agronomy

MDPI

Article

Effects of Grain Sprout Fertilizer Application Rate on Yield and Its Composition of Hybrid Middle Rice–Ratoon Rice System

Fuxian Xu [1], Chi Yuan [2], Dong Han [3], Rong Xie [1], Xingbing Zhou [1], Peng Jiang [1], Xiaoyi Guo [1], Hong Xiong [1], Lin Zhang [1] and Changchun Guo [1,*]

[1] Key Laboratory of Southwest Rice Biology and Genetic Breeding, Ministry of Agricultureand Rural Affairs, Rice and Sorghum Research Institute, Sichuan Academy of Agricultural Sciences, Deyang 618000, China; xufuxian@scrsri.cn (F.X.); xierong@scrsri.cn (R.X.); zhouxingbing@scrsri.cn (X.Z.); jiangpeng@scrsri.cn (P.J.); guoxiaoyi@scrsri.cn (X.G.); xionghong@scrsri.cn (H.X.); zhanglin@scrsri.cn (L.Z.)

[2] Neijiang Academy of Agricultural Sciences, Neijiang 641000, China; yuanchi@njnky.cn

[3] Yibin Academy of Agricultural Sciences, Yibin 644000, China; handong@ybsnky.cn

* Correspondence: guochangchun@scrsri.cn

Abstract: Enhancing yield and achieving environmental goals represent challenges for the future of agriculture. Rational nitrogen (N) management is one of the most promising ways to meet this challenge. However, complicated nitrogen management strategies and considerable input requirements still exist in rice–ratoon rice production. To address this issue, field experiments were conducted with two main high-yield rice crop genotypes and five fertilization treatments at six sites in Southwest China from 2018 to 2020. The results showed the following: (1) the yield of the main rice crop was extremely significantly affected by the year, location, and fertilization, but not by genotype; (2) the yield of the ratoon rice was extremely significantly affected by year, genotype, location, and fertilization; and (3) the total plant N content (TPN) and leaf SPAD value at the full heading stage of the main crop were significantly positively correlated with the total soil N content (TSN) and soil available N (SAN) content of the basic soil. The highly efficient N application rate of grain- and bud-promoting fertilizer for ratoon rice was 60–120 kg ha^{-1}. The TSN, SAN, TPN, and SPAD values higher than 0.247 kg N kg^{-1}, 298 mg N kg^{-1}, 2.159 kg N kg^{-1}, and 49.94 were, respectively, considered the reference values when not applying grain- and bud-promoting fertilizer. A regression equation was established to predict the amount of high-efficiency grain- and bud-promoting fertilizer based on the TSN and SPAD. Overall, the yield of rice–ratoon rice was significantly affected by year, genotype, location, fertilization, and their interactions. The use of the predicted grain- and bud-promoting fertilizer regression equation can achieve high yields under simplified and reduced N input practices in the rice–ratoon rice systems.

Keywords: rice–ratoon rice; yield and its composition; grain- and bud-promoting fertilizer; high-efficiency N application rate; ecological point

Citation: Xu, F.; Yuan, C.; Han, D.; Xie, R.; Zhou, X.; Jiang, P.; Guo, X.; Xiong, H.; Zhang, L.; Guo, C. Effects of Grain Sprout Fertilizer Application Rate on Yield and Its Composition of Hybrid Middle Rice–Ratoon Rice System. *Agronomy* **2024**, *14*, 1065. https://doi.org/10.3390/agronomy14051065

Academic Editor: Jiafa Luo

Received: 19 March 2024
Revised: 19 April 2024
Accepted: 14 May 2024
Published: 17 May 2024

1. Introduction

Meeting the substantial increase in food demand and decreasing the global environmental impact of agriculture are great challenges for the future of agriculture [1,2]. Ratoon rice is the cultivation practice of having a second harvest in one cropping season based on the tillers and originating from the stubble of the previous main crop. This practice can obtain high-yield, high-quality rice by making full use of light and heat resources after the main crop harvest and have a high efficiency, such as in saving seeds and reducing labor [3,4]. According to the calculation of the temperature conditions required for ratoon rice, the area where ratoon rice can be planted in China covers approximately 3.4 million ha [4]. Therefore, ratoon rice has become a research topic of major interest over the past 10 years [5–7].

The area of ratoon rice production in Southwest China covered by winter paddy fields is approximately 4×10^5 ha, and an additional 6×10^5 ha represents potential land, constituting the main producing areas for ratoon rice in China. Fertilization techniques are key for high yields in rice–ratoon rice systems. Previous researchers have conducted a systematic study on balanced fertilization techniques to ensure high yields of main crop rice and ratoon rice, including the mechanism of bud-promoting fertilizer, the relationship between spikelets per panicle of variety and the application of bud-promoting fertilizer, and the relationship between leaf SPAD value and grain fertilizer for the main crop and bud-promoting fertilizer for the ratoon rice [8–11]. These research results have played an important role in improving the yield of ratoon rice.

However, there are still two deficiencies in the high-yield fertilization technique of the rice–ratoon rice cultivation mode. One is that there are many fertilization applications, including basal fertilizer, tilling fertilizer, and grain fertilizer for the main crop, and bud-promoting fertilizer and N fertilizer application at the tilling stage of ratoon crops for ratoon rice, leading to difficult work and high labor costs [12,13]. Another deficiency is that the ratoon rice yield is approximately 30–50% of the first season's yield, but the bud-promoting fertilizer is equivalent to 105–135 kg ha^{-1} of that for the main crop, leading to low N use efficiency [14]. Therefore, reducing the fertilizer and N inputs is an urgent problem to be solved in rice production. Based on the research results that the N application rate for high-yield rice–ratoon rice systems is 90–150 kg ha^{-1}, and the observation that winter paddy fields have strong water and fertility retention in Southern China, the objectives of this study were to evaluate the effects of the "basal fertilizer for the main crop and grain- and bud-promoting fertilizer for ratoon crop" two-time, two-crop fertilization mode on rice–ratoon rice yield in different ecological points and provide management options to increase resource use efficiency in rice–ratoon rice systems.

2. Materials and Methods

2.1. Experimental Site and Materials

The experiment was conducted from 2018 to 2020 in typical paddy fields at six rural community sites of four cities (Fuji (FJ-LZ), Desheng (DS-LZ) and Taihe (TH-LZ) in Luzhou, Daguan (DG-YB) in Yibin, Yunding (YD-NJ) in Neijiang, and Huzhu (HZ-ZG) in Zigong) in the Sichuan Province of China, and different fields adjacent to each other at the same location were adopted over the different years. The sites and their basic soil properties, with a 0–30 cm depth range, at the six rural community experimental sites are described in Table 1. The six rural community sites have almost the same climate characteristics.

Nei 6 you 107 (N 107) and Rong 18 you 1015 (R 1015), two elite Indica three-line hybrid rice cultivars, are widely planted upstream of China's Yangtze River because of their good yield, high quality, and strong ratooning ability. The seedlings were raised in seedbeds with sowing dates from 5 to 10 March. The 4.5 leaf seedlings were then transplanted to a seedbed with a spacing of 30 cm $\times$ 20 cm and two seedlings per hill.

Table 1. Geographic locations of the soil at the experimental sites and basic fertility before applying the fertilizers.

Site	Year	Geography Position			Basic Fertility of Soil							
		Longitude (°)	Latitude (°)	Altitude (m)	Organic Matter (kg kg^{-1})	Total N (kg kg^{-1})	Total P (kg kg^{-1})	Total K (kg kg^{-1})	pH Value	Available N (mg kg^{-1})	Available P (mg kg^{-1})	Available K (mg kg^{-1})
YD-NJ	2018	105.12	29.15	335	3.22	0.182	0.018	1.13	4.50	176.8	46.0	59
	2019				3.97	0.163	0.021	0.99	3.85	161.9	15.6	71
	2020				3.44	0.169	0.034	1.16	4.36	194.5	13.7	88.2
DS-LZ	2018	105.26	29.50	287	4.58	0.139	0.047	1.72	4.50	112.6	13.8	167
	2019				3.27	0.153	0.026	1.53	4.96	179.4	11.0	173
	2020				3.31	0.125	0.019	1.62	4.71	121.8	13.2	145.3
FJ-LZ	2018	105.23	29.10	303	2.88	0.115	0.036	1.89	4.66	89.9	14.6	98.0
	2019				2.92	0.103	0.014	1.40	5.15	48.9	10.1	119.0
	2020				3.16	0.138	0.024	1.73	5.18	96.9	17.7	107.4
TH-LZ	2018	105.19	29.11	330	2.80	0.171	0.0273	1.88	5.33	152.2	14.7	158
	2019				3.55	0.133	0.024	1.47	5.43	122.2	15.0	108
	2020				3.35	0.191	0.036	1.63	5.85	163.0	7.5	136
HZ-ZG	2018	104.97	29.27	284	3.46	0.205	0.048	1.99	7.53	198.6	15.8	116
	2019				3.09	0.178	0.046	1.65	7.18	228.1	18.2	187
	2020				2.87	0.174	0.038	1.51	7.30	1773	23.1	126.5
DG-YB	2018	104.54	28.58	289	4.08	0.176	0.036	1.89	7.78	184.2	17.4	149
	2019				3.45	0.183	0.044	1.74	7.26	185.6	21.1	132
	2020				3.25	0.141	0.031	1.64	7.59	1351	17.3	139.7

2.2. Experimental Design

The experiment was laid out in a split-plot design. The main plot treatments constituted two varieties, and the split plot treatments constituted five fertilization treatments. No fertilizer was applied throughout the reproductive period as a control (CK). In addition to the control treatment, urea (Pure N, 46.3%), phosphate fertilizer (P_2O_5), and potash fertilizer (K_2O) were applied as basal fertilizers at 105 kg ha^{-1}, 40 kg ha^{-1}, and 60 kg ha^{-1}, respectively, before the transplantation. The grain- and bud-promoting fertilizer was applied at the full heading stage of the main crop, and the N application rate of the grain- and bud-promoting fertilizer comprised four levels as follows: 0 kg N ha^{-1} (N_0), 60 kg N ha^{-1} (N_{60}), 120 kg N ha^{-1} (N_{120}), and 180 kg N ha^{-1} (N_{180}). The experiment was conducted in three replicates with a plot size of 5 m $\times$ 3 m. To prevent the flow of water and fertilizer between neighboring plots, the plots were separated by a 40 cm wide ridge created by a plastic film inserted into the soil to a depth of 30 cm. Individual inlets and outlets on the boundary side of the ridges were established in each plot for irrigation and drainage. The cutting height of the plant culms was 35 cm for the ratoon crop while the main crop was harvested in all treatments. Diseases and insects were intensively controlled with chemicals to avoid yield losses in certain years.

2.3. Indexes and Measurement Methods

2.3.1. SPAD Values

At the full heading stage of the main crop, an SPAD-502 chlorophyll meter (Minolta, Osaka, Japan) was used to obtain the SPAD values (SPAD units) from the three uppermost, fully expanded leaves on 5 stems of each plant. Three SPAD readings per leaf were obtained, i.e., one near the leaf blade midpoint and the other two located 1/3 to either side of the midpoint, which were then averaged as the mean SPAD reading of a leaf. Five plants were measured in every plot.

2.3.2. N Accumulation

The five measured plants were dug out with a spade (20 cm $\times$ 20 cm $\times$ 20 cm soil volume around the roots). The plants were washed and the roots were removed. The fresh samples were dried at 105 °C for 30 min and then oven dried at 80 °C until they reached a constant weight to determine the dry matter weight. Then, the samples were milled and sieved to determine their total N content using the Kjeldahl method.

2.3.3. Yield and Its Components

The maximum tiller number of the main crop was recorded for 20 plants once a week until the tillers began to fall from 20 d after transplanting. The yield components, including the panicles m^{-2}, spikelets per panicle, percentage of grain filling and grain weight, were determined from 20 plants sampled randomly from each plot. The grain yield was determined from all plants within a 12.0 m^2 area in each plot. The crops were harvested manually and threshed by a hand-driven thresher. The grain moisture content was determined immediately after threshing (Riceter grain moisture meter, Kett Electric Laboratory, Tokyo, Japan). The grain yields and grain weights were reported based on the standard moisture content of 135 g H_2O kg^{-1} fresh weight. The methods for investigating ratoon crop grain yield and yield components were the same as those used for the main crop.

2.4. Statistical Analysis

The software used for statistical analysis was the Statistical Software Package for Social Science (version 19.0; SPSS Inc., Chicago, IL, USA), and the treatment means were compared by the least significant difference test at the 0.05 probability level. Correlation analyses, regression analyses, and plots were performed using Origin 2019 software (OriginLab Corp., Northampton, MA, USA).

3. Results

3.1. Yield and Its Components of the Main Crop

The rice yield and yield components of the main crop are extremely significantly affected by year and location (Table 2). The yield of the main crop from highest to lowest occurred in 2019, 2018, and 2020. The highest yield of the main crop was 9644.7 kg ha^{-1} in YD-NJ, and the lowest was 8113.8 kg ha^{-1} in TH-LZ. The yield components of the main crop were extremely significantly affected by genotype as well, but the yield was not significant due to the coordination effect between the panicle–grain structure. There was no significant difference in the grain yield of the main rice crop among the four grain- and bud-promoting fertilizer treatments, and the yields under the grain- and bud-promoting fertilizer treatments were significantly higher than those under the control. In terms of the interaction between the experimental factors, the interaction between the factors exhibited extremely significant effects on the yield. This shows that the application rate of "basic fertilizer" in this experiment can fully meet the nutrient requirements of the high-yield rice of the main crop, and it is universally suitable. The application of grain- and bud-promoting fertilizer at the full heading stage had no adverse effect on the yield of the main crop regardless of the application amount. The output was also affected by many factors, such as the climate in different years, location, genotype, and fertilization. In addition, the results show that the number of panicles m^{-2} have the largest direct effect on the yield, followed by spikelets per panicle of the main crop, and both exhibit a positive effect. The sum of the indirect effects of the highest maximum tillers m^{-2} on the yield is the largest, and the trend of the results has been consistent for 3 years (Table 3). Therefore, the main goal of achieving a high yield for the main crop is to increase the numbers of panicles m^{-2} and spikelets per panicle by increasing the rate of panicle formation on the basis of higher seedling peaks across the winter paddy fields in Southern China.

Table 2. Analysis of variance for the grain yield and the yield-related traits of the main crop under different treatments in the rice–ratoon rice system.

Treatments		Maximum Tillers m^{-2}	Panicles m^{-2}	Spikelets Per Panicle	Grain Filling (%)	Grain Weight (mg)	Grain Yield (kg ha^{-1})
Year (Y)	2018	312.1 a	216.6 a	155.5 c	92.4 a	30.7 c	9086.1 b
	2019	314.8 a	217.2 a	164.4 b	88.9 b	31.3 b	9225.4 a
	2020	277.4 b	193.3 b	167.6 a	89.1 b	31.7 a	8562.3 c
Genotype (G)	R 1015	271.4 b	200.2 b	173.9 a	89.5 b	30.5 b	8938.8 a
	N 107	329.7 a	217.1 a	151.1 b	90.8 a	32.0 a	8977.1 a
Location (L)	YD-NJ	422.0 a	252.1 a	143.4 e	88.7 c	32.0 a	9644.7 a
	DS-LZ	245.5 d	202.5 c	175.3 a	88.9 c	29.8 d	8997.2 c
	FJ-LZ	284.0 c	192.7 d	166.2 c	91.2 a	31.4 bc	8855.1 d
	TH-LZ	220.0 e	189.9 d	153.1 d	92.2 a	31.6 b	8113.8 f
	HZ-ZG	273.1 c	189.3 d	169.8 b	89.7 bc	31.6 b	8701.3 e
	DG-YB	358.8 b	225.6 b	167.3 bc	90.1 b	31.1 c	9435.4 b
Fertilization (F)	CK	262.4 b	171.5 b	165.0 a	89.9 ab	31.3 a	7480.7 b
	N_0	304.6 a	215.0 a	164.0 ab	90.1 ab	31.1 a	9322.9 a
	N_{60}	311.0 a	218.2 a	161.2 bc	90.6 a	31.3 a	9325.5 a
	N_{120}	309.2 a	219.5 a	160.2 c	90.3 ab	31.3 a	9331.4 a
	N_{180}	315.6 a	219.1 a	162.2 abc	89.7 b	31.2 a	9329.1 a

Table 2. *Cont.*

Treatments		Maximum Tillers m^{-2}	Panicles m^{-2}	Spikelets Per Panicle	Grain Filling (%)	Grain Weight (mg)	Grain Yield (kg ha^{-1})
F-value	Y	61.9 **	199.0 **	110.1 **	132.4 **	55.2 **	280.4 **
	L	443.1 **	356.4 **	195.9 **	32.4 **	72.5 **	341.9 **
	G	394.4 **	240.3 **	1075.3 **	45.3 **	358.9 **	2.5
	F	43.7 **	290.6 **	6.5 **	2.7 *	0.8	938.8 **
	Y × L	54.2 **	127.1 **	70.9 **	18.3 **	45.1 **	61.2 **
	Y × G	3.5 *	13.5 **	9.8 **	62.8 **	15.0 **	25.4 **
	Y × F	2.6 *	6.7 **	2.1 *	0.5	0.8	29.5 **
	L × G	16.1 **	11.8 **	12.7 **	21.5 **	7.4 **	12.8 **
	L × F	4.7 **	3.1 **	2.5 **	1.7	1.3	2.4 **
	V × F	0.8	2.1	1.7	0.7	0.5	0.3
	Y × L × G	3.7 **	7.7 **	7.7 **	9.9 **	5.0 **	10.8 **
	Y × L × F	1.9 *	2.3 **	2.1 **	1.2	1.7 *	4.0 **
	Y × G × F	0.6	1.1	2.0	1.4	0.4	0.9
	L × G × F	0.7	1.7	1.6	0.8	1.2	0.6

R 1015, Rong 18 you1015; N 107, Nei 6 you 107; YD-NJ, Yunding in the city of Neijiang City; FJ-LZ, Fuji in the city of Luzhou; DS-LZ, Desheng in the city of Luzhou; TH-LZ, Taihe in the city of Luzhou; HZ-ZG, Huzhu in the city of Zigong; DG-YB, Daguan in the city of Yibin; N_0, 0 kg N ha^{-1} for grain- and bud-promoting fertilizer; N_{60}, 60 kg N ha^{-1} for grain- and bud-promoting fertilizer; N_{120}, 120 kg N ha^{-1} for grain- and bud-promoting fertilizer; N_{180}, 180 kg N ha^{-1} for grain- and bud-promoting fertilizer; CK, without fertilization. * Significant at the 0.05 probability level. ** Significant at the 0.01 probability level. Different lowercase letters represent statistical differences at the 5% probability level for the same column, different years, different varieties, different ecological sites, and different N application rates.

Table 3. Path analysis of the yield and yield traits of the main crop rice.

Year	Traits	Correlation Coefficient	Direct Effect	Indirect Effect					
				Total	$\to x_1$	$\to x_2$	$\to x_3$	$\to x_4$	$\to x_5$
2018	x_1	0.7122	0.0118	1.3864		1.4380	−0.6169	−0.0702	−0.0506
	x_2	0.7720	1.6014	0.2444	0.0106		−0.6259	−0.0794	−0.1347
	x_3	−0.0975	1.1820	−1.0714	−0.0061	−0.8481		−0.0479	−0.3773
	x_4	−0.2371	0.2262	−0.6068	−0.0037	−0.5622	−0.2502		0.3527
	x_5	−0.2707	0.6398	−0.7134	−0.0009	−0.3371	−0.6971	0.1247	
2019	x_1	0.6590	−0.2870	0.9460		1.3137	−0.4024	−0.0167	0.0514
	x_2	0.8333	1.5620	−0.7287	−0.2414		−0.4302	−0.0237	−0.0334
	x_3	−0.2435	0.6936	−0.9371	0.1665	−0.9688		−0.0203	−0.1145
	x_4	−0.2450	0.0840	−0.329	0.0570	−0.4408	−0.1677		0.2225
	x_5	−0.0571	0.3299	−0.3869	−0.0447	−0.1582	−0.2407	0.0567	
2020	x_1	0.4469	0.1472	0.2997		0.5566	−0.3575	−0.0464	0.1470
	x_2	0.7838	1.0627	−0.2789	0.0771		−0.3709	−0.0285	0.0434
	x_3	0.0327	0.7680	−0.7354	−0.0685	−0.5133		0.0015	−0.1551
	x_4	−0.0020	0.1974	−0.1994	−0.0346	−0.1534	0.0059		−0.0173
	x_5	−0.0329	0.2181	−0.251	0.0992	0.2116	−0.5461	−0.0157	
Total	x_1	0.6200	−0.0542	0.6742		1.0915	−0.4284	−0.0433	0.0544
	x_2	0.8051	1.3757	−0.5706	−0.0430		−0.4519	−0.0431	−0.0326
	x_3	−0.1443	0.8006	−0.9449	0.0290	−0.7765		−0.0639	−0.1335
	x_4	−0.1085	0.2519	−0.3604	0.0093	−0.2353	−0.2031		0.0687
	x_5	−0.1489	0.3036	−0.4524	−0.0097	−0.1478	−0.3519	0.0570	

x_1, Maximum tiller m^{-2} of main crop rice; x_2, Panicles m^{-2} of main crop rice; x_3, Spikelets per panicle of main crop rice; x_4, Grains filling of main crop rice (%); x_5, Grain weight of main crop rice (mg). The residual path coefficients for 2018, 2019, 2020, and total years were 0.3121, 0.3095, 0.2893 and 0.3379, respectively.

3.2. Yield and Its Components of the Ratoon Crop

The yield and yield components of ratoon rice are significantly different (Table 4). The years of ratoon rice yield from highest to lowest were 2018, 2019, and 2020. The grain yield of ratoon rice was 29.23% and 25.02% in YD-NJ and HZ-ZG, respectively, which were higher than that of DS-LZ. The yield of N 107 was 6.16% higher than that of R 1015.

The fertilization treatments had extremely significant effects on yield and the other yield components, excluding the grain weight. The amounts of nitrogen applied to the grain- and bud-fertilizer was 120 kg and 180 kg, respectively. The grain yield of ratoon rice was significantly increased by 9.43–188.75% and 8.72–186.86% under the N_{120} and N_{180} treatments, respectively, compared with those under the other fertilization treatments. The yield of ratoon rice was still heavily affected by the year, location, genotype, fertilization, and their interactions. The results showed that the number of panicles m^{-2} had the greatest direct effect on the yield, followed by the spikelets per panicle. The total indirect effects of the number of maximum tillers on yield were the largest. The trend of the results was consistent for 3 years (Table 5). Therefore, the way to increase the yield of ratoon rice is to coordinate the numbers of effective panicles and of grain panicles^{-1}, which are consistent with the main rice crop.

Table 4. Analysis of variance for the grain yield and yield-related traits of ratoon rice under different treatments in the rice–ratoon rice system.

Treatments		Maximum Tillers m^{-2}	Panicles m^{-2}	Spikelets Per Panicle	Grain Filling (%)	Grain Weight (mg)	Grain Yield (kg ha^{-1})
Year (Y)	2018	279.0 a	208.5 a	65.6 a	72.1 b	27.7 a	2513.1 a
	2019	268.8 a	204.2 a	60.2 b	78.6 a	27.4 b	2406.6 b
	2020	250.9 b	182.2 b	61.1 b	67.5 c	26.6 c	1822.4 c
Genotype (G)	R 1015	247.2 b	182.8 b	66.5 a	71.9 b	26.8 b	2180.2 b
	N 107	278.6 a	211.2 a	58.2 b	73.6 a	27.7 a	2314.5 a
	YD-NJ	291.6 a	224.1 a	61.7 b	70.5 c	28.0 a	2542.7 a
Location (L)	DS-LZ	228.4 d	179.8 c	61.2 b	73.4 b	27.1 c	1967.6 c
	FJ-LZ	264.7 bc	197.2 b	60.1 b	70.7 c	27.6 b	2198.4 b
	TH-LZ	251.0 c	178.5 c	64.8 a	74.7 ab	26.9 c	2172.5 b
	HZ-ZG	268.2 bc	199.0 b	66.3 a	75.6 a	26.9 c	2459.9 a
	DG-YB	273.6 ab	203.2 b	59.7 b	71.5 c	27.1 c	2142.9 b
Fertilization (F)	CK	158.2 d	104.6 d	61.0 b	71.3 b	27.3 a	1053.5 d
	N_0	201.0 c	123.5 c	62.4 ab	72.9 a	27.2 a	1339.1 c
	N_{60}	310.0 b	237.7 b	63.2 a	73.5 a	27.1 a	2779.8 b
	N_{120}	314.9 ab	255.7 a	63.2 a	73.3 a	27.4 a	3042.1 a
	N_{180}	330.4 a	263.4 a	61.7 ab	72.7 a	27.2 a	3022.1 a
F-value	Y	11.0 **	36.4 **	66.2 **	551.6 **	96.6 **	343.1 **
	L	23.4 **	31.3 **	29.2 **	40.8 **	29.2 **	57.0 **
	G	75.6 **	134.4 **	420.2 **	37.8 **	215.5 **	33.5 **
	F	370.9 **	782.3 **	4.5 **	8.2 **	1.8	401.5**
	Y × L	18.1 **	15.4 **	13.8 **	41.6 **	24.0 **	24.8 **
	Y × G	1.3	7.6 **	8.7 **	0.9	0.2	4.4 **
	Y × F	0.7	3.5 **	2.2 *	0.5	0.7	12.7 **
	L × G	10.6 **	2.6 *	3.7 **	6.1 **	1.8	3.7 **
	L × F	4.6 **	4.5 **	1.3	1.3	1.3	5.7 **
	V × F	4.8 **	10.5 **	1.3	0.6	0.5	7.1 **
	Y × L × G	5.1 **	3.6 **	4.7 **	11.3 **	3.2 **	5.2 **
	Y × L × F	2.8 **	1.8 *	1.7 *	1.9 *	1.3	3.8 **
	Y × G × F	0.7	1.3	0.6	2.1	0.6	1.1
	L × G × F	1.2	1.1	1.2	1.6	1.6	0.9

R 1015, Rong 18 you 1015; N 107, Nei 6 you 107; YD-NJ, Yunding in the city of Neijiang; FJ-LZ, Fuji in the city of Luzhou; DS-LZ, Desheng in the city of Luzhou; TH-LZ, Taihe in the city of Luzhou; HZ-ZG, Huzhu in the city of Zigong; DG-YB, Daguan in the city of Yibin; N_0, 0 kg N ha^{-1} for grain- and bud-promoting fertilizer; N_{60}, 60 kg N ha^{-1} for grain- and bud-promoting fertilizer; N_{120}, 120 kg N ha^{-1} for grain- and bud-promoting fertilizer; N_{180}, 180 kg N ha^{-1} for grain- and bud-promoting fertilizer; CK, without fertilization. * Significant at the 0.05 probability level. ** Significant at the 0.01 probability level. Different lowercase letters represent statistical differences at the 5% probability level for the same column, different years, different varieties, different ecological sites, and different N application rates.

Table 5. Path analysis of the yield and yield traits of ratoon rice.

Year	Traits	Correlation Coefficient	Direct Effect	Indirect Effect					
				Total	→x_1	→x_2	→x_3	→x_4	→x_5
2018	x_1	0.8952	−0.0097	0.9049		0.8908	−0.0195	0.0262	0.0074
	x_2	0.9372	0.9573	−0.0201	−0.0090		−0.0379	0.0169	0.0099
	x_3	0.1651	0.2939	−0.1288	0.0006	−0.1233		0.0119	−0.0180
	x_4	0.2907	0.0923	0.1985	−0.0027	0.1751	0.0378		−0.0117
	x_5	0.1102	0.0598	0.0505	−0.0012	0.1585	−0.0887	−0.0181	
2019	x_1	0.8888	−0.0653	0.9541		1.0037	−0.0677	0.0173	0.0008
	x_2	0.9635	1.0717	−0.1082	−0.0612		−0.0601	0.0093	0.0038
	x_3	−0.0916	0.2221	−0.3138	0.0199	−0.2898		−0.0096	−0.0343
	x_4	0.1592	0.0647	0.0946	−0.0175	0.1535	−0.0329		−0.0085
	x_5	−0.0006	0.0644	−0.0651	−0.0008	0.0625	−0.1182	−0.0086	
2020	x_1	0.8415	−0.0329	0.8743		0.8730	−0.0191	0.0084	0.0120
	x_2	0.9583	0.9655	−0.0073	−0.0298		−0.0054	0.0198	0.0081
	x_3	0.1631	0.1995	−0.0364	0.0031	−0.0259		0.0244	−0.0380
	x_4	0.2881	0.1622	0.1258	−0.0017	0.1179	0.0300		−0.0204
	x_5	−0.0035	0.0574	−0.061	−0.0069	0.1356	−0.1321	−0.0576	
Total	x_1	0.8530	−0.0368	0.8898		0.8854	−0.0345	0.0272	0.0117
	x_2	0.9377	0.9636	−0.0259	−0.0338		−0.0334	0.0272	0.0141
	x_3	0.1209	0.2661	−0.1451	0.0048	−0.1210		−0.0044	−0.0245
	x_4	0.3148	0.1563	0.1585	−0.0064	0.1677	−0.0075		0.0047
	x_5	0.1711	0.0846	0.0865	−0.0051	0.1602	−0.0772	0.0086	

x_1, Maximum tiller m^{-2} of ratoon rice; x_2, Panicles m^{-2} of ratoon rice; x_3, Spikelets per panicle of ratoon rice; x_4, Grain filling of ratoon rice (%); x_5, Grain weight of ratoon rice (mg). The residual path coefficients for 2018, 2019, 2020, and the total years were 0.1719, 0.1886, 0.1528, and 0.1788, respectively.

3.3. Accurate Quantification of Grai-n and Bud-Promoting Fertilizers under Different Locations

The TSN of each test site was different. The TPN and SPAD at the full heading stage of the main crop increased with increasing TSN and SAN values (Figure 1A–D). Therefore, the TPN and SPAD values were significantly different when the grain- and bud-promoting fertilizer was applied (Table 6), which ultimately led to the different highly efficient N application rates of the grain- and bud-promoting fertilizers at each test point. The highly efficient N application rate of the grain- and bud-promoting fertilizers of 60 kg ha^{-1} and 120 kg ha^{-1} accounted for 11 and 7, respectively, among the 18 locations in 3 years. The performances of the two varieties were consistent (Table 7). The performance of the highly efficient N application rate of the grain- and bud-promoting fertilizer in Southern Sichuan was quite different, where most of which were 60–120 kg ha^{-1}.

Table 6. Total plant N content (TPN) and leaf SPAD value (SPAD) at the full heading stage.

Genotype	Location	TPN			SPAD		
		2018	2019	2020	2018	2019	2020
R 1015	YD-NJ	1.72 a	1.35 ab	1.28 a	44.14 a	42.25 ab	40.42 b
	DS-LZ	1.30 c	1.35 ab	1.07 b	36.38 d	41.72 b	38.07 c
	FJ-LZ	1.34 c	1.22 bc	0.86 c	38.07 c	36.43 c	33.30 d
	TH-LZ	1.48 b	1.17 c	1.26 a	41.30 b	35.41 d	40.92 ab
	HZ-ZG	1.68 a	1.36 ab	1.24 a	43.88 a	42.53 ab	41.45 a
	DG-YB	1.73 a	1.42 a	1.02 b	44.74 a	42.87 a	37.67 c

Table 6. *Cont.*

Genotype	Location	TPN			SPAD		
		2018	2019	2020	2018	2019	2020
N 107	YD-NJ	1.59 ab	1.45 ab	1.30 a	40.60 b	43.70 a	41.06 b
	DS-LZ	1.26 c	1.32 b	1.17 bc	35.25 d	39.31 b	39.21 c
	FJ-LZ	1.35 bc	1.06 c	0.92 d	36.97 c	35.03 c	34.32 e
	TH-LZ	1.45 b	1.14 c	1.27 ab	38.60 b	35.08 c	42.09 a
	HZ-ZG	1.47 ab	1.51 a	1.29 ab	39.79 b	43.26 a	40.93 b
	DG-YB	1.62 a	1.39 ab	1.05 c	42.52 a	39.28 b	36.88 d

R 1015, Rong 18 you 1015; N 107, Nei 6 you 107; YD-NJ, Yunding in the city of Neijiang; FJ-LZ, Fuji in the city of Luzhou; DS-LZ, Desheng in the city of Luzhou; TH-LZ, Taihe in the city of Luzhou; HZ-ZG, Huzhu in the city of Zigong; DG-YB, Daguan in the city of Yibin; Different lowercase letters indicate statistical differences at the 5% probability level for the same column, the same year, the same variety, and different ecological sites.

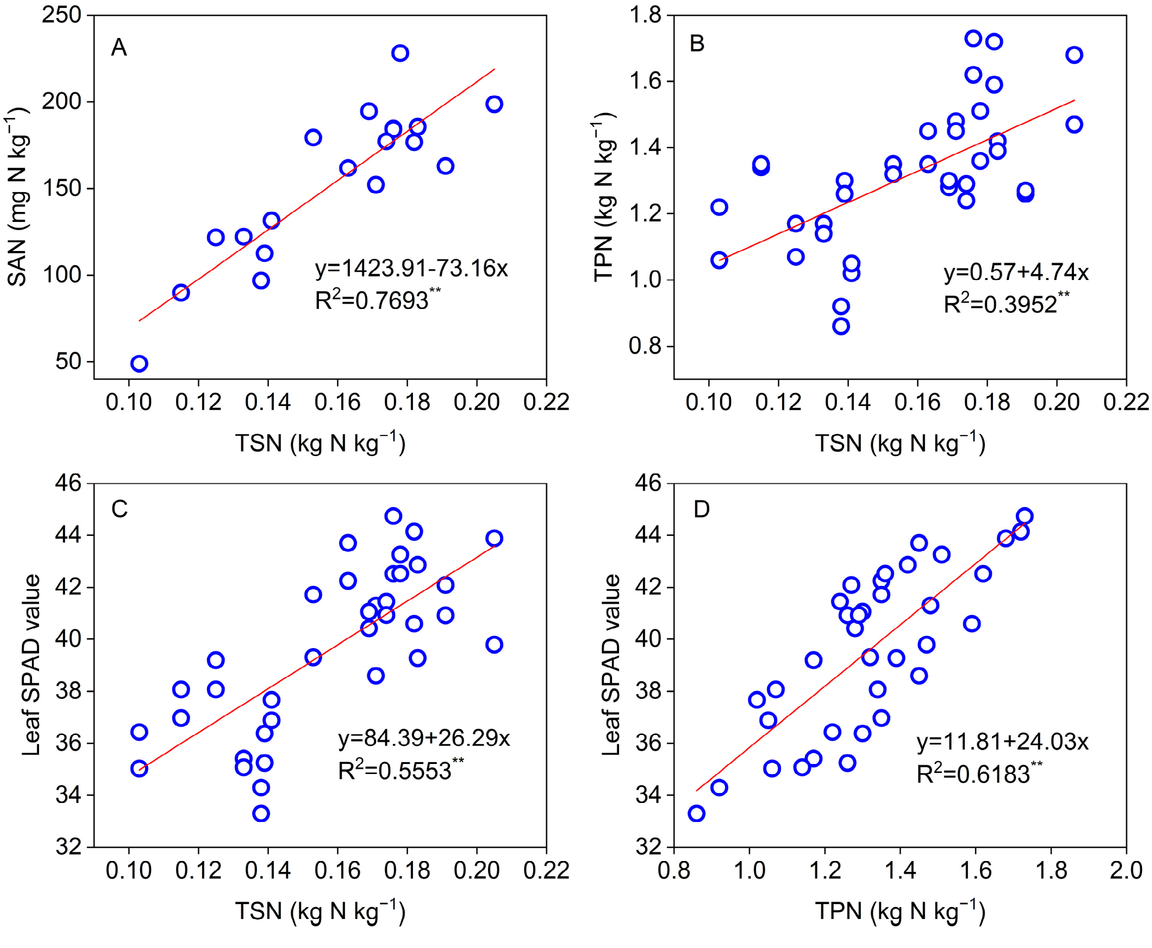

Figure 1. Correlation of TSN with SAN (**A**), TPN (**B**) and SPAD (**C**) and correlation of SPAD with TPN (**D**). TSN, Total soil N content; SAN, Soil available N; TPN, Total plant N content at full heading stage; SPAD, Leaf SPAD value at the full heading stage. ** Significant at the 0.01 probability level.

Table 7. The grain yield of ratoon rice and the highly efficient N application rate of the grain- and bud-promoting fertilizer (HN-GBF) at different locations.

Year	Genotype	Fertilization (kg ha^{-1})	Grain Yield of Ratoon Rice (kg ha^{-1})					
			YD-NJ	DS-LZ	FJ-LZ	TH-LZ	HZ-ZG	DG-YB
2018	R 1015	CK	1274.1 c	901.7 d	1082.1 c	1120.3 b	1157.6 c	1469.4 b
		N_0	2030.3 b	1241.0 c	1288.0 c	1490.6 b	1542.3 b	1521.0 b
		N_{60}	3568.5 a	2319.5 b	2439.4 b	2709.5 a	3460.5 a	3013.0 a
		N_{120}	3566.1 a	2836.4 a	3609.2 a	2988.5 a	3959.6 a	3015.9 a
		N_{180}	3542.3 a	2813.6 a	3614.7 a	3151.6 a	3876.5 a	2800.2 a
		HN-GBF	60	120	120	60	60	60
	N 107	CK	1419.2 c	966.9 c	1199.6 c	1150.8 d	1139.4 c	1584.0 b
		N_0	2339.9 b	1211.2 c	1429.1 c	1686.5 c	1560.2 b	1622.7 b
		N_{60}	4740.3 a	2292.1 b	2629.5 b	2949.1 ab	3428.5 a	3111.6 a
		N_{120}	4494.7 a	2906.8 a	3667.8 a	3166.7 a	3425.8 a	3166.4 a
		N_{180}	4463.4 a	2854.6 a	3884.0 a	3210.5 a	3488.3 a	3191.4 a
		HN-GBF	60	120	120	60	60	60
2019	R 1015	CK	990.5 b	1161.5 b	1325.2 d	1175.1 c	1387.5 b	1389.6 b
		N_0	1477.5 b	1389.4 b	1656.2 c	1358.7 c	1582.5 b	1429.1 b
		N_{60}	3261.8 a	2782.1 a	2543.8 b	2298.9 b	3025.5 a	2831.6 a
		N_{120}	3567.0 a	3100.8 a	2966.3 a	2649.2 ab	3024.5 a	3093.7 a
		N_{180}	3616.8 a	3072.6 a	2844.6 a	2682.5 a	2984.5 a	3140.0 a
		HN-GBF	60	60	120	120	60	60
	N 107	CK	1020.1 b	1210.4 b	1224.5 c	1160.8 c	1319.5 c	921.6 c
		N_0	1227.0 b	1422.3 b	1526.0 c	1384.9 c	1652.5 b	1385.1 b
		N_{60}	3357.2 a	3025.6 a	3380.1 b	2362.9 b	3209.5 a	3421.2 a
		N_{120}	3633.4 a	3158.0 a	3873.9 a	2753.6 a	3432.5 a	3546.5 a
		N_{180}	3489.9 a	3097.9 a	3798.6 a	2805.3 a	3312.5 a	3572.7 a
		HN-GBF	60	60	120	120	60	60
2020	R 1015	CK	997.6 b	754.5 d	754.5 c	842.8 b	1028.8 c	865.8 c
		N_0	1118.2 b	967.9 c	967.9 c	908.4 b	1356.5 b	980.4 c
		N_{60}	2396.1 a	1662.8 b	1662.8 b	2577.0 a	2949.6 a	2092.5 b
		N_{120}	2506.4 a	2087.9 a	2087.9 a	2641.3 a	3058.5 a	2352.5 a
		N_{180}	2549.8 a	2030.4 a	2030.4 a	2655.2 a	2935.2 a	2372.5 a
		HN--GBF	60	120	120	60	60	120
	N 107	CK	873.4 c	705.2 d	705.2 d	845.4 b	1036.1 c	767.5 c
		N_0	1067.4 b	982.8 c	982.8 c	910.4 b	1380.5 b	887.5 c
		N_{60}	2579.9 a	1802.6 b	1802.6 b	2842.7 a	3074.2 a	1847.5 b
		N_{120}	2576.5 a	2171.2 a	2171.2 a	2844.2 a	3032.3 a	2540 a
		N_{180}	2536.6 a	2097.3 a	2097.3 a	2750.5 a	2975.7 a	2555 a
		HN-GBF	60	120	120	60	60	120

R 1015, Rong 18 you 1015; N 107, Nei 6 you 107; YD-NJ, Yunding in the city of Neijiang; FJ-LZ, Fuji in the city of Luzhou; DS-LZ, Desheng in the city of Luzhou; TH-LZ, Taihe in the city of Luzhou; HZ-ZG, Huzhu in the city of Zigong; DG-YB, Daguan in the city of Yibin; N_0, 0 kg N ha^{-1} for grain- and bud-promoting fertilizer; N_{60}, 60 kg N ha^{-1} for grain- and bud-promoting fertilizer; N_{120}, 120 kg N ha^{-1} for grain- and bud-promoting fertilizer; N_{180}, 180 kg N ha^{-1} for grain- and bud-promoting fertilizer; CK, without fertilization. Different lowercase letters represent statistical differences at the 5% probability level for the same column, different years, different varieties, different ecological sites, and different N application rates.

3.4. Prediction of the Highly Efficient N Application Rate of the Grain- and Bud-Promoting Fertilizer

The TSN and SAN prior to transplanting and the TPN and SPAD at the full heading stage were significantly and extremely negatively correlated, respectively, with a highly efficient N application rate of grain- and bud-promoting fertilizer (Table 8). The test varieties showed a relatively consistent trend for 3 years. Furthermore, a regression equation was established to calculate the highly efficient N application rate of grain- and bud-promoting fertilizer with the average data of more than six test sites of two varieties for 3 years (Table 9). When the TSN, SAN, TPN, and SPAD values reached as high as 0.247 kg N kg^{-1}, 298 mg N kg^{-1}, 2.159 kg N kg^{-1}, and 49.94, respectively, the reference value for not applying the grain- and bud-promoting fertilizer could have been reached. However, further multiple stepwise regression analysis showed that the factors with a significant partial phase relationship regarding the highly efficient N application rate of the grain- and bud-promoting fertilizer were not completely consistent over the years for the two varieties (Table 10). TAN, TPN, and SPAD were significantly positively correlated with TSN (Figure 1A–C), and SPAD was significantly positively correlated with TPN (Figure 1D). Therefore, regardless of R 1015, N 107 or the two varieties, the effect of TSN and SPAD on the highly efficient N application rate of the grain- and bud-promoting fertilizer was extremely significant, and the coefficient of determination reached as high as 0.8562–0.871. It is more stable and reliable to predict the highly efficient N application rate of grain- and bud-promoting fertilizer using the leaf SPAD at the heading stage and TSN before transplanting.

Table 8. Correlation analysis of the highly efficient N application rate of grain- and bud-promoting fertilizer (HN-GBF, y: kg ha^{-1}) and the TSN, SAN, TPN, and SPAD under the different treatments.

Year	Genotype	TSN	SAN	TPN	SPAD	n
2018	R 1015	−0.9029 **	−0.9217 **	−0.8825 *	−0.9291 **	6
	N 107	−0.9029 **	−0.9217 **	−0.8535 *	−0.8463 *	6
	Total	−0.9029 **	−0.9217 **	−0.8270 **	−0.8101 **	12
2019	R 1015	−0.8801 *	−0.8588 *	−0.9475 **	−0.9890 **	6
	N 107	−0.8801 *	−0.8588 *	−0.9238 **	−0.8673 *	6
	Total	−0.8801 **	−0.8588 **	−0.8926 **	−0.9138 **	12
2020	R 1015	−0.9342 **	−0.9130 **	−0.9066 **	−0.8273 *	6
	N 107	−0.9342 **	−0.9130 **	−0.8552 *	−0.8422 *	6
	Total	−0.9342 **	−0.9130 **	−0.8710 **	−0.8319 **	12
Total	R 1015	−0.8755 *	−0.8631 **	−0.6581 **	−0.8943 **	18
	N 107	−0.8755 *	−0.8631 **	−0.7547 **	−0.8310 **	18
	Total	−0.8755 **	−0.8631 **	−0.6985 **	−0.8521 **	36

R 1015, Rong 18 you 1015; N 107, Nei 6 you 107; TSN, Total soil N content; SAN, Soil available N; TPN, Total plant N content at full heading stage; SPAD, Leaf SPAD value at full heading stage. * Significant at the 0.05 probability level. ** Significant at the 0.01 probability level.

Table 9. Regression analysis of the highly efficient N application rate of grain- and bud-promoting fertilizer (HN-GBF, y: kg ha^{-1}) and the TSN, SAN, TPN, and SPAD at the full heading stage under the different treatments.

Traits (x)	Regression Equation	*r*	R Square	n
TSN	y = 231.07 − 936.66x	−0.8755 **	0.7666	36
SAN	y = 169.45 − 0.5687x	−0.8631 **	0.7450	36
TPN	y = 214.00 − 99.117x	−0.6985 **	0.4879	36
SPAD	y =402.22 − 8.0538x	−0.8521 **	0.7261	36

y, Highly efficient N application rate of grain- and bud-promoting fertilizer (HN-GBF, kg ha^{-1}); TSN, Total soil N content; SAN, Soil available N; TPN, Total plant N content at full heading stage; SPAD, Leaf SPAD value at full heading stage. ** Significant at the 0.01 probability level.

Table 10. Multiple stepwise regression analysis of the highly efficient N application rate of grain- and bud-promoting fertilizer (HN-GBF, y: kg ha^{-1}) and the TSN, SAN, TPN, and SPAD at the full heading stage.

Genotype	Year	Regression Equation	*F*	R Square	Partial Correlation	t
R 1015	2018	$y = 421.05 - 8.23x_4$	25.24 **	0.8632	$r(y,x_4) = -0.93$	5.02 **
	2019	$y = 447.36 - 9.14x_4$	178.90 **	0.9781	$r(y,x_4) = -0.99$	13.38 **
	2020	$y = 266.84 - 734.09x_1 - 0.42x_2$	37.76 **	0.9618	$r(y,x_1) = -0.88$ $r(y,x_2) = -0.84$	3.17 * 2.64 *
	Total	$y = 354.46 - 475.82x_1 - 4.89x_4$	50.66 **	0.8710	$r(y,x_1) = -0.60$ $r(y,x_4) = -0.67$	2.88 ** 3.49 **

Table 10. *Cont.*

Genotype	Year	Regression Equation	*F*	R Square	Partial Correlation	t
N 107	2018	$y = 180.13 - 0.65x_2$	15.44 *	0.8373	$r(y,x_2) = -0.92$	3.93 *
	2019	$y = 291.55 - 161.29x_3$	23.30 **	0.8535	$r(y,x_3) = -0.92$	4.83 **
	2020	$y = 259.84 - 729.11x_1 - 0.42x_2$	35.36 **	0.9413	$r(y,x_1) = -0.87$ $r(y,x_2) = -0.83$	3.26 * 2.53 *
	Total	$y = 348.83 - 616.02x_1 - 4.30x_4$	44.78 **	0.8565	$r(y,x_1) = -0.73$ $r(y,x_4) = -0.62$	4.17 ** 3.07 **
Total	2018	$y = 181.24 - 0.66x_2$	56.50 **	0.8496	$r(y,x_2) = -0.92$	7.52 **
	2019	$y = 343.17 - 415.26x_1 - 5.03x_4$	36.26 **	0.8896	$r(y,x_1) = -0.57$ $r(y,x_4) = -0.71$	2.31 * 3.06 **
	2020	$y = 266.84 - 734.09x_1 - 0.42x_2$	113.28 **	0.9618	$r(y,x_1) = -0.88$ $r(y,x_2) = -0.84$	5.50 ** 4.58 **
	Total	$y = 342.65 - 578.66x_1 - 4.24x_4$	98.28 **	0.8562	$r(y,x_1) = -0.69$ $r(y,x_4) = -0.62$	5.47 ** 4.54 **

y, Highly efficient N application rate of grain- and bud-promoting fertilizer (HN-GBF, kg ha^{-1}); x_1, Total soil N content (TSN); x_2, Soil available N (SAN); x_3, Total plant N content at full heading stage (TPN); x_4, Leaf SPAD value at full heading stage (SPAD). * Significant at the 0.05 probability level. ** Significant at the 0.01 probability level.

4. Discussion

4.1. Nitrogen Management Methods for Rice–Ratoon Rice

Ratoon rice is a planting model that uses the dormant buds of the main crop to grow into panicles to allow for a second harvest on the grounds the main crop is planted well. Therefore, the fertilizer management method mostly involves the simple addition of high-yield fertilization for the main crop and high-yield fertilization for ratoon rice [15,16]. Fertilization occurs as many as six times in the rice–ratoon rice system, which requires considerable work and time and is not suitable for the current production demand. The total N application rate is 180 kg ha^{-1}, and the N application method of 45% fertilizer at pre-planting, 15% fertilizer at the boot, and 40% fertilizer during grain filling can achieve high yields and reduce N inputs in the rice–ratoon rice systems. Applying the panicle fertilizer does not increase yield when the main crop yield exceeds a certain threshold. The highly efficient N application rate of the main crop rice was 90–150 kg ha^{-1} in Southwestern China. These studies show that a high yield of rice–ratoon rice can be obtained without multiple fertilization treatments [17]. Therefore, with the period of 10–15 days leading up to the full heading stage of the main crop, and a rate of application that is higher than traditional grain fertilizer, the grain filling and the grain weight of the main crop, the rate of the living buds of ratoon rice for the numbers of panicles m^{-2}, and the yield of ratoon rice can all be increased [18]. Therefore, grain- and bud-promoting fertilizer plays a dual role as a grain fertilizer for the main crop and bud-promoting fertilizer for the ratoon rice.

In this study, a uniform basal fertilizer was applied based on a winter paddy field, with strong water and fertility retention, and a grain- and bud-promoting fertilizer was subsequently applied for different basic soil Na at different locations. The results show that the main crop rice yield was not significantly different among the four grain- and bud-promoting fertilizer treatments with the two varieties under six locations across 3 years. The average yield was 9322.9 kg ha^{-1} under N_0, which demonstrated that the basal fertilizer can fully meet the high-yield nutrient requirements of the main crop and has universal adaptability. It further shows that the panicle fertilizer has no effect on yield when the main crop yield exceeds a certain threshold. Previous studies have pointed out that both excessive nitrogen application in the early stage of rice growth and weak light in the filling stage led to extended growth and delayed maturity [19]. In this study, the basal fertilizer of the main crop was not high, the heading and filling date of rice had the strongest light of the year, and the length of each internode of rice was finalized. Therefore, N_{180} would not lead to extended growth and lodging. The yield of ratoon rice showed an increasing trend in the range of 0–120 kg ha^{-1} of grain- and bud-promoting fertilizer. The yield of ratoon rice under N_{180} was slightly lower than that under N_{120}, but the difference was not significant. Above all, using the "basal fertilizer for main crop and grain- and bud-promoting fertilizer for ratoon crop" two-time, two-crop fertilization mode can ensure the high yield of rice–ratoon rice and reduce the fertilization time.

4.2. Prediction Method of the Highly Efficient N Application Rate of Grain- and Bud-Promoting Fertilizer

The application rate of bud-promoting fertilizer in the range of 0–225.0 kg ha^{-1} is significantly or extremely significantly positively correlated with the yield and yield components of ratoon rice, respectively [20]. The optimal application rate of bud-promoting fertilizer is 112.5–225.0 kg ha^{-1}. However, the effect of bud-promoting fertilizer is related to the dry matter weight of a single stem at the filling stage of the main crop. The application of the bud-promoting fertilizer had an obvious effect when the dry matter weight of a single stem was 1.22–1.78 g, more grains per panicle of rice is achieved when more N was applied [21]. Furthermore, the regression equation is simulated ($y = -25.733x + 1212.4$, $R^2 = 0.9090$) when predicting the highly efficient N application rate of the grain- and bud-promoting fertilizer of ratoon rice (y) according to the SPAD value (x) at the full heading stage of the main crop [22]. Lin et al. [12] established the regression equation between the total dry matter accumulation (y) and bud-promoting fertilizer (x) ($y = 647.48 + 28.37x - 0.4939x^2$, r = 0.9819 **) and between the ratoon rice yield (y) and bud-promoting fertilizer (x) ($y = 465.26 + 12.396x - 0.2576x^2$, r = 0.9566 **). Yu et al. [23] constructed a regression equation between the ratoon rice yield (y) and the N application rate (x) ($y = 5166.8 + 20.1383x - 0.0517x^2$) and found that the average application rate was approximately 2.5 kg N per 100 kg rice production when the cutting height of the plant culms was 15 cm. The results of the above studies were conducted at one experimental site without considering the impact of soil fertility on the N application rate at different sites.

The results showed that the highly efficient N application rate of the grain- and bud-promoting fertilizer was 60 kg ha^{-1} or 120 kg ha^{-1} at 18 sites across different years. Quantitative grain- and bud-promoting fertilizer has difficulty achieving the goal of high yield and high efficiency for ratoon rice at large changes in TSN production. Therefore, it is necessary to establish an accurate prediction method for the highly efficient N application rate of grain- and bud-promoting fertilizer. The precise application rate of grain- and bud-promoting fertilizer is closely related to the plant nutrition level. More TSN would cause a higher TPN and SPAD. A higher level of SPAD values would cause a higher net photosynthetic rate and more photosynthetic substances to be produced in the main crop. Therefore, the higher the leaf SPAD, the lower the highly efficient N application rate of the grain- and bud-promoting fertilizer. Considering the differences in the varieties of nitrogen absorption capacity [24] and SPAD values under the same TPN, a regression equation was established to predict the highly efficient N application rate of grain- and bud-promoting fertilizer (y) based on TSN (x_1) and SPAD (x_4) ($y = 342.65 - 578.66x_1 - 4.24x_4$, $R^2 = 0.8562$). The prediction accuracy was higher than that of single measures of TSN, TPN, and SPAD. Therefore, using the soil testing formula data with field files and detecting the SPAD of the top 1–3 leaves at the full heading stage with the SPAD-502 meter, it can quickly and accurately obtain the scientific reference value of the highly efficient N application rate of the grain- and bud-promoting fertilizer in production practice.

4.3. Technical Approaches for High-Yield Rice–Ratoon Rice Systems

The selection of high-yield varieties is the basic technique in the cultivation of rice–ratoon rice. Earlier studies have shown that multi-panicle-type varieties with fewer spikelets per panicle have a stronger ratooning ability, but the total yield is not high because of their small main crop yield potential. While the main crop rice yield potential of the heavy-panicle type varieties with more spikelets per panicle is great, the total yield is still not high due to its weak ratooning ability. The type with 160–190 spikelets per panicle can obtain a higher total yield [25,26]. The main crop yields of II youhang 1 hao, II youhang

2 hao, II you 148, II you 936, and other varieties reached have 12,000–13,500 kg ha^{-1}, and the ratoon rice yield has reached 7500–8250 kg ha^{-1} planting at Youxi Mayang Demonstration Film in Fujian Province of China [27]. Therefore, the panicle and spikelet structure characteristics of high yields of the main crop, ratoon rice and total crops were different. In this study, the results showed that the numbers of panicles m^{-2} and spikelets per panicle of the main crop and the number of panicles m^{-2} and spikelets per panicle of ratoon rice had greater direct contributions to yield. The maximum tiller numbness had the greatest indirect contribution to yield. This reminds us that choosing mid-big panicle varieties with high spikelets per panicle values and strong tillering abilities and ensuring sufficient seedling density are important ways to obtain high yields of main crop and ratoon rice. In terms of cultivation and management, according to the ecological conditions of the winter paddy field in Southern Sichuan, one possible strategy is to ensure a density of 150,000–180,000 plants per ha when transplanting the main crop rice to increase the number of panicles m^{-2} and increase the leaf-to-grain ratio to ensure the high yield of the main crop rice. There is more photosynthetic matter remaining under the soil, which lays a sufficient material basis for the high yield of ratoon rice [28]. In addition, N fertilizer that promotes bud development should be applied during the full panicle stage of the main crop, and replaced 10–15 days after the full panicle stage of the main crop; this is beneficial for the filling and fruiting of the main crop, while providing sufficient N nutrition for the harvested ratoon shoots, ultimately reducing the mortality rate of ratoon shoots and promoting the yield increase in ratoon rice [29].

5. Conclusions

Overall, the yield of rice–ratoon rice was significantly affected by the year, genotype, location, fertilization, and their interactions. The present study indicated that the application of 60–120 kg ha^{-1} grain- and bud-promoting fertilizer helped in obtaining high yields of ratoon rice at various ecological sites. Also, the use of the predicted grain- and bud-promoting fertilizer regression equation can achieve high yields under simplified and reduced N input practices in rice–ratoon rice systems.

Author Contributions: Conceptualization, writing—original draft preparation, and methodology, F.X.; software and methodology, C.Y.; validation and formal analysis, D.H.; resources and formal analysis, R.X.; data curation and visualization, X.Z.; visualization and investigation, P.J.; supervision and investigation, X.G. and H.X.; project administration and visualization, L.Z.; writing—review and editing and funding acquisition, C.G. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Key Science and Technology Project of Sichuan Province (2022ZDZX0012-02), the National Key Research and Development Program Foundation of Ministry of Science and Technology of China (2023YFD2301901), the Sichuan Provincial Finance Special Programme for Independent Innovation (2022ZZCX072), the earmarked fund for China Agriculture Research System (CARS-01-25), the original innovation program of the Sichuan Academy of Agricultural Sciences (YSCX2035-010), the Ten Thousand Talents Program of Sichuan Province.

Data Availability Statement: Data are contained within the article.

Acknowledgments: We sincerely thank Kun Chen and Shiqing Zeng for the assistance in this work.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Sheng, Y.; Song, L. Agricultural production and food consumption in China: A long-term projection. *Chin. Econ. Rev.* **2019**, *53*, 15–29. [CrossRef]
2. Cassman, K.; Dobermann, A.; Walters, D.; Yang, H. Meeting cereal demand while protecting natural resources and improving environmental quality. *Annu. Rev. Environ. Resour.* **2003**, *28*, 315–358. [CrossRef]
3. Xie, W.; Ata-Ul-Karim, S.; Shiotsu, F.; Kato, Y. Crop productivity in a rice–ratoon-rice system vs. a single-crop system in central Japan. *Field Crops Res.* **2023**, *303*, 109140. [CrossRef]

4. Shen, X.; Zhang, L.; Zhang, J. Ratoon rice production in central China: Environmental sustainability and food production. *Sci. Total Environ.* **2020**, *764*, 142850. [CrossRef]
5. Peng, S. Reflection on China's rice production strategies during the transition period. *Sci. Sin. Vitae* **2014**, *44*, 845–850. [CrossRef]
6. Fitri, R.; Erdiman, K.; Yamaoka, K. SALIBU technology in Indonesia: An alternative for efficient use of agricultural resources to achieve sustainable food security. *Paddy Water Environ.* **2019**, *17*, 403–410. [CrossRef]
7. Tanaka, R.; Hakata, M.; Nakano, H. Grain yield response to cultivar and harvest time of the first crop in rice ratooning in southwestern Japan. *Crop Sci.* **2022**, *621*, 455–465. [CrossRef]
8. Dong, H.; Chen, Q.; Wang, W.; Peng, S.; Huang, J.; Cui, K.; Nie, L. The growth and yield of a wet-seeded rice-ratoon rice system in central china. *Field Crops Res.* **2017**, *208*, 55–59. [CrossRef]
9. Yang, D.; Peng, S.; Zheng, C.; Xiang, H.; Huang, J.; Cui, K.; Wang, F. Effects of nitrogen fertilization for bud initiation and tiller growth on yield and quality of rice ratoon crop in central China. *Field Crops Res.* **2021**, *272*, 108286. [CrossRef]
10. Yu, X.; Guo, Y.; Yang, G.; Zhang, Z.; Liang, Y.; Zheng, C.; Xu, L.; Yuan, S.; Wang, F.; Huang, J.; et al. Nitrogen response of regenerated tillers varied among node positions in ratoon rice. *Field Crops Res.* **2022**, *289*, 108717. [CrossRef]
11. Wang, Y.; Zheng, C.; Xiao, S.; Sun, Y.; Huang, J.; Peng, S. Agronomic responses of ratoon rice to nitrogen management in central China. *Field Crops Res.* **2019**, *241*, 107569. [CrossRef]
12. Lin, W.; Chen, H.; Zhang, Z.; Xu, Q.; Tu, N.; Fang, C.; Ren, W. Research and prospect on physio-ecological properties of ratoon rice yield formation and its key cultivation technology. *Chin. J. Eco-Agric.* **2015**, *23*, 392–401.
13. Cao, Y.; Zhu, J.; Hou, J. Yield Gap of Ratoon Rice and Their Influence Factors in China. *Sci. Agric. Sin.* **2020**, *53*, 707–719.
14. Lin, W. Developmental status and problems of rice ratooning. *J. Integr. Agr.* **2019**, *18*, 246–247. [CrossRef]
15. Huang, J.; Wu, J.; Chen, H.; Zhang, Z.; Fang, C.; Shao, C.; Lin, W.; Weng, P.; Muhammad, U.; Lin, W. Optimal management of nitrogen fertilizer in the main rice crop and its carrying-over effect on ratoon rice under mechanized cultivation in Southeast China. *J. Integr. Agric.* **2022**, *21*, 351–364.
16. Wang, Y.; Li, X.; Lee, T.; Peng, S.; Dou, F. Effects of nitrogen management on the ratoon crop yield and head rice yield in South USA. *J. Integr. Agric.* **2021**, *20*, 1457–1464. [CrossRef]
17. Mengel, D.; Wilson, F. Water management and nitrogen fertilization of ratoon crop rice. *Agron. J.* **1981**, *73*, 1008–1010. [CrossRef]
18. Begum, M.; Hasana, K.; Hossain, S.; Hossain, M. Effect of culm cutting height and nitrogenous fertilizer on the yield of ratoon of late boro rice. *Agron. J.* **2002**, *3*, 136–138.
19. Lal, B.; Gautam, P.; Nayak, A.; Raja, R.; Panda, B.; Tripathi, R.; Shahid, M.; Chatterjee, D.; Bhattacharyya, P.; Bihari, P.; et al. Agronomic manipulation in main season and ratoon rice influences growth, productivity, and regeneration ability in tropical lowlands. *Field Crops Res.* **2023**, *294*, 108872. [CrossRef]
20. Zou, J.; Pang, Z.; Li, Z.; Guo, C.; Lin, H.; Li, Z.; Chen, H.; Huang, J.; Chen, T.; Xu, H. The underlying mechanism of variety-water-nitrogen-stubble damage interaction on yield formation of ratoon rice with low stubble height under mechanized harvesting. *J. Integr. Agric.* **2023**, *23*, 806–823. [CrossRef]
21. Xu, F.; Xiong, H.; Zhu, Y.; Zhang, L.; Wan, X.; Liu, M.; Wang, G. Relationship between the efficient amount of nitrogen application for grain filling and the SPAD value at full panicle stage in mid-season hybrid rice. *Acta Agron. Sin.* **2007**, *33*, 449–454.
22. Xu, F.; Xiong, H.; Zhu, Y.; Zhang, L.; Guo, X. Estimation of efficient rate of nitrogen application for promoting ratooning bud development using chlorophyll meter reading (SPAD Value) of flag leaf at the full heading stage of main crop in mid-season hybrid rice. *Chin. J. Rice Sci.* **2009**, *23*, 51–56. [CrossRef]
23. Yu, D.; Zhang, Y.; Zhao, Y.; Li, X.; Jiang, Z.; Chen, S. Nitrogen application technique of ratoon rice with machine harvest in low cutting. *Chin. Agric. Sci. Bull.* **2013**, *29*, 210–214.
24. Ju, C.; Buresh, R.; Wang, Z.; Zhang, H.; Liu, L.; Yang, J.; Zhang, J. Root and shoot traits for rice varieties with higher grain yield and higher nitrogen use efficiency at lower nitrogen rates application. *Field Crops Res.* **2015**, *175*, 47–55. [CrossRef]
25. Zheng, C.; Wang, Y.; Yuan, S.; Xiao, S.; Sun, Y.; Huang, J.; Peng, S. Heavy soil drying during mid-to-late grain filling stage of the main crop to reduce yield loss of the ratoon crop in a mechanized rice ratooning system. *Crop J.* **2022**, *10*, 280–285. [CrossRef]
26. Zheng, C.; Wang, Y.; Xu, W.; Yang, D.; Yang, G.; Yang, C.; Hung, J.; Peng, S. Border effects of the main and ratoon crops in the rice ratooning system. *J. Integr. Agric.* **2023**, *22*, 80–91. [CrossRef]
27. He, H.; Weng, G.; Guo, L.; Zhang, D. Research progress on factors affecting axillary bud germination of ratoon rice. *Fujian Rice Wheat Sci. Tech.* **2008**, *26*, 61–63.
28. Zhang, W.; Duana, X.; Yao, X.; Liu, Q.; Xia, R.; Zhang, X.; Luo, X.; Tang, Y.; Yao, Y.; Li, J. Progress and challenges of rice ratooning technology in Chongqing Municipality, China. *Crop Environ.* **2023**, *2*, 137–146. [CrossRef]
29. Bond, J.; Bollich, P. Ratoon rice response to nitrogen fertilizer. *Plant Health Prog.* **2006**, *5*, 1–5. [CrossRef]