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Effects of Different Straw Returning Periods and Nitrogen Fertilizer Combinations on Rice Roots and Yield in Saline–Sodic Soil

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Abstract: Straw return is an effective management practice for improving physical and chemical properties of saline–sodic soil in Northeast China. Straw decomposition and nutrient release are deeply influenced by soil and climatic factors. In Northeast China, straw decomposes slowly due to the long winter with low temperatures. Therefore, the season of straw return may be a key issue affecting rice. However, the impact of returning straw in different seasons on rice is disregarded and not commonly researched. We conducted a 2-year field experiment, including two residue management treatments: spring straw return treatment (SR) and autumn straw return treatment (AR), each containing five different N rates (0, 90, 180, 270, and 360 kg ha^{-1}) as sub-treatments. The results reveal that, compared with the spring straw returning treatment, the autumn straw returning treatment significantly improved root morphology and root vigor and increased the number of spikes per unit area, which directly increased rice yield by 4.76% (2020) and 6.62% (2021). In addition, rice yield showed an increasing and then decreasing trend with the increase in N fertilizer application, and it was at its maximum when the N application rate was 270 kg ha^{-1}. Compared to the spring straw return treatment, the autumn straw return treatment was able to reduce 31.46% (2020) and 38.48% (2021) of N fertilizer application without decreasing rice yield. Our findings demonstrate that straw return combined with nitrogen fertilization may be a promising management practice for improving rice root systems and yield in saline–sodic soils, and under the conditions of the autumn straw returning treatment, the best nitrogen fertilizer application rate was 270 kg ha^{-1}.

Keywords: saline–sodic rice area; straw return period; nitrogen fertilizer; soil physicochemical properties; rice root system

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1. Introduction

As an important land reserve resource for food production, saline–alkaline farmlands play an important role in ensuring national food security at a time when agricultural arable land is decreasing due to high urbanization [1]. China is one of the countries with the most serious soil salinization. The total area of saline–alkaline land in China is about 1.0×10^9 hectares, accounting for 10% of the world's saline–alkaline land area [2]. The salinized area on the west side of the Songnen Plain is about 3.73×10^6 hectares, which is one of the three largest concentrated distribution areas of soda saline–alkaline land in the world [3]. Saline–sodic soil exhibits high levels of soluble salts with a composition distinct from other types of saline–alkaline soils, predominantly comprising $NaHCO_3$ and Na_2CO_3, and typically has a soil pH above 8.5 [4]. Studies have shown that high pH can inhibit protein synthesis and produce cytotoxicity, leading to direct toxicity to plants [5]. In addition, high pH can reduce the effectiveness of phosphorus and impair nutrient uptake by rice roots [6]. Therefore, appropriate agronomic measures need to be taken to improve soil salinity, reduce damage to rice roots, and improve soil properties to increase the production potential of saline–sodic paddy fields.

Previous research has always focused on water, crops, chemical amendment, electric current, and tillage as prima amelioration tools for saline–alkaline soils [7]. Most of these methods are not suitable for large-scale promotion due to high costs, complex operations, and low acceptance among farmers. Recent studies have shown that straw return application to soil is more utilizable and sustainable [8,9]. Returning straw to the fields can not only solve the problem of resource waste and environmental pollution caused by agricultural wastes but can also significantly change the physical, chemical, and biological properties of the improved soil, thereby improving soil quality and crop yields [10,11], especially when applied together with nitrogen fertilizers [12]. Long-term straw return can significantly reduce soil bulk density, increase soil aggregate structure, increase soil total porosity and soil O^2 content, reduce N_2O emissions, improve soil ventilation and drainage capacity, and promote root growth in deep soil layers [13].

Nitrogen can serve both as a nutrient and for osmotic adjustment under saline–alkaline conditions, effectively mitigating the harm caused by salt and alkali stress to crops [14]. The effects of nitrogen application on root morphology, vigor, and distribution are significant and complex, and nitrogen use is well known for promoting root growth and downward rooting depth in the soil layer. Root length and number in mid-N treatment increased by 29.0% and 85.0%, compared with high-N treatment [15]. This also suggests that there is an optimal amount of nitrogen fertilizer application for root growth. However, in the saline–sodic rice area, farmers usually apply a large amount of nitrogen fertilizer in pursuit of high yields [3]. Chronic over-application of nitrogen fertilizer will cause a decline in soil quality (i.e., loss of soil organic matter, decreased soil fertility and inefficient nutrient use) and increase environmental pollution. [16,17].

Related studies have shown that under straw return in spring conditions, the rapid decomposition period of straw coincides with the rice rejuvenation and tillering stage, a process where significant amounts of nitrogen are absorbed and substantial toxic gases are produced, adversely impacting rice root growth and subsequently influencing the growth and development of rice [18,19]. However, the effects of seasonal differences in straw return on rice roots and yield in saline rice fields are unknown. Therefore, this study focuses on saline–sodic rice fields, examining the impacts of various straw return periods and nitrogen fertilization on rice root characteristics and yield under the conditions of full straw return. The aim is to identify the best straw return period and the most effective nitrogen application rate in these areas, thereby offering a theoretical foundation for enhancing the productivity of these fields and expanding the practice of rice straw return on a large scale in saline–sodic regions.

2. Materials and Methods

2.1. Study Site

The field experiment was carried out at Yixin Family Farm, Shili Town, Baicheng City, Jilin Province, China, from October 2019 to October 2021. Situated in the southwest of the Songnen Plain, Shili Town is a quintessential example of an area with moderate-to-severe saline–sodic soil. The average annual precipitation and evaporation are 413.7 and 1696.9 mm, respectively. The annual average sunshine duration, effective cumulative temperature, and frost-free period are 2996.2 h, 4.7 °C, and 144 days, respectively. Information on average precipitation and temperature during the experiment period is shown in Figure 1.

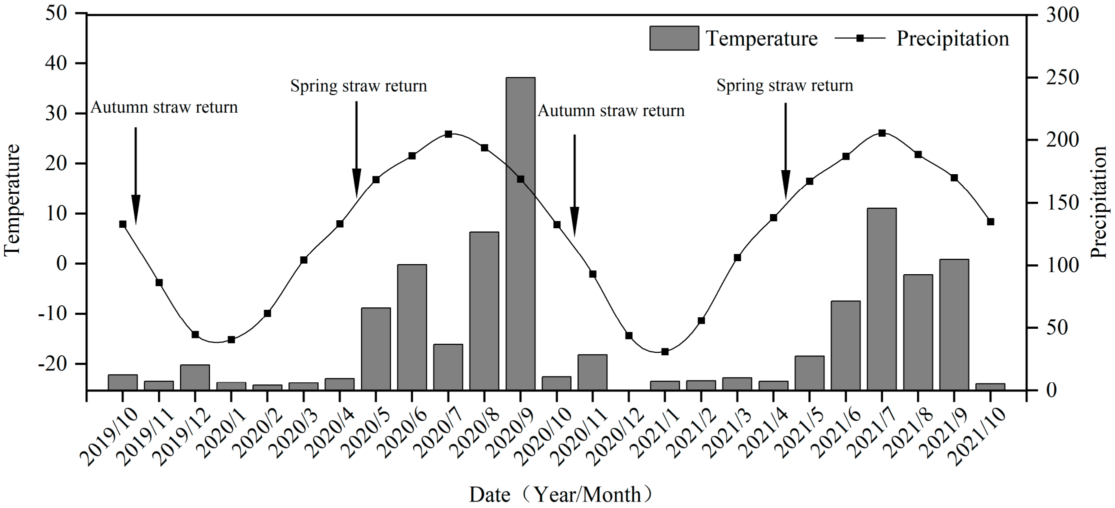

Figure 1. Monthly average temperature (°C) and monthly total precipitation (mm) from October 2019 to October 2021.

Prior to the experiment in October 2019, soil was collected from a depth of 0–20 cm to assess its physical and chemical properties. Table 1 shows the basic physical and chemical properties of the soil. At the experiment site, rice had been cultivated for five consecutive years. In non-experimental years, the rice straw produced was burned on-site before the spring ploughing in the second year. The tested variety was the local large-scale cultivar Baijing 1 (*Oryza saliva* subsp *keng*), which is characterized by its salt and alkali tolerance. The straw utilized in the experiment was harvested from the rice fields of the experimental site during the autumn, and its nutrient composition is detailed in Table 2.

Table 1. Basic physical and chemical properties of the tested soil.

Parameter	Mean	Parameter	Mean
BD (g cm^{-3})	1.52	Soil pH	8.91
EC$_e$ (dS m^{-1})	12.58	ENa$^+$ (cmol$_c$ kg^{-1})	5.34
ESP (%)	37.87	SOM (g kg^{-1})	6.08
Total N (g kg^{-1})	0.18	Available P (mg kg^{-1})	8.84
CEC (cmol$_c$ kg^{-1})	14.11	Available K (mg kg^{-1})	102.34

Note: BD: bulk density; EC$_e$: soil electrical conductivity of saturated paste extraction; ENa$^+$: exchangeable sodium; CEC: cation exchange capacity; ESP: exchangeable sodium percentage; SOM: soil organic matter.

Table 2. Nutrient content of tested straw.

Year	Total C (%)	Total N (mg g^{-1})	Total P (mg g^{-1})	Total K (mg g^{-1})	C/N Ratio	Cellulose (mg g^{-1})	Hemicellulose (mg g^{-1})	Lignin (mg g^{-1})
2019	38.09	4.56	1.72	8.09	83.40	366.07	265.57	54.95
2020	37.67	4.73	1.66	8.13	79.57	378.66	272.69	58.63

2.2. Experimental Design

The experiment was conducted using a split plot design, with the straw returning period as the main plot and nitrogen fertilizer as the secondary plot. The experiment was carried out continuously on the same plot for two years. The straw returning periods were spring straw returning (SR) and autumn straw returning (AR), and the five nitrogen fertilizer levels were 0 (N0), 90 (N90), 180 (N180), 270 (N270), and 360 (N360) kg ha^{-1}, for a total of 10 treatments with three replicates. The plot size was 30 m^2 (6 × 5 m). To prevent nutrient or water exchange between plots, the plots were separated by field ridges (0.6 m wide and 0.4 m high), and each plot had independent irrigation and drainage outlets. The nitrogen fertilizer for each treatment was applied according to a base fertilizer–tillering fertilizer–ear fertilizer ratio of 6:3:1. Phosphorus fertilizer (P_2O_5) and zinc fertilizer ($ZnSO_4$)

were applied as base fertilizer once, with application rates of 50 kg ha^{-1} and 20 kg ha^{-1}, respectively. Potassium fertilizer (K_2O) was applied at 45 and 30 kg ha^{-1} as a base fertilizer and ear fertilizer, respectively. The straw used was produced during the previous rice planting season. The straw was collected manually from the experimental field. After the straw was air-dried under natural conditions, it was cut into 5–7 cm long pieces with a straw chopper. The spring straw return treatment (SR) was carried out by rotary tillage in mid-April each year, and the straw was evenly spread on the soil surface together with basal fertilizer before being mixed into the soil with a reverse stubble rotary tiller. In the plants treated by autumn straw return (AR), all rice straw was applied after the previous year's harvest (mid to late October), and the same field was then tilled with a reverse stubble rotary tiller. All treatments were plowed again on May 9 of the following year, and base fertilizer was applied at the same time. The amount of straw returned to the field was converted to 8 t ha^{-1} based on the local rice yield and a rice-to-straw ratio of 1:1.1.

2.3. Plant Sampling Collection

At the tillering stage (MT), panicle initiation stage (PI), heading stage (HD), filling stage (FI), and physiological maturity stage (PM), nine rice samples were collected from each plot. Of these, three samples were designated for the assessment of root morphological traits and root-to-shoot ratio, while the remaining six were reserved for the measurement of root physiological traits. A sampler was employed to extract a cubic soil block (30.0 cm in length, 16.5 cm in width, and 30.0 cm in depth) encompassing each rice plant. This soil block contained about 95% of the total rice root biomass [20]. The roots in each soil block were then carefully rinsed with distilled water.

2.4. Morphological and Physiological Characteristics Analysis

The roots were evenly dispersed on a glass dish filled with shallow water and positioned optimally before being scanned using an Epson scanner (V850, Seiko Epson Corporation, Suwa, Nagano, Japan). The captured images were then processed and analyzed using WinRHIZO (2021a) software to derive metrics such as total root length (RL), total root surface area (RSA), and total root volume (RV). Subsequently, to ascertain the dry weight (RDW) of both the above-ground portion and the roots, the root samples were gathered following the scanning process. Both the above-ground and root samples were then blanched at 105 °C for half an hour and subsequently dried to a constant weight at 80 °C. Finally, the root-to-shoot ratio was computed based on the weights of the root and above-ground components.

The total root absorption surface area (RTA) and the root active absorption surface area (RAA) were measured using the methylene blue method. Following the protocol outlined by Yang et al., three rice plants were selected from each plot, based on the average number of tillers, for the collection of root bleeding sap [21]. This process was carried out as follows. At 18:00, during the tillering, panicle initiation, heading, filling, and physiological maturity stages, the rice plants were severed at an internode approximately 12 cm above the soil surface. A pre-weighed glass tube and absorbent cotton were then placed adjacent to the incision on the field stem, and the entire setup was wrapped in plastic film to prevent water infiltration. The absorbent cotton and glass tube were collected and re-weighed the following morning at 6:00. The difference in weight represented the root bleeding sap of each growth stage, expressed as the concentration per hour (mg h^{-1} plant^{-1}) per plant.

2.5. Nitrogen Use Efficiency and Rice Yield

During the mature stage, three rice plants with uniform growth were collected from each plot. The above-ground portion of the rice was subsequently divided into leaves, stem sheaths, and spikes. Samples were heated at 105 °C for half an hour to deactivate enzymes, followed by drying at 80 °C until a constant weight was achieved. Afterward, the samples were weighed and grounded. To ascertain the total nitrogen absorption, the above-ground samples from each part were sifted through a 0.5 mm sieve. The nitrogen content in various rice organs was determined using the Kjeldahl method through a Kjeldahl nitrogen analyzer (FOSS-8400) [22]. The nitrogen absorption of the plant was calculated based on the derived nitrogen concentration of rice and the weights of the different parts. The agronomic efficiency of nitrogen fertilizer (AEN), partial factor productivity of nitrogen fertilizer (PFP), and apparent utilization rate of nitrogen fertilizer (REN) were computed according to the methodology outlined by Wang et al. The corresponding calculation formulas are detailed as follows [23].

$$\mathrm{AEN}\left(\mathrm{kg\ kg^{-1}}\right) = \frac{\mathrm{Y} - \mathrm{Y_0}}{\mathrm{F}} \tag{1}$$

$$\mathrm{PFP}\left(\mathrm{kg\ kg^{-1}}\right) = \frac{\mathrm{Y}}{\mathrm{F}} \tag{2}$$

$$\mathrm{REN} = \frac{\mathrm{TPN} - \mathrm{TP0}}{\mathrm{F}} \tag{3}$$

TPN: total nitrogen absorption of rice plants in the nitrogen application area; TP0: total nitrogen absorption of rice plants under nitrogen-free conditions; F: nitrogen application rate; Y: rice yield under nitrogen application conditions; $\mathrm{Y_0}$: rice yield under nitrogen-free conditions.

2.6. Statistical Analysis

All the data were analyzed using SPSS 22.0 software (SPSS Inc., Chicago, IL, USA). The LSD method was employed to assess the significance of differences in the data across treatments, with a significance level set at $p < 0.05$. Additionally, Sigmaplot 14.0 software was utilized to generate graphical representations. All numerical values presented in the charts represent the mean ± standard error.

3. Results

3.1. Morphological Characteristics of the Rice Root System

Root length and root surface area initially increased and then decreased throughout the rice growth process, peaking in the heading phase and decreasing thereafter (Table 3). The application of nitrogen fertilizer significantly enhanced both root length and root surface area. However, no significant difference was observed between the N270 and N360 treatments during the same straw returning period (Table 3). It is indicated that excessive nitrogen application did not lead to a notable increase in total root length or root surface area. Furthermore, at equivalent nitrogen levels, the autumn straw returning treatments exhibited higher root length and root surface area than the spring straw returning treatments. This observation was indirectly corroborated by the field growth and root length of rice during the tillering stage (Figure 2). In comparison to spring straw returning, autumn straw returning resulted in significant increases in rice root length by 30.6%, 23.8%, 14.4%, 11.3%, and 13.5% (two-year average) during the tillering, panicle initiation, heading, filling, and physiological maturity stages, respectively. Similarly, the root surface area increased significantly by 14.5%, 20.7%, 28.5%, 25.8%, and 12.9% (two-year average) across the same stages.

As depicted in Table 4, the dry weight of rice roots exhibited a pattern of initial increase followed by a decline throughout the growth cycle, peaking at the heading stage. When comparing the same straw returning period, the application of nitrogen fertilizer resulted in significant enhancement in the dry weight of rice roots across all stages. Specifically, the dry weight of rice roots increased significantly with increasing nitrogen application throughout the life span of rice. However, there was no significant difference between the N270 and N360 treatments, indicating that excessive nitrogen application did not promote rice root growth under straw returning conditions. Furthermore, when comparing autumn straw returning with spring straw returning, the dry weight of rice roots increased significantly by 11.31%, 9.82%, 10.03%, and 10.26% on average over a two-year period during the tillering stage, panicle initiation stage, heading stage, and filling stage, respectively. It is noteworthy that the ratio of root to shoot in rice gradually decreased as the growth cycle progressed. The application of nitrogen fertilizer significantly reduced this ratio at each growth stage.

As the growth process of rice progressed (Table 4), the root volume reached a peak at the heading stage and then decreased. In the same straw returning period, the application of nitrogen fertilizer significantly increased the root volume of rice at various growth stages, but there was no significant difference between N270 and N360. Compared with SR, the root volume achieved with the autumn straw returning treatment at the tillering stage, panicle initiation stage, heading stage, and filling stage significantly increased by 9.4%, 13.9%, 13.5%, and 15.0% (two-year average), respectively.

Figure 2. Root length and field expression of rice in the spring straw return and autumn straw return rice fields at the tillering stage. Note: SR: straw returned to the field in spring; AR: straw returned to the field in autumn; N0: nitrogen application of 0 kg ha^{-1}; N180: nitrogen application of 180 kg ha^{-1}; N360: nitrogen application of 360 kg ha^{-1}.

Table 3. Effect of straw return period and nitrogen fertilizer application on the root length and root surface area of rice.

Treatment			Root Length (km m^{-2})					Root Surface Area (m^2 m^{-2})				
			MT	PI	HD	FI	PM	MT	PI	HD	FI	PM
2020	SR	N0	0.46 c	1.05 c	2.16 c	2.00 d	1.40 c	0.96 c	1.89 d	3.15 d	2.83 d	2.14 d
		N90	0.51 c	1.18 bc	2.51 b	2.39 c	1.56 bc	1.05 bc	2.44 c	3.96 c	3.79 c	2.37 c
		N180	0.65 b	1.35 b	2.62 b	2.53 b	1.63 ab	1.15 b	2.85 b	4.19 b	3.91 b	2.84 b
		N270	0.78 a	1.68 a	2.98 a	2.89 a	1.72 a	1.27 a	3.51 a	4.60 a	4.48 a	3.15 a
		N360	0.80 a	1.76 a	3.05 a	2.91 a	1.79 a	1.33 a	3.66 a	4.72 a	4.57 a	3.26 a
	AR	N0	0.66 d	1.25 c	2.46 c	2.37 d	1.61 c	1.18 c	2.21 d	4.52 d	4.28 e	2.52 d
		N90	0.79 c	1.42 c	2.95 b	2.58 c	1.70 c	1.25 bc	2.71 c	5.37 c	4.97 d	3.12 c
		N180	0.86 b	1.79 b	3.06 b	2.85 b	1.77 bc	1.34 ab	3.30 b	5.93 b	5.48 c	3.25 bc
		N270	0.95 a	2.07 a	3.58 a	3.40 a	1.91 ab	1.45 a	4.41 a	6.49 a	6.30 a	3.44 ab
		N360	0.91 ab	2.05 a	3.49 a	3.36 a	1.97 a	1.40 a	4.33 a	6.31 a	5.95 b	3.64 a
2021	SR	N0	0.52 c	1.15 c	2.49 c	2.30 d	1.43 c	1.07 c	2.09 d	4.21 d	3.95 d	2.57 d
		N90	0.58 bc	1.21 c	2.86 b	2.65 c	1.63 b	1.13 c	2.61 c	4.68 c	4.55 c	2.72 c
		N180	0.68 b	1.49 b	2.98 b	2.88 b	1.73 ab	1.29 b	2.94 b	5.19 b	4.89 b	3.11 b
		N270	0.84 a	1.71 a	3.45 a	3.12 a	1.87 a	1.37 ab	3.62 a	5.48 a	5.25 a	3.67 a
		N360	0.88 a	1.80 a	3.53 a	3.27 a	1.92 a	1.46 a	3.68 a	5.57 a	5.39 a	3.73 a
	AR	N0	0.78 d	1.32 d	2.80 d	2.62 c	1.88 b	1.30 b	2.53 d	4.69 d	4.26 d	2.66 d
		N90	0.85 c	1.56 c	3.13 c	2.70 c	1.90 b	1.37 b	2.92 c	5.53 c	5.09 c	3.20 c
		N180	0.92 b	1.83 b	3.50 b	3.11 b	1.95 ab	1.39 b	3.81 b	6.39 b	5.95 b	3.68 b
		N270	0.99 a	2.41 a	3.91 a	3.50 a	2.09 a	1.57 a	4.60 a	6.82 a	6.43 a	3.87 ab
		N360	0.98 a	2.32 a	3.82 a	3.27 a	2.10 a	1.53 ab	4.51 a	6.73 ab	6.12 ab	3.93 a
ANOVA		Y	**	**	**	*	*	*	**	**	*	**
		N	**	**	**	**	**	**	**	**	**	**
		T	*	**	*	*	*	**	**	**	*	*
		N × T	*	*	*	*	ns	*	*	*	*	ns
		Y × N	*	*	*	*	ns	*	*	*	*	ns
		T × Y	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
		N × T × Y	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

Note: The data in the table are the mean values of three replications. Different lowercase letters in the column under the same straw treatment in the same year indicate significant differences between treatments ($p < 0.05$). SR: straw returned to the field in spring; AR: straw returned to the field in autumn; MT: mid-tillering stage; PI: panicle initiation stage; HD: heading stage; FI: filling stage; PM: physiological maturity stage; Y: year; N: nitrogen fertilizer; T: straw returning period; *, ** mean $p < 0.05$, $p < 0.01$; ns means non-significant.

Table 4. Effects of straw return period and nitrogen fertilizer combination on root dry weight and root–shoot ratio of rice.

Treatment			Root Dry Weight (g m^{-2})					Root–Shoot Ratio (%)				
			MT	**PI**	**HD**	**FI**	**PM**	**MT**	**PI**	**HD**	**FI**	**PM**
2020	SR	N0	19.53 c	40.17 d	89.48 d	88.40 d	73.73 d	26.5 a	25.7 a	21.2 a	16.2 a	9.1 a
		N90	20.87 c	67.82 c	128.44 c	124.07 c	99.47 c	25.8 ab	24.8 ab	20.4 a	16.0 a	8.8 ab
		N180	28.47 b	79.27 b	138.57 b	137.55 b	111.87 b	24.1 b	23.2 ab	20.1 a	15.8 ab	8.7 ab
		N270	30.41 ab	89.66 a	155.24 a	158.51 a	139.73 a	24.1 b	23.1 ab	20.0 ab	15.2 ab	8.5 ab
		N360	31.08 a	92.65 a	160.57 a	160.25 a	142.47 a	23.0 b	22.8 b	19.5 b	14.6 b	8.3 b
	AR	N0	19.92 d	46.72 c	96.80 d	92.15 d	74.13 e	27.9 a	28.2 a	22.8 a	16.5 a	9.0 a
		N90	23.81 c	79.00 b	146.81 c	145.14 c	102.20 d	26.1 b	26.1 b	21.8 a	16.5 a	8.3 ab
		N180	32.12 b	84.86 b	154.73 b	161.73 b	114.07 c	24.9 bc	24.7 c	21.7 a	15.9 a	7.9 b
		N270	36.60 a	99.80 a	167.10 a	182.30 a	141.40 b	24.2 cd	24.3 c	20.4 ab	15.1 ab	7.8 b
		N360	36.81 a	108.72 a	179.21 a	187.82 a	155.13 a	23.1 d	23.1 c	19.1 b	14.2 b	7.5 b
2021	SR	N0	18.60 d	50.81 d	90.47 d	95.35 c	77.35 d	28.5 a	27.7 a	21.0 a	16.0 a	9.5 a
		N90	21.73 c	67.55 c	140.59 c	144.22 b	100.67 c	25.0 ab	24.9 ab	20.9 a	15.8 a	8.7 ab
		N180	30.62 b	80.95 b	158.72 b	160.53 ab	114.33 b	24.8 b	23.1 b	19.9 ab	15.2 a	8.5 ab
		N270	33.48 a	94.58 a	166.77 a	163.21 a	139.85 a	23.1 b	22.1 bc	18.9 ab	14.3 ab	8.2 ab
		N360	34.80 a	99.72 a	170.21 a	165.37 a	146.73 a	22.1 b	20.9 c	18.7 b	13.6 b	7.9 b
	AR	N0	20.00 d	54.53 d	97.40 d	98.40 d	78.47 d	28.5 a	30.0 a	22.0 a	17.7 a	9.4 a
		N90	24.60 c	75.60 c	147.60 c	153.20 c	103.60 c	25.1 b	24.5 b	21.4 a	17.3 ab	8.6 ab
		N180	32.47 b	89.00 b	169.80 b	166.20 b	117.73 b	25.1 b	24.5 b	21.3 a	16.2 b	7.9 bc
		N270	36.67 a	98.80 ab	187.27 a	172.93 ab	147.87 a	23.5 c	23.9 bc	20.4 ab	14.9 c	7.8 bc
		N360	37.07 a	101.13 a	192.47 a	180.73 a	150.80 a	22.7 c	21.1 c	19.4 b	12.8 d	7.0 c
ANOVA		Y	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
		N	**	**	**	**	**	*	*	*	*	*
		T	*	*	*	*	ns	ns	ns	ns	ns	ns
		N × T	*	*	*	*	ns	ns	ns	ns	ns	ns
		Y × N	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
		T × Y	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
		N × T × Y	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

Note: The data in the table are the mean values of three replications. Different lowercase letters in the column under the same straw treatment in the same year indicate significant differences between treatments ($p < 0.05$). SR: straw returned to the field in spring; AR: straw returned to the field in autumn; MT: mid-tillering stage; PI: panicle initiation stage; HD: heading stage; FI: filling stage; PM: physiological maturity stage; Y: year; N: nitrogen fertilizer; T: straw returning period; *, ** mean $p < 0.05$, $p < 0.01$; ns means non-significant.

3.2. Physiological Characteristics of Rice Root System

As the growth process of rice progresses, the root bleeding sap of rice increased first and then decreased, reaching its maximum at the heading stage (Table 5). Compared with spring straw returning, autumn straw returning significantly increased the root bleeding sap of rice at various growth stages, with significant increases of 17.4%, 16.2%, 7.3%, 11.6%, and 16.7% (two-year average) in the tillering stage, panicle initiation stage, heading stage, grain filling stage, and physiological maturity stage, respectively. The application of nitrogen fertilizer significantly increased the root bleeding sap of rice at various growth stages. The amount of rice root bleeding sap increased significantly with increasing nitrogen application throughout the life span of rice. However, there was no significant difference in the root bleeding sap of rice between the N270 and N360 treatments at the same straw returning period.

As rice grows, the total root absorption area and active absorption area first increased and then decreased, reaching a peak at the heading stage, and then gradually decreased (Table 6). In each growth stage of rice, at the same nitrogen level, the total absorption area and active absorption area of rice roots in the autumn straw returning treatment were higher than those in the spring straw returning treatment and were significantly higher than those in the spring straw returning treatment in the tillering stage, panicle initiation stage, heading stage, and filling stage. Compared with the spring straw returning treatment, the total absorption area of the root system in the autumn straw returning treatment increased significantly by 18.3%, 30.8%, 24.8%, and 9.9% (average of two years) in the tillering stage, panicle initiation stage, heading stage, and filling stage, respectively. The active absorption area of the root system in the autumn straw returning treatment increased significantly by 10.6%, 6.7%, 6.9%, and 5.9% (average of two years) in the tillering stage, panicle initiation stage, heading stage, and filling stage, respectively. In the context of identical straw returning periods, the application of nitrogen fertilizer significantly enhanced the total root absorption surface area and the active absorption area across various growth stages of rice. Specifically, under spring straw returning conditions, both the total root absorption surface area and the active absorption area progressively increased with the augmentation of nitrogen application rates. Conversely, under autumn straw returning conditions, there was an initial increase followed by a decrease in both parameters with the rise in nitrogen application rates, peaking at the N270 level. However, regardless of whether it was spring or autumn straw returning, no significant differences were observed in the total root absorption surface area and the active absorption area between the N270 and N360 levels across the growth stages of rice. In summary, the integration of autumn straw returning with nitrogen fertilizer application demonstrated a superior promotional effect on the root exudates, the total root absorption surface area, and the active absorption area in soda saline-alkaline paddy fields. However, it is essential to note that the dosage of nitrogen fertilizer should not be excessively high.

Table 5. Effect of straw return period and nitrogen fertilizer allocation on rice root volume and root bleeding sap.

Treatment			**Root Volume (cm^3 m^{-2})**					**Root Bleeding Sap (mg h^{-1} $plant^{-1}$)**				
			MT	**PI**	**HD**	**FI**	**PM**	**MT**	**PI**	**HD**	**FI**	**PM**
2020	SR	N0	115.51 d	314.50 d	631.24 d	600.08 d	338.60 d	13.83 d	44.47 c	90.25 c	85.77 d	15.69 b
		N90	124.70 c	394.53 c	728.11 c	686.98 c	360.23 c	17.19 c	50.47 bc	100.21 b	92.55 c	16.37 b
		N180	136.85 b	468.57 b	806.40 b	752.47 b	442.07 b	20.58 b	58.00 b	108.87 ab	100.24 b	17.33 ab
		N270	158.83 a	485.67 ab	845.77 a	817.57 a	493.67 a	26.88 a	67.99 a	112.29 a	104.63 ab	18.19 a
		N360	160.25 a	509.72 a	869.52 a	822.12 a	517.22 a	27.85 a	70.25 a	114.58 a	111.19 a	18.83 a
	AR	N0	136.53 b	366.93 d	741.93 d	720.73 d	360.20 d	15.38 d	50.25 c	96.86 d	97.38 d	17.19 b
		N90	144.33 b	433.93 c	800.86 c	789.13 c	389.46 c	20.72 c	62.80 b	108.27 c	107.22 c	18.63 ab
		N180	157.66 a	532.80 b	933.80 b	892.13 b	461.86 b	26.91 b	69.05 b	118.77 b	114.66 b	19.94 a
		N270	168.13 a	631.93 a	995.46 a	931.00 a	513.46 a	31.19 b	85.80 a	128.50 a	127.27 a	23.08 a
		N360	163.60 a	569.13 b	952.53 b	906.53 ab	518.53 a	30.11 ab	82.19 a	124.19 a	122.19 a	23.52 a
2021	SR	N0	120.44 d	349.83 d	680.51 d	649.10 d	376.71 c	16.74 c	46.98 d	99.17 d	92.42 d	16.36 c
		N90	138.53 c	428.07 c	781.55 c	721.25 c	390.81 c	19.99 bc	55.73 c	118.36 c	105.58 c	17.72 bc
		N180	155.22 b	493.66 b	813.48 b	793.60 b	447.55 b	22.95 b	66.84 b	122.37 bc	115.63 b	18.28 ab
		N270	162.73 a	553.73 ab	853.82 a	810.40 ab	498.35 a	26.67 a	76.57 a	127.22 ab	123.49 a	19.67 a
		N360	167.53 a	571.22 a	890.75 a	836.98 a	518.23 a	27.71 a	78.84 a	130.65 a	125.57 a	20.25 a
	AR	N0	143.20 c	397.26 e	772.40 d	753.93 c	390.20 c	18.72 c	52.88 d	108.05 c	105.44 c	18.05 c
		N90	149.73 c	467.06 d	831.40 c	806.93 b	411.13 c	24.19 b	65.58 c	122.02 b	115.30 b	19.02 bc
		N180	164.73 b	547.33 c	951.40 b	921.80 a	471.20 b	27.08 b	77.36 b	130.16 ab	125.44 a	20.27 b
		N270	178.06 a	647.20 a	1020.06 a	969.53 a	514.93 a	33.44 a	85.55 a	134.97 a	133.52 a	23.72 a
		N360	170.40 ab	610.20 b	967.86 b	920.06 a	520.93 a	30.86 a	84.72 a	133.61 a	130.77 a	25.05 a
ANOVA		Y	*	*	*	*	*	*	*	*	*	*
		N	**	**	**	**	*	**	**	**	**	*
		T	*	*	*	*	ns	*	*	*	*	*
		N × T	*	*	*	*	ns	*	*	*	*	*
		Y × N	*	*	*	*	ns	*	*	*	*	ns
		T × Y	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
		N × T × Y	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

Note: The data in the table are the mean values of three replications. Different lowercase letters in the column under the same straw treatment in the same year indicate significant differences between treatments ($p < 0.05$). SR: straw returned to the field in spring; AR: straw returned to the field in autumn; MT: mid-tillering stage; PI: panicle initiation stage; HD: heading stage; FI: filling stage; PM: physiological maturity stage; Y: year; N: nitrogen fertilizer; T: straw returning period; *, ** mean $p < 0.05$, $p < 0.01$; ns means non-significant.

Table 6. Effect of straw return period combined with nitrogen fertilizer application on the root total absorbing surface area and root activity absorbing area of rice.

Treatment			RTA (m^2 m^{-2})					RAA (m^2 m^{-2})				
			MT	**PI**	**HD**	**FI**	**PM**	**MT**	**PI**	**HD**	**FI**	**PM**
2020	SR	N0	3.57 d	6.19 c	7.96 c	7.86 c	4.53 b	2.06 b	3.25 c	4.13 c	3.79 c	2.05 b
		N90	4.36 c	6.84 bc	8.01 c	8.03 c	5.04 ab	2.17 b	3.45 c	4.60 b	4.52 b	2.27 ab
		N180	5.08 b	7.35 b	9.97 b	9.69 b	5.15 a	2.45 ab	4.22 b	4.89 b	4.71 b	2.31 a
		N270	5.86 a	8.07 a	10.27 ab	10.08 ab	5.28 a	2.88 a	4.83 a	5.67 a	5.58 a	2.42 a
		N360	6.02 a	8.52 a	10.80 a	10.44 a	5.33 a	3.02 a	4.87 a	5.88 a	5.72 a	2.44 a
	AR	N0	4.02 c	7.49 c	9.69 d	8.36 d	4.85 c	2.27 c	3.51 d	4.35 d	4.26 d	2.15 c
		N90	5.10 b	8.22 c	10.92 c	9.35 c	5.43 b	2.52 b	3.70 d	4.91 c	4.77 c	2.36 b
		N180	6.64 a	9.67 b	12.21 b	10.19 b	5.53 b	2.95 ab	4.35 c	5.47 b	5.26 b	2.43 b
		N270	7.00 a	11.56 a	13.84 a	11.76 a	5.81 a	3.17 a	5.29 a	6.24 a	5.95 a	2.62 a
		N360	6.90 a	11.01 a	13.37 a	10.96 ab	5.93 a	2.95 ab	4.96 b	6.05 a	5.74 a	2.66 a
2021	SR	N0	3.78 d	6.50 d	8.21 d	8.05 c	5.09 b	2.21 c	3.53 c	4.48 d	4.21 d	2.24 b
		N90	4.69 c	7.18 c	9.29 c	9.03 b	5.23 b	2.41 c	3.86 bc	4.92 c	4.53 c	2.32 ab
		N180	5.36 b	7.79 b	10.02 b	9.89 b	5.82 a	2.80 b	4.34 ab	5.29 b	5.09 b	2.44 ab
		N270	6.19 a	8.72 a	11.35 a	11.03 a	6.22 a	3.01 ab	4.86 a	5.84 a	5.65 a	2.51 a
		N360	6.25 a	9.08 a	11.89 a	11.80 a	6.25 a	3.26 a	4.93 a	5.98 a	5.72 a	2.55 a
	AR	N0	4.43 d	8.12 d	10.03 d	9.72 b	5.40 c	2.52 c	3.61 d	4.65 d	4.37 d	2.30 c
		N90	5.53 c	8.92 c	11.55 c	10.22 b	5.54 c	2.73 c	4.01 c	5.11 c	4.75 c	2.37 c
		N180	6.73 b	10.44 b	12.80 b	11.41 a	6.11 b	3.15 b	4.68 b	5.66 b	5.37 b	2.53 b
		N270	7.27 a	12.28 a	13.94 a	12.30 a	6.35 ab	3.48 a	5.53 a	6.46 a	6.14 a	2.64 ab
		N360	6.92 ab	11.99 a	13.59 a	11.12 a	6.49 a	3.31 ab	5.31 a	6.32 a	5.85 a	2.67 a
ANOVA		Y	*	*	*	*	ns	*	*	*	*	ns
		N	**	**	**	**	**	**	**	**	**	*
		T	*	*	*	*	ns	*	*	*	*	ns
		N × T	*	*	*	*	ns	*	*	*	*	ns
		Y × N	*	*	*	*	ns	*	*	*	*	ns
		T × Y	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
		N × T × Y	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

Note: The data in the table are the mean values of three replications. Different lowercase letters in the column under the same straw treatment in the same year indicate significant differences between treatments ($p < 0.05$). SR: straw returned to the field in spring; AR: straw returned to the field in autumn; MT: mid-tillering stage; PI: panicle initiation stage; HD: heading stage; FI: filling stage; PM: physiological maturity stage; Y: year; N: nitrogen fertilizer; T: straw returning period; *, ** mean $p < 0.05$, $p < 0.01$; ns means non-significant.

3.3. Rice Yield

The year (Y), nitrogen fertilizer (N), straw returning period (T), the interaction between nitrogen fertilizer and straw returning periods (N × T), and the interaction between the year and different straw returning periods (Y × T) all exerted significant or extremely significant impacts on rice yield, as illustrated in Figure 3. Regardless of whether the straw was returned in spring or autumn, rice yield demonstrated a trend of initial increase followed by decrease with the augmentation of nitrogen application, peaking at the N270 level. Within the same straw returning period, no significant difference in rice yield was observed between the N180 and N360 treatments. Under the N270 condition, the two-year average yield for the autumn straw returning treatment was 8.01 t ha^{-1}, while the average yield for the spring straw returning treatment was 7.77 t ha^{-1}. On average across all nitrogen levels, the rice yield significantly increased by 4.8% (in 2020) and 6.6% (in 2021) with the autumn straw treatment compared to the spring straw returning treatment.

It can be seen from Table 7 that whether the straw was returned in spring or autumn, the theoretical yield of rice first increased and then decreased with the increase in nitrogen application rate and reached a maximum at N270, but there was no significant difference between N360 and N270 when using the same straw returning period. Compared with straw returning in spring, straw returning in autumn significantly increased the theoretical yield of rice by 6.6% in 2020 and 7.4% in 2021. Under the same straw returning period, the application of nitrogen fertilizer significantly increased the number of panicles and grains per panicle of rice and significantly reduced the seed setting rate, but there was no significant difference in the number of panicles, grains per panicle, and seed setting rate between N270 and N360. Compared with N0, the number of panicles in the N90, n180, N270 and N360 treatments increased significantly by 33.8%, 53.2%, 71.9% and 76.3% (two-year average), and the number of grains per panicle increased significantly by 18.1%, 33.7%, 41.9% and 42.9% (two-year average), respectively. Compared with spring straw returning, autumn straw returning increased the number of panicles, grain number per panicle, the seed setting rate, and the 1000-grain weight. However, straw returning in autumn only significantly increased the number of rice panicles, which increased by 6.9% and 4.4%, respectively, from 2020 to 2021. This shows that the theoretical yield of rice can be improved by increasing the number of rice panicles in the paddy field in autumn, but the amount of nitrogen fertilizer should not be too high when returning straw in autumn.

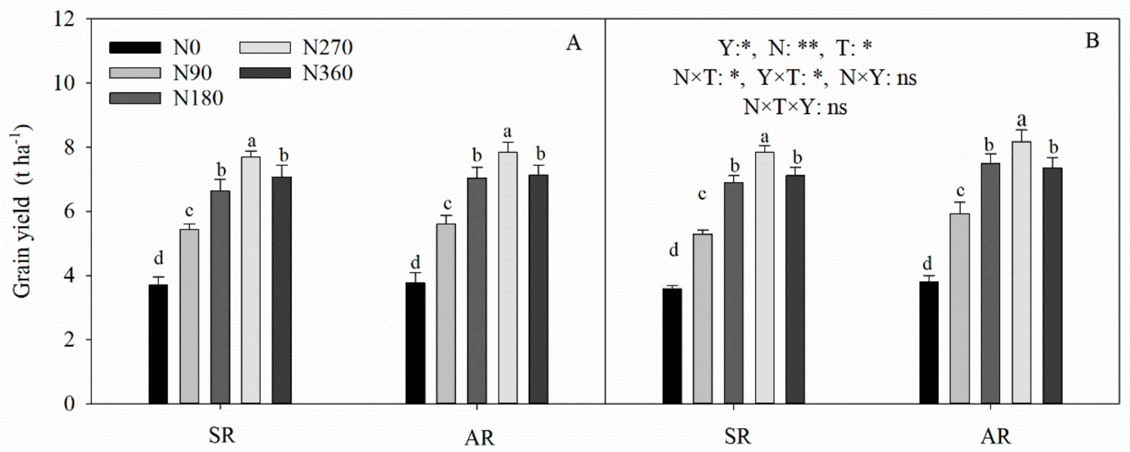

Figure 3. Effect of straw return period and combined application of nitrogen fertilizer on rice yield. Data in the figures are mean ± standard error. SR: straw returned to the field in spring; AR: straw returned to the field in autumn; Y: year; N: nitrogen fertilizer; T: straw returning period; N0: nitrogen application of 0 kg ha^{-1}; N90: nitrogen application of 90 kg ha^{-1}; N180: nitrogen application of 180 kg ha^{-1}; N270: nitrogen application of 270 kg ha^{-1}; N360: nitrogen application of 360 kg ha^{-1}; (**A**) denotes 2020, and (**B**) denotes 2021. Different lowercase letters in the graphs under the same straw management indicate that the values are significantly different at the 0.05 level; *, ** indicates significant differences at the 0.05 and 0.01 levels, respectively, and ns indicates no significant difference.

Table 7. Effect of straw return period and combined application of nitrogen fertilizer on the components of rice yield.

Treatment			Spike Number ($\times 10^4$ ha^{-1})	Spikelets per Panicle	Seed Setting Rate (%)	1000-Grain Weight (g)	Theoretical Yield (t ha^{-1})
2020	SR	N0	224.58 ± 20.38 d	66.05 ± 4.27 c	90.87 ± 3.25 a	25.87 ± 1.02 a	3.65 ± 0.23 d
		N90	313.66 ± 30.41 c	78.04 ± 3.58 b	89.58 ± 2.71 ab	25.43 ± 0.92 a	5.58 ± 0.51 c
		N180	353.53 ± 25.14 b	89.19 ± 2.92 a	88.42 ± 2.66 ab	24.88 ± 1.13 a	6.94 ± 0.32 b
		N270	396.57 ± 30.52 a	95.03 ± 4.22 a	86.45 ± 3.18 b	24.57 ± 0.89 a	8.01 ± 0.44 a
		N360	413.26 ± 29.58 a	95.57 ± 5.69 a	83.82 ± 1.50 c	23.85 ± 1.15 a	7.89 ± 0.35 a
	AR	N0	256.67 ± 30.18 d	66.55 ± 5.27 c	90.48 ± 2.42 a	25.07 ± 0.77 a	3.87 ± 0.29 d
		N90	327.67 ± 32.17 c	79.31 ± 6.35 b	89.29 ± 3.25 a	24.92 ± 0.92 a	5.78 ± 0.38 c
		N180	378.67 ± 40.22 b	90.91 ± 8.24 a	88.96 ± 2.71 ab	24.39 ± 1.15 ab	7.47 ± 0.55 b
		N270	423.33 ± 41.25 a	97.17 ± 9.11 a	88.25 ± 1.99 ab	23.93 ± 1.32 b	8.69 ± 0.23 a
		N360	433.33 ± 30.27 a	96.54 ± 7.23 a	86.13 ± 2.67 b	23.24 ± 0.89 b	8.37 ± 0.62 ab

Table 7. *Cont.*

Treatment			Spike Number ($\times 10^4$ ha^{-1})	Spikelets per Panicle	Seed Setting Rate (%)	1000-Grain Weight (g)	Theoretical Yield (t ha^{-1})
2021	SR	N0	236.89 ± 24.37 d	67.18 ± 6.17 c	91.23 ± 1.88 a	25.89 ± 0.93 a	3.76 ± 0.38 d
		N90	321.22 ± 32.19 c	76.58 ± 6.88 b	89.89 ± 2.64 a	25.62 ± 1.25 a	5.67 ± 0.55 c
		N180	371.27 ± 22.19 b	84.59 ± 7.59 ab	88.79 ± 2.72 ab	25.58 ± 1.53 a	7.13 ± 0.29 b
		N270	408.22 ± 30.20 a	89.71 ± 8.69 a	86.45 ± 1.86 b	25.48 ± 1.62 a	8.07 ± 0.36 a
		N360	423.33 ± 25.27 a	93.25 ± 9.57 a	83.26 ± 1.77 c	24.33 ± 1.21 a	8.00 ± 0.38 a
	AR	N0	250.37 ± 20.08 d	63.99 ± 4.69 c	90.67 ± 2.68 a	26.89 ± 0.85 a	3.91 ± 0.24 e
		N90	333.58 ± 32.15 c	77.67 ± 7.66 b	90.38 ± 2.79 a	26.16 ± 0.93 a	6.13 ± 0.29 d
		N180	380.18 ± 33.59 b	87.99 ± 5.08 ab	89.76 ± 2.93 ab	25.68 ± 1.26 ab	7.71 ± 0.35 c
		N270	436.77 ± 26.42 a	92.24 ± 6.77 a	87.17 ± 1.55 b	25.18 ± 1.33 ab	8.84 ± 0.39 a
		N360	437.52 ± 30.59 a	91.53 ± 8.24 a	84.98 ± 1.72 c	24.79 ± 1.25 b	8.44 ± 0.42 b
ANOVA		Y	ns	ns	ns	ns	*
		N	**	**	*	ns	**
		T	*	ns	ns	ns	*
		N × T	*	ns	ns	ns	*
		Y × T	ns	ns	ns	ns	ns
		N × Y	ns	ns	ns	ns	ns
	N × T × Y		ns	ns	ns	ns	ns

Note: The data represent the mean ± standard error. Different lowercase letters in the column under the same straw treatment in the same year indicate significant differences between treatments ($p < 0.05$). SR: straw returned to the field in spring; AR: straw returned to the field in autumn; N0: nitrogen application of 0 kg $^{-2}$; N90: nitrogen application of 90 kg ha^{-1}; N180: nitrogen application of 180 kg ha^{-1}; N270: nitrogen application of 270 kg ha^{-1}; N360: nitrogen application of 360 kg ha^{-1}; Y: year; N: nitrogen fertilizer; T: straw returning period; *, ** mean $p < 0.05$, $p < 0.01$; ns means non-significant.

3.4. Nitrogen Fertilizer Utilization

The total nitrogen uptake and nitrogen use efficiency of rice were significantly or extremely significantly affected by nitrogen fertilizer (N), straw returning period (T), and their interaction ($p < 0.05$, $p < 0.01$) (Table 8). No matter when the straw was returned to the field, the total nitrogen absorption and apparent nitrogen use efficiency of rice gradually increased with the increase in nitrogen fertilizer application. Compared with N0, the total nitrogen accumulation of N90, N180, N270 and N360 increased by 47.7%, 113.9%, 191.6% and 240.7%, respectively (two-year average). Compared with the spring straw returning treatment, the total nitrogen accumulation of the autumn straw returning treatment increased significantly by 9.6% and 6.1% from 2020 to 2021, respectively. Although the application of nitrogen fertilizer significantly improved the apparent nitrogen use efficiency of rice, there was no significant difference in the apparent nitrogen use efficiency of rice among the n180, N270 and N360 treatments using the same straw returning period. Compared with spring straw returning treatment, the apparent nitrogen use efficiency of the autumn straw returning treatment increased by 10.3% (2020) and 12.2% (2021), respectively.

Whether straw was returned in spring or autumn, the agronomic efficiency and partial productivity of nitrogen fertilizer decreased with the increase in the nitrogen application rate. With the same nitrogen application rate, straw returning significantly improved the agronomic efficiency of nitrogen fertilizer and the partial productivity of nitrogen fertilizer. Compared with the spring straw returning treatment, the autumn straw returning treatment increased the agronomic efficiency of nitrogen fertilizer and the partial productivity of nitrogen fertilizer by 8.1% and 6.0%, respectively (two-year average). Compared with N90, the agronomic efficiency of nitrogen fertilizer in the N180, N270 and N360 treatments decreased significantly by 10.6%, 24.7% and 53.3% (two-year average), respectively. The partial productivity of nitrogen fertilizer in N180, N270 and N360 treatments decreased significantly by 36.9%, 52.5% and 67.8% (two-year average), respectively. To summarize, the total nitrogen accumulation and nitrogen use efficiency of the soda saline–alkaline rice field were higher when straw was returned to the field in autumn combined with nitrogen fertilizer, but under the condition of straw returning to the field in autumn, considering the yield and nitrogen use efficiency, the best nitrogen application rate was 270 kg ha^{-1}.

Regression analysis showed that there was a close quadratic relationship between rice yield and nitrogen application rate ($p < 0.01$) (Figure 4). To achieve the maximum theoretical rice yield (i.e., the maximum value of the two curves), the nitrogen fertilizer application rate in the SR treatment was 297.90 kg ha^{-1} (2020) and 284 kg ha^{-1} (2021), while the corresponding values of AR treatment were 281 kg ha^{-1} (2020) and 265.8 kg ha^{-1} (2021). Under the same straw returning period, the theoretical optimal nitrogen fertilizer application rate in 2021 was lower than that in 2020. This shows to a certain extent that the optimal nitrogen fertilizer application rate of continuous straw returning in soda saline–alkaline rice area tends to gradually decrease with the increase in years. The reduced amount of nitrogen fertilizer (N-reduced) is the difference between the amount of nitrogen fertilizer required to reach the maximum theoretical rice yield in the spring straw returning treatment and the corresponding amount of nitrogen fertilizer in the autumn straw returning treatment. According to the regression results, the corresponding N-reduced amounts from 2020 to 2021 were 93.73 (297.90–204.17) kg ha^{-1} and 109.28 (284–174.12) kg ha^{-1}, respectively. Concerning the figures in brackets, the former represent the amount of nitrogen fertilizer required for the theoretical maximum rice yield when returning straw in spring, and the latter represent the amount of nitrogen fertilizer required for the straw returning in autumn treatment to reach the "theoretical maximum of rice yield when returning straw in spring". Therefore, from 2020 to 2021, compared with spring straw returning, autumn straw returning was able to reduce the amount of nitrogen fertilizer application by 31.5% and 38.5% respectively, without reducing the rice yield in the saline–sodic paddy field.

Table 8. Effect of straw return period and combined application of nitrogen fertilizer on nitrogen fertilizer utilization in rice.

Treatment			TPN kg ha^{-1}	REN %	AEN kg kg^{-1}	PFP kg kg^{-1}
2020	SR	N0	30.28 ± 2.38 e	—	—	—
		N90	44.69 ± 2.08 d	16.01 ± 1.72 b	19.33 ± 1.66 a	60.41 ± 1.77 a
		N180	63.97 ± 1.75 c	18.72 ± 0.54 a	16.33 ± 0.26 b	36.87 ± 0.78 b
		N270	82.31 ± 2.27 b	19.27 ± 1.32 a	14.80 ± 0.87 c	28.49 ± 0.49 c
		N360	99.55 ± 2.36 a	19.24 ± 0.83 a	9.27 ± 0.19 d	19.64 ± 0.44 d
	AR	N0	33.70 ± 1.65 e	—	—	—
		N90	51.34 ± 3.20 d	19.60 ± 1.69 b	20.30 ± 1.23 a	62.22 ± 1.11 a
		N180	70.17 ± 0.61 c	20.26 ± 1.25 ab	18.11 ± 1.79 b	39.07 ± 1.90 b
		N270	89.28 ± 2.31 b	20.59 ± 0.34 a	15.07 ± 0.62 b	29.62 ± 0.61 c
		N360	107.00 ± 1.52 a	20.36 ± 0.96 ab	9.32 ± 0.90 c	19.80 ± 0.86 d
2021	SR	N0	33.02 ± 4.52 e	—	—	—
		N90	48.83 ± 8.67 d	17.57 ± 1.25 c	18.97 ± 1.84 a	58.71 ± 1.29 a
		N180	75.18 ± 1.14 c	22.42 ± 2.79 b	18.47 ± 1.56 a	38.34 ± 1.06 b
		N270	107.85 ± 4.32 b	27.70 ± 3.23 a	15.81 ± 1.66 b	29.06 ± 0.20 c
		N360	125.39 ± 5.22 a	25.63 ± 1.47 a	9.81 ± 0.99 c	19.74 ± 0.93 d
	AR	N0	37.96 ± 2.14 e	—	—	—
		N90	54.41 ± 3.55 d	18.28 ± 1.22 c	23.52 ± 1.01 a	65.81 ± 1.97 a
		N180	79.29 ± 0.29 c	22.96 ± 2.67 b	20.49 ± 0.69 b	41.63 ± 0.53 b
		N270	114.10 ± 4.08 b	28.20 ± 2.67 a	16.17 ± 1.50 c	30.27 ± 1.36 c
		N360	128.04 ± 2.52 a	25.02 ± 1.36 a	9.85 ± 0.31 d	20.43 ± 0.54 d
ANOVA		Y	*	*	*	ns
		N	**	*	**	**
		T	*	*	*	*
		N × T	*	*	*	*
		Y × T	ns	ns	ns	ns
		N × Y	*	*	*	ns
		N × T × Y	ns	ns	ns	ns

Note: The data represent the mean ± standard error. Different lowercase letters in the column under the same straw treatment in the same year indicate significant differences between treatments ($p < 0.05$). SR: straw returned to the field in spring; AR: straw returned to the field in autumn; N0: nitrogen application of 0 kg ha^{-1}; N90: nitrogen application of 90 kg ha^{-1}; N180: nitrogen application of 180 kg ha^{-1}; N270: nitrogen application of 270 kg ha^{-1}; N360: nitrogen application of 360 kg ha^{-1}; Y: year; N: nitrogen fertilizer; T: straw returning period; *, ** mean $p < 0.05$, $p < 0.01$; ns means non-significant.

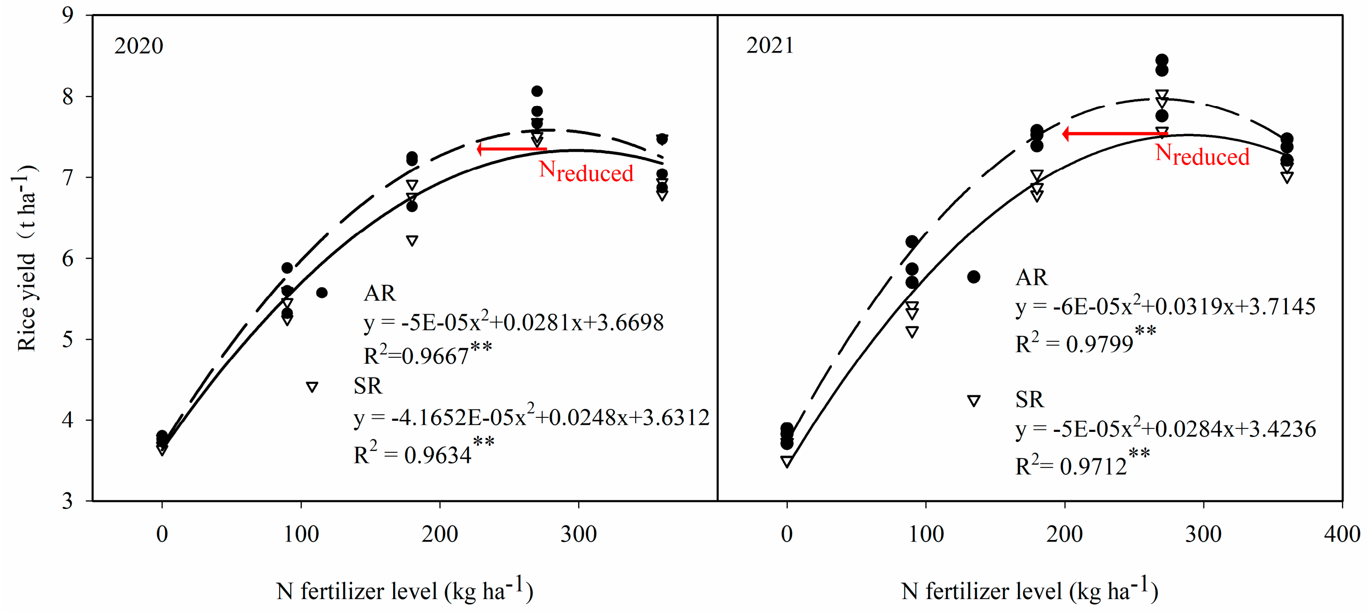

Figure 4. Relationship between nitrogen fertilizer and rice yield under different straw return periods. Note: SR: straw returned to the field in spring; AR: straw returned to the field in autumn; ** is signification correlation at $p < 0.01$.

4. Discussion

4.1. Effects of Combined Application of Straw Returning Period and Nitrogen Fertilizer on Root Characteristics in Saline–Sodic Paddy Field

In saline–sodic soil, crop growth inhibition is mainly affected by ion stress, osmotic stress, and high pH toxicity [24]. In response to salt stress, root growth regulates specific key features such as root length and branching, reorientation of root growth, and alteration of cell wall composition. Numerous studies have suggested that salinity stress significantly reduced plant root length, root volume, root surface area, and root dry weight, thus changing the root morphology [25,26], and root penetration obviously decreased in the seedling stage [27]. Under alkaline stress, it was observed that rice roots accumulated a large amount of Na^+, and the root cell membrane system was seriously damaged, resulting in a decrease in root activity. [28]. This seriously limits the absorption of nutrients and water by the root system, thus limiting the growth of above-ground plants and ultimately reducing the yield [29]. It is generally believed that moderate N application can increase root production, promote root penetration, improve N fertilizer utilization, and alleviate root growth inhibition induced by moderate soil salinity [30,31]. This is consistent with the data; N application was able to improve the root morphology and root growth, but there was no significant difference between the N270 and N360 treatments, indicating that beyond this range of N270, the effect of nitrogen fertilizer in alleviating saline stress and promoting root growth is inconspicuous (Tables 3–6). These changes may be attributed to the fact that moderate N application not only has a nutritive effect but also plays an important role in improving plant salt tolerance by increasing nutrient uptake and decreasing the accumulation of Na^+ in plant tissues [32]; it can also increase the accumulation of amino acids in plant tissues, which counteracts the increased osmotic potential of NaCl solution and protects membranes and metabolites by scavenging reactive oxygen species (ROS), which protects the cells from further damage [33].

Our previous research found that straw returning can have negative impacts on new germinating roots; on the contrary, in the later stage of rice growth, straw returning produces some positive impacts on rice roots, which enhances the yield of rice [34]. Methods of effectively alleviating the root growth inhibition caused by straw decay in the initial stages of rice growth are of great significance for straw returning in saline–sodic paddy areas. Therefore, this study compared straw returning in spring and autumn. This study found that compared with straw returning in spring, straw returning in autumn significantly improved the root morphology and physiological function of rice in saline–sodic paddy field (Tables 3–6). The effect of straw returning on rice root growth was better in autumn than in spring, which may be due to straw returned to the field in the autumn staying in the soil for 7 months longer than straw returned to the field in the spring. To prevent the return of salt in the paddy field, the paddy field is flooded for a long time in the rice growing season; thus, the aggregation of salts in saline–sodic rice field soils mainly occurs during the fallow period. Straw returning in autumn disturbs the continuity of soil capillary movement, hinders the upward movement of salt in groundwater or deep soil during the fallow period [35], improves the chemical properties of surface soil in sodic saline–sodic rice fields, and reduces the damage that saline–sodic stress causes to rice roots. In addition, the rapid decomposition of straw under flooding conditions led to a sharp decrease in soil oxygen content, releasing large amounts of reducing substances and harmful gases that worsen the growth conditions of rice roots [36,37]. Straw that is returned to the field in the autumn is partially decomposed during the fallow period; the amount of rice straw remaining in the soil at the rice growth stage the following year was lower than the amount of straw returned in spring. The damage to the root system was also less than that which occurred when straw was returned in spring. Kanal et al.'s research in Estonia also showed that the decomposition rate of wheat straw returned to the field in winter was significantly higher than that in spring, and 6–7% of the winter wheat straw returned to the field had decomposed from soil freezing (December) to thawing (April) in the second year [38].

Interestingly, this study found that the interaction between straw returning period and nitrogen fertilizer had a significant impact on the morphology and physiological function of rice roots from the tillering stage to the grain filling stage (Tables 3–6). This may be related to soil microorganisms, which take up and utilize large amounts of available nitrogen from the soil, compete with crops for nutrients, and are activated after straw returning [39,40]. The application of nitrogen fertilizer can effectively mitigate the phenomenon of "nitrogen competition" and reduce the inhibition caused by straw decomposition. At the same time, nitrogen application accelerates the straw decomposition process, allowing more nutrients enter the soil and promoting the growth of the rice root system [41,42]. In addition, the amount of nitrogen fertilizer application affects the rate of carbon and nitrogen exudation from the root system, limits microbial resources, and affects microbial carbon use efficiency [43]. Our study found that the amount of rice root bleeding sap increased significantly with increasing nitrogen application (Table 5), which made microbial diversity more complex, thus favoring soil N cycling and inorganic N accumulation [44]. This study also found that when using the same straw returning period, there was no significant difference between N360 and N270 treatments (Tables 3–6). This is probably because sufficient nitrogen fertilizer provides a sufficient nitrogen source for soil microorganisms, and nitrogen is no longer a factor limiting straw decomposition. In addition, the application of high amounts of nitrogen fertilizer significantly reduced the root–shoot ratio of rice [45]. A suitable root–shoot ratio favors the enhancement of rice yield. Therefore, it is necessary to find the optimum amount of nitrogen fertilizer to be applied when returning straw to the field in autumn in saline–sodic soil rice planting areas in order to obtain the maximum rice yield.

4.2. Effects of Straw Return Period and Nitrogen Fertilizer Application on Rice Yield and Nitrogen Use Efficiency in Saline–Sodic Paddy Fields

Many studies have shown that straw returning can improve the physical and chemical properties of saline–alkaline soil, root characteristics and photosynthetic characteristics, and rice yield in saline–sodic paddy fields [34,46,47]. However, there are few studies on rice yield in saline–alkaline paddy fields with different straw returning periods. This study found that compared with straw returning in spring, straw returning in autumn significantly increased rice yield and panicles per unit area (Figure 3, Table 7). The reason for this is that on the one hand, rice systems with autumn straw returning perform significantly better than those with spring straw returning (Tables 3–6), promote nutrient uptake, and increase yield. On the other hand, compared with straw returning in spring, autumn straw returning in alkaline soil in a saline–sodic paddy field undergoing a winter fallow period was equivalent to alkaline pretreatment and freezing–thawing treatment. The use of urea after alkaline pretreatment will accelerate the decomposition of straw [48]. Wang et al. suggested that the chemical bonds between lignin and carbohydrates in rice straw are further broken after winter freeze–thaw treatment, and organic nutrients are more quickly decomposed and released [49]. Furthermore, the rapid decomposition stage of straw overlaps with the tillering stage of rice, which can inhibit rice tillering, reduces the number of effective panicles of rice, and leads to yield loss [50]. The application of base fertilizer in spring soil preparation meets the above requirements, thus reducing the damage to rice in the tillering stage, which leads to a significantly higher number of ears per unit area when straw is returned in autumn rather than in spring [51,52]. This experiment also found that whenever the straw was returned to the field in spring or autumn, when the nitrogen fertilizer exceeded 270 kg ha^{-1}, the rice yield declined (Figure 3). This may be due to the fact that excessive application of nitrogen delayed the vegetative stage, reduced the efficiency of nitrogen fertilizer use and eventually led to lower rice yields [23]. The fact that rice yield first increases and then decreases with the increase in nitrogen fertilizer application also emphasizes the importance of scientific fertilizer application when returning straw (Figure 2).

Compared with straw returning in spring, straw returning in autumn significantly improved the total nitrogen content, apparent nitrogen use efficiency, agronomic nitrogen use efficiency and partial nitrogen productivity of rice plants (Table 8). This may be due to the improvement in soil physical and chemical properties [53,54], root morphology (Tables 3 and 4), and root physiological function (Tables 5 and 6) in the saline–sodic paddy field when returning straw in autumn compared to returning straw in spring; this promoted the absorption of nitrogen by roots and then improved the nitrogen use efficiency. This study also found that when using the same straw returning period, with the increase in the nitrogen application rate, the apparent utilization of nitrogen fertilizer increased first and then decreased and reached a maximum of 270 kg ha^{-1}. The agronomic efficiency and partial productivity of nitrogen fertilizer gradually decreased with the increase in the nitrogen fertilizer application rate (Table 8). This also emphasizes the importance of rational application of nitrogen fertilizer when returning straw. Compared with straw returning in spring, straw returning in autumn reduced the mineral nitrogen input by 31.5% (2020) and 38.5% (2021), which had no adverse effect on rice yield (Figure 3). Wang et al. also observed similar results in the study of other crops and found that continuous straw returning can increase the total yield of cotton while saving about 40% of nitrogen input [55]. In addition, according to Figure 4, when using the same straw returning period, the theoretical optimal nitrogen fertilizer application rate in 2021 was lower than that in 2020. This shows that the optimal nitrogen fertilizer application rate may tend to gradually decrease with the increase in years when there is continuous straw returning in saline–sodic rice areas. In addition, the theoretical optimal nitrogen fertilizer for straw returning in autumn was 281 kg ha^{-1} (2020) and 265.8 kg ha^{-1} (2021), and the theoretical optimal nitrogen fertilizer for straw returning in spring was 297.9 kg ha^{-1} (2020) and 284 kg ha^{-1} (2021); the rice yield of straw returning in autumn was higher than that of straw returning in spring (Figure 3). This shows that when returning straw to sodic saline–alkaline rice areas, the effect of straw returning in autumn is better, and less nitrogen fertilizer is required. However, as straw returning years increase, the optimal nitrogen application rate will require further study.

5. Conclusions

In the early stage of straw returning in saline–sodic rice area, the effect of straw returning in autumn was better than that in spring, and the effect of 270 kg ha^{-1} of nitrogen fertilizer combined with autumn straw returning in the rice growing season was better. Autumn straw returning combined with 270 kg ha^{-1} of nitrogen fertilizer significantly improved rice root morphology, root activity, nutrient uptake by rice roots, nitrogen use efficiency, and rice yield. The increase in effective panicles per unit area was the main factor of the increase in rice yield. The average yield of rice was 8.01 t ha^{-1} within two years when straw was returned to the field and 270 kg ha^{-1} of nitrogen fertilizer was applied in autumn. Compared with straw returning in spring, straw returning in autumn can reduce the amount of nitrogen fertilizer application by 31.5% (2020) and 38.5% (2021) without reducing rice yield. Moreover, the theoretical optimal nitrogen application rates of straw returned in autumn were 281 kg ha^{-1} (2020) and 265.8 kg ha^{-1} (2021), respectively. Therefore, for the sustainable development of saline–sodic rice planting areas, it is suggested that autumn straw returning measures are adopted after rice harvest and that 270 kg ha^{-1} of nitrogen fertilizer is applied in the following year. However, as the field experiment was only carried out for two years, a long-term study of straw return in autumn and the application of nitrogen fertilizer is needed to determine the optimum amount of nitrogen fertilizer that should be applied during the different stages of straw return.

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