, which can reduce effective tillering, increase SSR, and 1000-GW of the rice; this improved the grain yield of rice. The rice yield of the rapeseed–rice rotation was higher than that of wheat–rice rotation in 2018 and 2019. Farming folklore affirms that “rapeseed is a land-raising crop,” which is supported by the results of this study [32]. This can be attributed to the large, straight roots of the rapeseed plant and their ability to absorb nutrients. Rapeseed is beneficial in improving soil structure, and the organic acids secreted by the roots can dissolve the insoluble phosphorus in the soil and improve the phosphorus content of the soil [33]. From the perspective of the whole crop rotation cycle, reasonable N distribution is an important way for crops to efficiently use fertilizer resources and achieve high yields.

#### 5. Conclusions

Reduced N for rapeseed and the M3 N regime in rice under a rapeseed–rice rotation system (PrNrM3) can be recommended to stabilize yield and be used as a N-saving and environmentally friendly measure rapeseed–rice rotation systems in southern China. Further long-term studies should focus on exploring lower N fertilizer input to optimize

the application rates of N fertilizer and quantify the environment costs so that the best combination can be applied in agricultural systems.

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