agronomy

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Effects of Nitrogen Application Rate on Dry Matter Weight and Yield of Direct-Seeded Rice under Straw Return

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Abstract: Straw is an agricultural byproduct that results from the production of many crops, such as cereals, yet it is often considered a waste product. However, straw has both historical precedent and future potential as an agricultural resource. In this study, we aimed to determine the effects of returning straw to the soil on rice cultivation. To this end, we used the hybrid rice variety Luliangyou Jingling as the test material to study the effect of straw return under four different nitrogen application levels (0 kg N (N1), 120 kg N/hm^2 (N2), 150 kg N/hm^2 (N3), and 180 kg N/hm^2 (N4)) on rice tillering dynamics, leaf area index (LAI), dry matter accumulation, and yield. We found that rice under straw return had a higher number of effective panicles, along with a higher number of grains per panicle, compared to those without straw return. Additionally, the tiller number, LAI, total dry matter, and yield of rice in each main growth period under straw return were higher than those without straw return, and these values increased with an increase in nitrogen application rate. The yield was the highest at 9520.63 kg/hm^2 without straw return, while the highest yield with straw return was achieved at 10,738.26 kg/hm^2. Our results revealed the optimal nitrogen application level for high yield of two-line direct-seeded rice under straw return, which provides a theoretical reference for the precise reduction of fertilizer application in rice cultivation.

Keywords: straw return; N fertilization; leaf area index; dry matter; yield

Citation: Ma, P.; Zhang, K.-Y.; Liao, X.-H.; Aer, L.-S.; Yang, E.-L.; Deng, J.; Zhou, L.; Zhang, R.-P. Effects of Nitrogen Application Rate on Dry Matter Weight and Yield of Direct-Seeded Rice under Straw Return. *Agronomy* **2023**, *13*, 3058. https://doi.org/10.3390/agronomy13123058

Academic Editor: Junfei Gu

Received: 20 October 2023
Revised: 6 December 2023
Accepted: 11 December 2023
Published: 14 December 2023

1. Introduction

In recent years, the yield of crops, such as rice and wheat, has increased, and the volume of byproducts, such as straw, has also increased accordingly. However, as the economy has evolved to favor industrialized agriculture, crop straw that was previously incorporated back into the soil or used as animal feed is now considered agricultural waste. China is a country with high agricultural production and is rich in agricultural straw resources. The annual output of crop straw is approximately 800 million tons, accounting for 30% of the total global output [1]. However, a complete and effective institutional mechanism for the comprehensive utilization of straw in our country has not yet been established, and the utilization efficiency of crop straw remains relatively low. Currently, soil degradation, the loss of organic C and nutrients, and a decline in soil fertility are the main problems hindering China's agricultural development. As an important renewable agricultural resource, straw that is returned to the field can effectively increase the structure of soil aggregates [2–4], and it contains N, P, K, Ca, S, and other nutrients required for crop growth and development [5]. When crop straw is incorporated into the soil, it promotes the proliferation of microorganisms. Lignin, cellulose, hemicellulose, crude protein, and other substances contained in straw will decompose in the soil and become organic matter. An increase in organic matter content improves soil quality and fertility [6]. Straw return has become a popular research topic, as well as a widely promoted method in crop cultivation.

As an effective straw treatment method, straw return addresses the problem of excessive volumes of straw waste, reduces the amount of pollution caused by straw burning, and improves soil fertility.

Nitrogen is the nutrient most closely related to plant yield in global crop production [7]. It is not only the nutrient required by crops in the largest amount but also the most mobile element in the soil [8]. Approximately 75% of leaf nitrogen is related to chloroplasts [9], which have important physiological importance in the production of dry matter through photosynthesis [10]. Appropriate nitrogen fertilizer application provides rice with a suitable leaf area index at the heading stage and supports a strong production capacity of photosynthetic substances from flowering to filling maturity. In addition, adequate nitrogen fertilizer application can promote the transfer of photosynthetic products (carbohydrates) to grains [9]. To achieve a higher rice yield in China, the amount of nitrogen fertilizer used is increasing, resulting in low nitrogen use efficiency [11]. According to data from China's Ministry of Agriculture and Rural Affairs for 2020, the nitrogen use efficiency of three main cereal crops (rice, wheat, and maize) was only 35% [12]. Beckinghausen et al. found that at least 1.8 million tons of nitrogen fertilizer is wasted every year [13]. The rational application of nitrogen fertilizer can minimize waste, improve the utilization rate, and reduce environmental pollution, thereby promoting the sustainable development of farmlands. Previous studies have shown that straw return combined with nitrogen fertilization can promote crop yield, reduce the application of chemical fertilizer, and improve the fertilizer utilization rate, which can improve the sustainable supply potential of soil nutrients [14]. Studies have also found that under straw return, increasing the amount of base nitrogen fertilizer can effectively offset the nitrogen shortage of the rice population in the early growth stage and competition for nitrogen at the peak of straw decomposition [15].

In this study, we aimed to determine the effects of different nitrogen application levels on the dry matter weight and yield of rice under rapeseed straw return and identify the optimal nitrogen application level for two-line direct-seeded rice under different straw return treatments. The results of this study provide a theoretical reference and technical support for scientific straw return and the precise reduction of fertilizer under double-cropping rice cultivation systems.

2. Materials and Methods

2.1. Experimental Design

The experiment was carried out in a strict field micro-plot in Dayan (31°54′ N, 104°69′ E), which was the test base of Southwest University of Science and Technology in 2020–2021. The surface soil (0–20 cm depth) at the study site contained 1.95 g/kg total N, 27.20 mg/kg available P, and 58.32 mg/kg available K. We utilized the Sichuan oil–rice double-cropping system. The rice variety tested was a two-line hybrid rice, Luliangyou Jingling. A two-factor split-plot design was used for this experiment. The main plot was divided into an area with no straw return (T1) and an area with rapeseed straw return (T2), and the subplots were treated with four different levels of nitrogen application: 0 kg N (N1), 120 kg N/hm^2 (N2), 150 kg N/hm^2 (N3), and 180 kg N/hm^2 (N4). Each treatment plot area was 5.21 m^2, with three replicates. The nitrogen fertilizer was in the form of urea, and it was applied in a 4:3:3 ratio of base fertilizer, tillering fertilizer, and panicle fertilizer. The application methods of phosphorus and potassium fertilizers were the same for each treatment. Calcium superphosphate (90 kg P/hm^2) and potassium chloride (225 kg K/hm^2) were applied to each subplot before rice sowing, and all phosphorus and potassium fertilizers were applied as base fertilizers.

The experiment was conducted based on a rapeseed seed yield of 2250 kg/hm^2, an economic coefficient of 0.28, and non-fertilization treatment of previous rape. The rapeseed straw was returned to the field at 5785.65 kg/hm^2. After crushing and incorporating rape straw into the soil, direct seeding of rice was carried out around May 16. The planting holes were 37 cm long and 16.5 cm wide, with 3–4 grains per hole and 2 seedlings (3-leaf stage) per hole. The ridge between each treatment plot was wrapped with plastic film to prevent movement of fertilizer between plots. Tap water was used for irrigation to minimize the influence of water source on the experiment. After the rice seedlings were transplanted, the surface water layer of the field was maintained at 3–5 cm. During the rice planting period, except for drainage during the baking period, cultivation and management were carried out according to local high-yield cultivation methods. The meteorological data of rainfall and temperature during the experiment are shown in Figure 1.

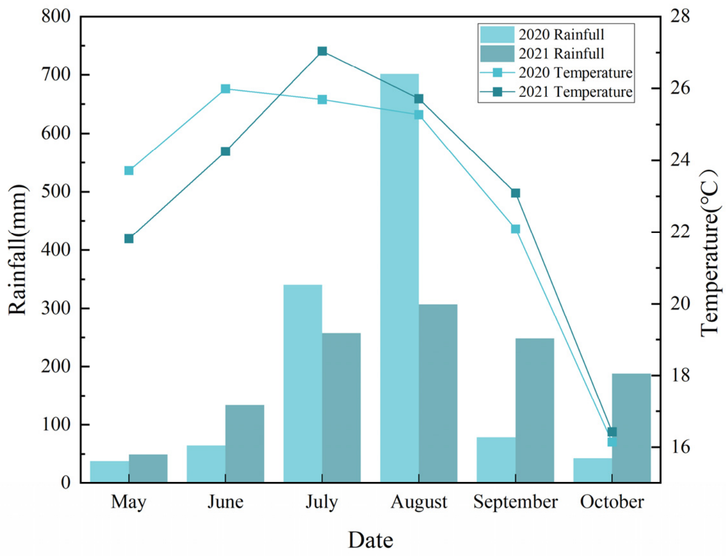

Figure 1. Meteorological data of rainfall and temperature during the experiment.

2.2. Variables

2.2.1. Tillering Dynamics

At the 5–6 leaf stage, 10 holes of plants with consistent growth were selected, and the number of tillers were recorded every 7 days until the number of tillers decreased.

$$\text{Tiller spike rate (\%)} = \text{effective panicle/maximum tiller number} \times 100.$$

Relative tillering rate (tiller/d) = [ln(n2) − ln(n1)]/(t2 − t1), n1 and n2 are the average numbers of tillers per plant at times t1 and t2, respectively [16].

2.2.2. Leaf Area Index (LAI)

At the full heading and maturity stages, the average tiller number of each treatment was used as the standard, and three representative plants were selected to measure the length and width of green leaves to calculate the leaf area.

Leaf area = leaf length × leaf width × correction coefficient k (correction coefficient 0.75 for rice) [17].

LAI = total leaf area per unit land area/unit land area [18].

2.2.3. Dry Matter

Three plants were taken from each treatment at maximum tillering stage, full heading stage, and mature stage. The samples were placed in an oven at 105 °C for 30 min, dried to constant weight at 75 °C, and weighed after cooling to room temperature.

2.2.4. Yield

When the rice matured, 15 plants were selected for seed testing based on the average effective panicles. The panicles of the sampled plants were removed and placed in nylon mesh bags until the moisture content reached approximately 13.5%. The number of grains per panicle, number of filled grains, seed setting rate, and 1000-grain weight were measured, and the theoretical yield was calculated.

2.3. Statistical Analyses

Microsoft Excel 2010 software was used for data collation, DPS 7.05 data analysis software was used to analyze the variance according to LSD at a significance level of $p < 0.05$, and Origin 2021 was used for drawing.

3. Results

3.1. Effects of Straw Return and Nitrogen Application Rate on LAI

As shown in Figure 2, compared with the LAI of direct-seeded rice with no straw return, samples at each growth stage after straw return showed a different degree of increase, and the two-year trend was consistent. The LAI of direct-seeded rice at the maximum tillering stage under T2 was 2.3–25.3% higher than that under T1. The LAI of direct-seeded rice at the full heading stage increased by 2.3–55.5%. In terms of nitrogen application, the LAI of direct-seeded rice with and without straw return increased with an increase in the nitrogen application rate in each growth period throughout the two years. At the maximum tillering stage, the LAI under N2, N3, and N4 increased by 41.4–81.9%, 65.5–102.5%, and 116.2–152.3%, respectively, compared with that under N1. At the full heading stage, the LAI under N2, N3, and N4 increased by 39.5–141.1%, 60.1–154.8%, and 90.4–211.2%, respectively, compared with that under N1.

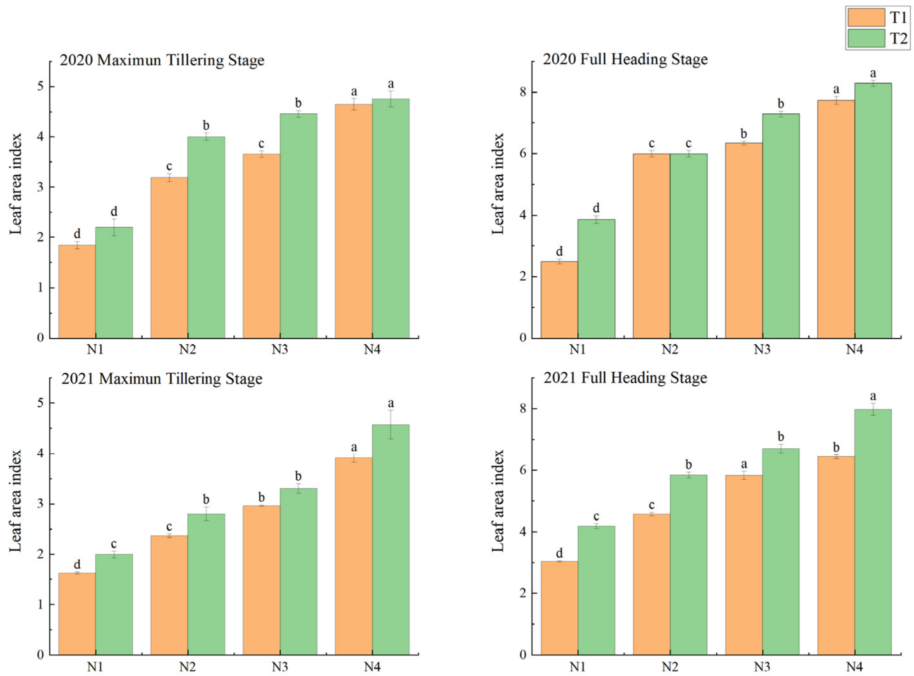

Figure 2. The effects of different straw returning and nitrogen application rates on the LAI of direct-seeded rice in the 2020–2021 experiment. Note: T1, no straw return; and T2, straw returning. N1—0 kg N application; N2—120 kg N/hm^2 application; N3—150 kg N/hm^2 application; N4—180 kg N/hm^2 application. The different lowercase letters in the same group indicate that there is a significant difference between different straw treatments at the 5% level under the same nitrogen application rate.

3.2. Effects of Straw Return and Nitrogen Application Rate on Tillering Dynamics

As shown in Figure 3a, the number of tillers in direct-seeded rice in each treatment reached a maximum during the same period (28 d), and the trend of T2 > T1 was apparent. At the maximum tillering stage, the tiller numbers of direct-seeded rice in T2 were 20.6, 8.4, 4.1, and 7.0 higher than those in T1 under N1, N2, N3, and N4, respectively. Under the same straw returning conditions, an increase in the nitrogen fertilizer level substantially promoted rice tillering. Compared with the tiller number under N1, those under N2, N3, and N4 increased by 27.3–41.6, 25.1–45.0, and 41.8–59.7, respectively. The relative tillering rate of direct-seeded rice in each treatment was the highest at 7–14 d, after which the tillering rate gradually decreased. Except for the tillering rate of T2 under the 7–14 d N3 and N4 treatment, which was less than that of T1, the tillering rate in the other periods showed a clear trend of T2 > T1. Compared with the tillering rate of T1, the relative values of T2 under N1, N2, N3, and N4 were lower. The tillering rate increased by 8.7–21.0, 2.9–46.1, 10.5–59.5, and 4.3–17.4 under N1, N2, N3, and N4, respectively. As shown in Figure 3b, under each nitrogen application rate, the tiller spike rate of the direct-seeded rice was T1 > T2. Under the same straw returning conditions, the tiller earing rate of direct-seeded rice was the highest under N3, followed by that under N4, N2, and N1. Compared with that under N1, the spike rate of tillers under N3, N4, and N2 increased by 10.4–12.9, 0.4–3.9, and 0.03–3.2, respectively, indicating that N3 was beneficial to the improvement of the spike rate in hybrid rice.

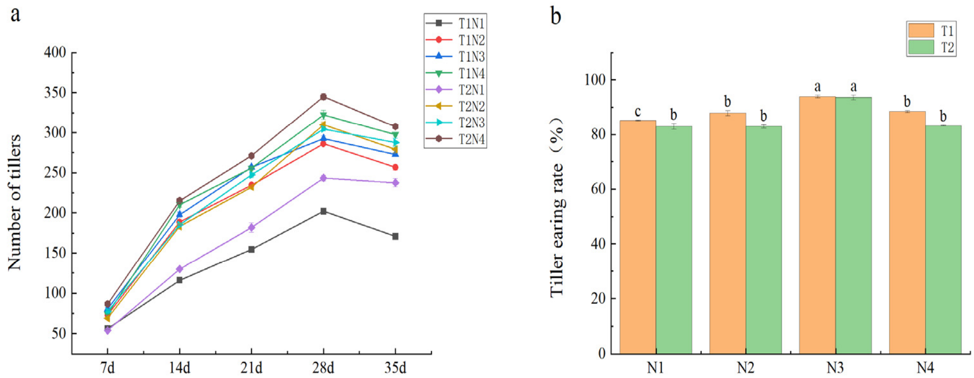

Figure 3. Effects of different straw returning and nitrogen application rates on tillering dynamics of direct-seeded rice in the 2020–2021 experiment: (**a**) tiller spike rate; (**b**) tiller earing rate. Note: T1, no straw return; and T2, straw returning. N1—0 kg N application; N2—120 kg N/hm^2 application; N3—150 kg N/hm^2 application; N4—180 kg N/hm^2 application. The different lowercase letters in the same group in Figure (**b**) indicate that the difference between different nitrogen application treatments under the same straw returning treatment is significant at the 5% level.

3.3. Effects of Straw Return and Nitrogen Application Rate on Dry Matter Accumulation

As shown in Table 1, under the same nitrogen application level, the dry matter accumulation of rice under T2 at the maximum tillering stage in 2021 was lower than that under T1, and the dry matter accumulation under T2 was higher than that under T1 during other periods. At the maximum tillering stage in 2020, the dry matter under T2 increased by 26.4%, 6.4%, 2.3%, and 2.5% under N1, N2, N3, and N4, respectively, compared to that under T1, whereas at the maximum tillering stage in 2021, the dry matter under T2 decreased by 17.8%, 12.2%, 10.4%, and 9.9% under N1, N2, N3, and N4, respectively, compared to that under T1. Compared to that under T1, the dry matter weight under T2 at the full heading stage increased by 26.1%, 14.6%, 15.5%, and 6.3% under N1, N2, N3, and N4, respectively. Compared to that under T1, the dry matter accumulation under T2 increased by 26.1%, 14.4%, 12.5%, and 2.8% under N1, N2, N3, and N4, respectively. Under the same straw returning conditions, the dry matter accumulation of rice was the highest when the nitrogen application level was N4 (180 kg N/hm^2) in 2020 and 2021, followed by N3, N2, and N1. Compared with that under N1, the dry matter accumulation under N2 increased by 13.9–91.7%, 24.7–61.2%, and 29.6–56.2% at the maximum tillering stage, full heading stage, and mature stage, respectively. The dry matter accumulation under N3 increased by 53.3–148.1%, 38.2–80.5%, and 39.2–86.5% in each growth period, respectively. That under N4 increased by 53.1–164.2%, 58.7–107.9%, and 58.0–108.9% in each growth period, respectively.

Table 1. Effects of straw returning and nitrogen fertilizer application on dry matter accumulation and translocation of rice at main growth stages (kg hm^{-2}).

Year	Treatment		Maximum Tillering Stage		Full Heading Stage		Mature Stage		Dry Matter Accumulation After Full Heading
			Stem	Leaf	Stem and Leaf	Panicle	Stem and Leaf	Panicle	
2020	T1	N1	891.07c	626.44d	5282.19d	624.18c	2946.08d	4526.39d	1566.10c
		N2	1562.11b	1346.98c	8100.41c	1420.88b	3821.40c	7847.33c	2147.45b
		N3	1926.29a	1838.93b	9274.91b	1383.75b	5200.84b	8738.29b	3280.47a
		N4	2025.12a	1887.52a	10,433.16a	1843.30a	6255.46a	9356.98a	3335.98a
		Mean	1601.15	1424.97	8272.67	1318.03	4351.94	7617.25	2582.50
	T2	N1	1057.33c	860.86c	6851.03d	982.26d	3470.56d	5954.73c	1592.00c
		N2	1576.85b	1518.06b	9273.27c	1524.25c	4825.92c	8012.56b	2040.95b
		N3	1995.09a	1856.40a	10,668.85b	1806.53b	5775.23b	9643.28a	2943.13a
		N4	1969.42a	2039.31a	10,901.99a	1933.39a	6144.14a	9761.22a	3069.98a
		Mean	1649.67	1568.66	9423.79	1561.61	5053.96	8342.95	2411.51
2021	T1	N1	1199.84c	573.85d	5112.75d	507.23d	3337.70d	5199.29d	2917.01d
		N2	1306.31c	713.08c	6654.68c	589.95c	4856.95c	6869.78c	4482.09c
		N3	1732.46a	986.08b	7450.18b	700.52b	5156.43b	7922.69b	4928.42b
		N4	1815.45a	1196.56a	8953.78a	933.66a	6974.64a	9399.67a	6486.87a
		Mean	1513.52	867.39	7042.85	682.84	5081.43	7347.86	4703.60
	T2	N1	945.40d	512.97d	6103.19d	619.16c	4327.60d	6426.70d	4031.94c
		N2	1135.95c	636.09c	7632.05c	749.93b	5465.30c	8467.10c	5550.42b
		N3	1528.53b	907.18b	8477.73b	815.18b	6342.75b	8627.08b	5676.93b
		N4	1574.67b	1140.60a	9711.30a	958.50a	7479.28a	9507.78a	6317.25a
		Mean	1296.14	1025.96	7981.07	785.69	5903.73	8257.17	5394.14
F Value		Y	386.97 **	964.59 **	21,634.69 **	5491.30 **	1307.79 **	42.79 **	14,693.69 **
		T	0.3	0.23	16,432.18 **	107.96 **	1032.01 **	2588.20 **	1175.44 **
		N	386.72 **	622.19 **	8864.67 **	519.40 **	5450.63 **	5902.37 **	2264.68 **
		Y ×T	20.94 *	3.55	170.62 **	17.81 *	62.26 **	32.64 **	3232.06 **
		Y × N	29.75 **	92.63 **	295.19 **	138.74 **	80.31 **	185.34 **	222.01 **
		T × N	7.42 **	3.81 *	63.02 **	13.00 **	73.07 **	95.95 **	74.81 **
		Y × T × N	10.86 **	12.04 **	23.88 **	9.70 **	43.89 **	86.24 **	39.03 **

Note: T1, no straw return; and T2, straw returning. N1—0 kg N application; N2—120 kg N/hm^2 application; N3—150 kg N/hm^2 application; N4—180 kg N/hm^2 application. The same column of different lowercase letters indicates that there is a significant difference at the 5% level between the same straw treatment and different nitrogen application treatments; Y, T and N in the F value are year, straw returning treatment, and nitrogen application rate, respectively. Y × T, Y × N, T × N, and Y × T × N are the interaction between year, straw returning treatment, and nitrogen application rate, respectively. * and ** represent significant levels of 0.05 and 0.01, respectively.

Dry matter accumulation after full heading was greater in T1 than in T2 in 2020 and lower in T1 than in T2 in 2021; however, dry matter accumulation after full heading showed an increasing trend with increasing nitrogen application rates over the two years. Compared with that under N1, the dry matter accumulation after full heading under N2, N3, and N4 increased by 28.2–53.7%, 40.8–109.5%, and 56.7–122.4%, respectively. In the two-year field experiment, the total amount of dry matter in the main growth stages of rice increased with an increase in nitrogen application rate, and the difference between the treatments was significant in both T1 and T2. Straw return had no significant effect on the dry matter accumulation of direct-seeded rice at the maximum tillering stage, and the effect was highly significant during the other periods. Both straw return and nitrogen fertilizer application can increase the total dry matter of rice in the main growth period, and the interaction between the two has a significant effect on the increase in the dry matter accumulation of rice. Year (Y), straw return treatment (T), nitrogen application rate (N), Y × T, Y × N, and Y × T × N had significant effects on the dry matter accumulation of rice at each stage and dry matter accumulation after heading. By contrast, Y × T had no significant effect on the dry matter accumulation of leaves at the maximum tillering stage.

3.4. Effects of Straw Return and Nitrogen Application Rate on Yield

As shown in Table 2, straw return combined with nitrogen fertilizer application had a significant effect on rice yield. In the two-year field experiment, under the same nitrogen application level, the rice yield of each treatment under T2 was higher than that under T1, and the yield was 7.8–25.6%, 2.0–10.6%, 6.9–7.5%, and 13.4–13.8% higher under N1, N2, N3, and N4, respectively. Furthermore, there was a significant difference in the yield under each nitrogen application rate. Under T1, the yield of rice first increased and then decreased with the increase in nitrogen fertilizer application rate: T1N3 > T1N4 > T1N2 > T1N1. Compared with the yield under T1N1, those under T1N3, T1N4, and T1N2 were 50.0–119.9%, 49.2–118.8%, and 32.7–102.4% higher, respectively. Under T2, rice yield increased with an increase in the nitrogen application rate, but at a gradually decreasing rate. Compared with the yield under T2N1, those under T2N2, T2N3, and T2N4 were 36.1–64.3%, 48.7–88.2%, and 47.4–97.5% higher, respectively. The yield after two years showed T2N3 > T1N4, indicating that straw returning can compensate for the effect of less nitrogen fertilizer to a certain extent and even obtain higher yield.

Table 2. Effects of straw returning and nitrogen fertilizer application on rice yield and yield traits.

Year	Treatment		1000-Grain Weight (g)	Grain Filling (%)	Panicles ($\times 10^4 \cdot hm^{-2}$)	Spikelets per Panicle	Grain Yield ($kg \cdot hm^{-2}$)
2020	T1	N1	26.53a	82.71c	171.99d	114.72d	4329.61d
		N2	26.50a	88.28a	251.35c	149.06c	8764.84c
		N3	26.63a	86.11b	275.18b	150.93b	9520.63a
		N4	26.56a	80.04d	285.39a	156.17a	9471.93b
		Mean	26.55	80.29	245.98	142.72	8021.75
	T2	N1	26.59b	82.77c	197.17c	125.40b	5438.22d
		N2	26.81ab	87.18b	257.33b	148.61a	8936.52c
		N3	26.80ab	86.98b	285.39a	153.91a	10,236.67b
		N4	26.90a	89.76a	287.55a	154.65a	10,738.26a
		Mean	26.77	86.67	256.86	145.64	8837.42
2021	T1	N1	25.46b	85.60a	181.40c	146.15c	5776.07c
		N2	26.01b	88.35a	218.55b	152.62b	7662.26b
		N3	26.89a	87.30a	223.86b	164.82a	8661.46a
		N4	26.06b	85.91a	232.44a	165.62a	8618.70a
		Mean	26.10	86.79	214.06	157.30	7678.98
	T2	N1	25.50b	86.19a	181.51d	156.17b	6228.93d
		N2	27.00a	87.83a	227.80c	156.92b	8478.09c
		N3	26.92a	87.76a	236.14b	166.00a	9260.87b
		N4	27.07a	88.14a	247.52a	166.08a	9804.17a
		Mean	26.62	87.48	223.24	161.29	8443.01
F Value		Y	10.26	92.95 *	1719.11 **	120.13 **	105.58 **
		T	39.45 **	36.84 **	113.62 **	15.21 *	480.15 **
		N	16.27 **	21.36 **	1075.23 **	246.20 **	2466.26 **
		Y × T	6.48	11.16 *	0.81	0.36	0.51
		Y × N	15.30 **	3.40 *	109.40 **	88.22 **	161.95 **
		T × N	3.21 *	20.38 **	1.44	11.13 **	17.48 **
		Y × T × N	3.31 *	8.46 **	16.67 **	1.7	11.77 **

Note: T1, no straw return; and T2, straw returning. N1—0 kg N application; N2—120 kg N/hm^2 application; N3—150 kg N/hm^2 application; N4—180 kg N/hm^2 application. The same column of different lowercase letters indicates that there is a significant difference at the 5% level between the same straw treatment and different nitrogen application treatments; Y, T, and N in the F value are year, straw returning treatment, and nitrogen application rate, respectively. Y × T, Y × N, T × N, and Y × T × N are the interaction between year, straw returning treatment, and nitrogen application rate, respectively. * and ** represent significant levels of 0.05 and 0.01, respectively.

Panicle number and number of grains per panicle are important components of rice yield. The effective panicle number was higher under T2, and the effective panicle number and grain number per panicle under both T1 and T2 showed increasing trends with an increasing nitrogen application rate. Compared with that under T1, the effective panicle number under T2 increased by 0.1–14.6%, 2.4–4.2%, 3.7–5.5%, and 0.86.5% under N1, N2, N3, and N4, respectively. Under the same straw return conditions, the effective panicle number under N2, N3, and N4 increased by 20.5–46.1%, 9.5–44.7%, and 3.7–45.8%, respectively, compared to that under N1 where the number of grains per panicle increased by 0.5–29.9%, 6.3–31.6%, and 6.3–36.1%, respectively. The 1000-grain weight under T2 was slightly higher than that under T1, and it increased with an increasing nitrogen application rate. Under N2, the seed setting rate of T1 was higher than that of T2; however, the seed setting rate of T2 was higher than that of T1 under the other nitrogen application levels.

The significance levels of rice traits affected by the test year (Y), straw return treatment (T), N application rate (N), Y × T, Y × N, and Y × T × N are shown in Table 2. Except for the effect of Y × T on the yield, the effects of other treatments and their interactions on the yield were significant. Under T1, the optimal nitrogen application level was N3 (150 kg N/hm^2), and under T2, the optimal nitrogen application level was N4 (180 kg N/hm^2).

4. Discussion

As a carbon-rich energy source, crop straw contains large amounts of nitrogen, phosphorus, potassium, and other nutrients required for crop growth [19]. It plays an important role in alleviating the imbalance of nitrogen, phosphorus, and potassium in farmland soil and compensates for the lack of phosphorus and potassium fertilizers. Zhang and Wu et al. [20,21] found that the total amount of returned straw could improve the contents of soil organic carbon, alkali-hydrolyzable nitrogen, available phosphorus and available potassium, increase the number of grains per panicle and effective panicle number, and increase rice yield. Yang et al. [22] found that straw return increased soil fertility and crop yield by 6.8% and 4.4%, respectively, in southern China. Yaozhu et al. [23] demonstrated that the effect of adding composted straw on rice population quality was significantly higher than that of returning straw directly to the field: the high-efficiency LAI increased by approximately 4.71–6.50% at the full heading stage, and the population dry matter increased significantly by approximately 9.22–13.30% with straw return compared to the values without straw return. Additionally, the number of effective panicles and number of grains per panicle increased by approximately 5.9–9.8% and 1.5–5.2%, respectively, with straw return, and the yield increased by 9.5–13.4% compared to that without straw return.

Leaf area is an important factor that determines dry matter accumulation and final yield of rice, and tiller number can also reflect the potential rice yield. The results of this study show that the LAI and tiller number of direct-seeded rice under the straw return treatment were significantly higher than those without straw return, which is consistent with the results of previous studies. Although the number of tillers and effective panicles of direct–seeded rice under the straw return treatment significantly increased, the percentage of tillers decreased. A similar result was reported in a study by Wei et al. [24], indicating that straw return may cause rice to produce more ineffective tillers. Straw return can increase topsoil C, N, and P stocks, which can benefit crop growth and increase grain yield [25]. Under the same nitrogen application level, the dry matter accumulation at the full heading and mature stages in the straw return treatment was higher than that without straw return; however, the total dry matter in the straw return treatment at the maximum tillering stage was lower than that without straw return. These results were consistent with those of Yajie et al. [26]. Straw return can release nitrogen and effectively promote dry matter accumulation; thus, the dry matter accumulation of the straw return treatment showed a significant increase. However, the straw nutrient release was slow, so the effect on dry matter weight was not apparent in the early stages. LAI and dry matter are directly related to rice yield [27]. In this study, the rice yield under different nitrogen treatments was also higher under the straw return treatment than without straw return. This was mainly due to an increase in the effective panicle and seed setting rates of rice, which verified the conclusion of Yan et al. [28]. A possible reason for this is that the full decomposition of straw in the middle and late growth stages provides a continuous nutrient supply for rice, which is essential for achieving an economic yield and improving nitrogen use efficiency [29].

Previous studies have shown that the effect of straw return on rice growth is closely related to nitrogen fertilizer application [30]. In a study by Zheng Huantong [31], it was shown that straw return combined with appropriate nitrogen fertilization could effectively increase rice LAI, thereby increasing the net photosynthetic rate of rice and improving its photosynthetic ability. However, Xie Fang et al. [32] demonstrated that the absorption of nitrogen by rice increases with an increase in nitrogen application rate within a certain range, but beyond that, not only will the absorption decrease, but also the yield of rice will decrease. In this study, the tiller number, leaf area, and total dry matter of rice increased with the increase in nitrogen application rate under the two straw return treatments, which was similar to the findings of Zhou Liyan et al. [33]. The greater the amount of nitrogen applied, the greater the peak number of tillers of rice, thus increasing the yield of rice. However, increased nitrogen application also increases the number of ineffective tillers. Increasing the amount of nitrogen fertilizer will increase the LAI of rice in each growth period, indicating that increasing the amount of nitrogen application can increase the leaf area of the plant, promote photosynthesis, and increase the yield of rice, which verified the conclusion of Xie et al. [34]. The yield without straw return showed a trend of gradually increasing and then decreasing with the increase in nitrogen fertilizer application rate, and the yield was the highest at N3 (10 kg N/667 m^2), indicating that this was the optimal nitrogen application rate without straw return, which is consistent with the conclusions of Yang Yihua et al. [35]. The yield of rice is proportional to the application of nitrogen fertilizer. Within the appropriate range of nitrogen application, the rice yield increases with an increase in nitrogen application rate, but when the nitrogen application rate exceeds a certain range, the yield decreases again. The yield under the straw return treatment gradually increased with an increasing nitrogen fertilizer application rate, and the yield was the highest at N4 (12 kg N/667 m^2), indicating that this was the optimal nitrogen application rate under straw return. The effective panicle number and number of grains per panicle also showed the same growth trend as the yield, indicating that the increase in production due to nitrogen fertilization was mainly achieved by increasing the number of effective panicles and the number of grains per panicle, which was consistent with the results of Han et al. [36]. In terms of the interaction effect of straw return and nitrogen fertilization, the yield of T2N4 was the highest, which was 12.8–13.2% higher than that of T1N3, indicating that straw return combined with appropriate nitrogen fertilization rates could increase yield. This study provides a scientific basis for optimizing the application rate of nitrogen fertilizer in combination with straw return.

5. Conclusions

Straw return, nitrogen application, and their interaction had considerable regulatory effects on tiller number, tiller earing rate, LAI, and dry matter accumulation during the main growth stages, as well as rice yield. Straw return can substantially increase rice yield, and appropriate nitrogen fertilizer application can further increase the yield. In this study, the highest yield (9520.63 kg/hm^2) without straw return was obtained under the N3 treatment, indicating that the optimal rate of nitrogen application was N3 (150 N kg/hm^2). Meanwhile, the highest yield (10,738.26 kg/hm^2) under straw return was obtained under the N4 treatment, indicating that the optimal rate of nitrogen application was N4 (180 kg N/hm^2). The results of this study provide a valuable reference for the optimal nitrogen application level in rice cultivation with and without straw return.

Author Contributions: P.M., K.-Y.Z. and X.-H.L.: Data curation, writing—original draft. L.-S.A.: Investigation. E.-L.Y. and J.D.: Methodology, software. L.Z. and R.-P.Z.: Methodology. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by high-efficiency cultivation technology integration and industrial application of Yuehesimiao series direct-seeded rice, grant number 2022ZYDF039.

Data Availability Statement: Data are contained within the article.

Acknowledgments: The research team wishes to extend their gratitude to Jian-chao Shu, Xue-wu He, Fei Gao and all the authors for their contributions to this manuscript.

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

References

1. Wang, J.; Qiu, Y.; Zhang, X.; Zhou, Z.; Han, X.; Zhou, Y.; Qin, L.; Liu, K.; Li, S.; Wang, W. Increasing basal nitrogen fertilizer rate improves grain yield, quality and 2-acetyl-1-pyrroline in rice under wheat straw returning. *Front. Plant Sci.* **2023**, *13*, 1099751. [CrossRef] [PubMed]
2. Hu, Y.; Sun, B.; Wu, S.; Feng, H.; Gao, M.; Zhang, B.; Liu, Y. After-effects of straw and straw-derived biochar application on crop growth, yield, and soil properties in wheat (*Triticum aestivum* L.)-maize (*Zea mays* L.) rotations: A four-year field experiment. *Sci. Total Environ.* **2021**, *780*, 146560. [CrossRef] [PubMed]
3. Huang, W.; Wu, J.-F.; Pan, X.-H.; Tan, X.-M.; Zeng, Y.-J.; Shi, Q.-H.; Liu, T.-J.; Zeng, Y.-H. Effects of long-term straw return on soil organic carbon fractions and enzyme activities in a double-cropped rice paddy in South China. *J. Integr. Agric.* **2021**, *20*, 236–247. [CrossRef]

4. Wang, Q.X.; Li, M.L.; Chen, X.J.; Su, Y.; Yu, M.; Shen, A.L. Effects of nitrogen management on soil microbial community structure at different growth stages under straw returning in paddy soils. *Ying Yong Sheng Tai Xue Bao* **2020**, *31*, 935–944. [CrossRef] [PubMed]
5. Jin, Z.; Shah, T.; Zhang, L.; Liu, H.; Peng, S.; Nie, L. Effect of straw returning on soil organic carbon in rice–wheat rotation system: A review. *Food Energy Secur.* **2020**, *9*, e200. [CrossRef]
6. Zheng, W.; Shao, X.; Geng, Y.; Jin, F.; Sun, Q.; Liu, L.; Fan, H.; Guo, L. Effects of straw returning and nitrogen application on rice yield and nitrogen utilization. *J. Irrig. Drain.* **2019**, *38*, 8. [CrossRef]
7. Guo, C.; Li, P.; Lu, J.; Ren, T.; Cong, R.; Li, X. Application of Controlled-Release Urea in Rice: Reducing Environmental Risk While Increasing Grain Yield and Improving Nitrogen Use Efficiency. *Commun. Soil Sci. Plant Anal.* **2016**, *47*, 1176–1183. [CrossRef]
8. Timsina, J.; Panaullah, G.M.; Saleque, M.A.; Ishaque, M.; Pathan, A.B.M.B.U.; Quayyum, M.A.; Connor, D.J.; Saha, P.K.; Humphreys, E.; Meisner, C.A. Nutrient Uptake and Apparent Balances for Rice-Wheat Sequences. I. Nitrogen. *J. Plant Nutr.* **2006**, *29*, 137–155. [CrossRef]
9. Bai, Z. Effects of Nitrogen Application on Nitrogen Metabolism of Rice and Nitrogen Use Efficiency in Paddy Field. Ph.D. Thesis, Chinese Academy of Agricultural Sciences, Beijing, China, 2019.
10. Gotoh, E.; Suetsugu, N.; Yamori, W.; Ishishita, K.; Kiyabu, R.; Fukuda, M.; Higa, T.; Shirouchi, B.; Wada, M. Chloroplast Accumulation Response Enhances Leaf Photosynthesis and Plant Biomass Production. *Plant Physiol.* **2018**, *178*, 1358–1369. [CrossRef]
11. Liang, B.; Yang, X.; Murphy, D.V.; He, X.; Zhou, J. Fate of 15 N-labeled fertilizer in soils under dryland agriculture after 19 years of different fertilizations. *Biol. Fertil. Soils* **2013**, *49*, 977–986. [CrossRef]
12. Network CAI. Available online: http://www.agri.cn/V20/ZX/nyyw/202007/t20200703_7444643.htm (accessed on 3 July 2023).
13. Beckinghausen, A.; Odlare, M.; Thorin, E.; Schwede, S. From removal to recovery: An evaluation of nitrogen recovery techniques from wastewater. *Appl. Energy* **2020**, *263*, 114616. [CrossRef]
14. Soon, Y.K.; Lupwayi, N.Z. Straw management in a cold semi-arid region: Impact on soil quality and crop productivity. *Field Crops Res.* **2012**, *139*, 39–46. [CrossRef]
15. Grzyb, A.; Wolna-Maruwka, A.; Niewiadomska, A. The Significance of Microbial Transformation of Nitrogen Compounds in the Light of Integrated Crop Management. *Agronomy* **2021**, *11*, 1415. [CrossRef]
16. Tian, G.; Zhou, Y.; Sun, B.; Zhang, R.; Zhou, X.; Guo, S. The mechanism of the effects of nitrogen and planting density on rice tillering dynamics. *J. Plant Nutr. Fertil.* **2018**, *24*, 896–904.
17. Tao, H.; Lin, S. Comparison of punching weighing method, copy weighing method and length-width correction method for determination of rice leaf area. *Plant Physiol. J.* **2006**, *42*, 496–498.
18. Mo, J. Brief introduction of rice leaf area index determination method. *Guangxi Agric. Sci.* **1978**, *8*, 22–23.
19. Ye, W.; Xie, X.; Wang, K.; Li, Z. Effects of straw returning at different stages on growth and yield of rice. *Chin. J. Rice Sci.* **2008**, *1*, 65–70. [CrossRef]
20. Wu, Y.; Wang, L.; Cui, Y.; Hao, X.; Wang, B.; Tian, X.; Li, X.; Qin, Y. Effects of rotation mode and straw returning on rice yield, rice quality and soil fertility. *Plant Nutr. Fert. Sci.* **2021**, *27*, 1926–1937.
21. Zhang, R.-P.; Huang, Z.; Ashen, R.; Zhou, N.-N.; Zhou, L.; Feng, T.-Y.; Zhang, K.-Y.; Liao, X.-H.; Aer, L.; Ma, P. Phosphorus Application during Rapeseed Season Combined with Straw Return Improves Crop Productivity and Soil Bacterial Diversity in Rape-Rice Rotation. *Agronomy* **2023**, *13*, 506. [CrossRef]
22. Yang, F.; Dong, Y.; Xu, M.; Bao, Y. Effects of straw returning on the integrated soil fertility and crop yield in southern China. *Chin. J. Appl. Ecol.* **2012**, *23*, 3040–3044. [CrossRef]
23. Yin, R.; Guo, C.; Sun, Y.; Wu, Y.; Yu, H.; Sun, Z.; Zhang, Q.; Wang, H.; Yang, Z.; Ma, J. Effects of rape straw returning and water and nitrogen management on population quality and yield of hybrid rice under rice-rape rotation. *Chin. J. Rice Sci.* **2019**, *33*, 257–268. [CrossRef]
24. Su, W.; Feng, Y.; Xu, G.; Guan, Z.F.; Ou, D.; Zhang, J.; Wang, L. Effects of straw returning and nitrogen application rate on dry matter accumulation and yield of indica hybrid rice in karst area. *Acta Agric. Nucl. Sin.* **2019**, *33*, 1856–1864.
25. Liu, J.; Fang, L.; Qiu, T.; Chen, J.; Wang, H.; Liu, M.; Yi, J.; Zhang, H.; Wang, C.; Sardans, J.; et al. Crop residue return achieves environmental mitigation and enhances grain yield: A global meta-analysis. *Agron. Sustain. Dev.* **2023**, *43*, 78. [CrossRef]
26. Hu, Y.; Zhu, D.; Xing, Z.; Gong, J.; Zhang, H.; Dai, Q.; Huo, Z.; Xu, K.; Wei, H.; Guo, B. Effects of improved nitrogen application on rice yield and nitrogen uptake and utilization. *Plant Nutr. Fert. Sci.* **2015**, *21*, 12–22.
27. Iqbal, A.; He, L.; Khan, A.; Wei, S.; Akhtar, K.; Ali, I.; Ullah, S.; Munsif, F.; Zhao, Q.; Jiang, L. Organic Manure Coupled with Inorganic Fertilizer: An Approach for the Sustainable Production of Rice by Improving Soil Properties and Nitrogen Use Efficiency. *Agronomy* **2019**, *9*, 651. [CrossRef]
28. Yan, J.; Wang, W.; Li, B.; Li, Y.; Jiang, R.; Shen, M.; Wang, C.; Cui, B. Effects of chemical fertilizer reduction under straw returning on rice yield and nitrogen absorption and utilization in northern Jiangsu. *China Soils Fert.* **2021**, *5*, 74–82.
29. Sheng-Gang, P.; Sheng-Qi, H.; Jing, Z.; Jing-Ping, W.; Cou-Gui, C.; Ming-Li, C.; Ming, Z.; Xiang-Ru, T. Effects of N Management on Yield and N Uptake of Rice in Central China. *J. Integr. Agric.* **2012**, *11*, 1993–2000.
30. Shan, A.; Pan, J.; Kang, K.J.; Pan, M.; Wang, G.; Wang, M.; He, Z.; Yang, X. Effects of straw return with N fertilizer reduction on crop yield, plant diseases and pests and potential heavy metal risk in a Chinese rice paddy: A field study of 2 consecutive wheat-rice cycles. *Environ. Pollut.* **2021**, *288*, 117741. [CrossRef]

31. Zheng, W. Effects of Straw Returning and Nitrogen Application on Growth and Yield of Rice. Master's Thesis, Jilin Agricultural University, Jilin, China, 2021.
32. Xie, F.; Han, X.; Yang, J.; Liu, X.; Zuo, R.; Wu, Z. Effects of different nitrogen treatments on nitrogen uptake and yield of rice. *China. Soils Fert.* **2010**, *4*, 24–26+45.
33. Zhou, L.; Huang, Y.; Zhang, S.; Guo, Z.; Hong, R.; Wang, Y.; Xia, L.; Fu, L.; Li, Y.; Chen, Q. Effects of different nitrogen fertilizer regulation on tiller number and leaf area index of rice. *Hubei Agric. Sci.* **2020**, *59*, 33–37. [CrossRef]
34. Xie, H.; Wu, K.; Iqbal, A.; Ali, I.; He, L.; Ullah, S.; Wei, S.; Zhao, Q.; Wu, X.; Huang, Q.; et al. Synthetic nitrogen coupled with seaweed extract and microbial inoculants improves rice (*Oryza sativa* L.) production under a dual cropping system. *Ital. J. Agron.* **2021**, *16*, 1800. [CrossRef]
35. Yang, Y.; Zhang, Y.; Su, Z. Effects of nitrogen application rate on yield components and dry matter accumulation of hybrid rice. *J. Tianjin Agric. Coll.* **2005**, *1*, 5–8+30.
36. Cong, X.; Shi, F.; Ruan, X.; Luo, Y.; Ma, T.; Luo, Z. Effects of nitrogen fertilizer levels on nitrogen use efficiency, yield and quality of different rice genotypes. *Chin. J. Appl. Ecol.* **2017**, *28*, 1219–1226. [CrossRef]