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Impacts of Returning Straw and Nitrogen Application on the Nitrification and Mineralization of Nitrogen in Saline Soil

Chunyan Yin [1,2], Lijun Li [1,*], Ju Zhao [2,*], Jingsong Yang [3,*] and Haogeng Zhao [1,2]

1 Agricultural College, Inner Mongolia Agricultural University, Hohhot 010020, China
2 Inner Mongolia Academy of Agricultural & Animal Husbandry Sciences, Hohhot 010030, China
3 Institute of Soil Science, Chinese Academy of Sciences, Nanjing 210018, China
* Correspondence: imaullj@163.com (L.L.); zjuren@163.com (J.Z.); jsyang@issas.ac.cn (J.Y.); Tel.: +86-158-4815-4170 (L.L.); +86-132-0471-1182 (J.Z.); +86-136-0516-0961 (J.Y.)

Abstract: In order to discuss the problems of the transformation of soil nitrogen and nitrogen leaching in saline farmland, this study carried out a split-plot experiment with returning straw and various nitrogen application rates. The main treatment of the experiment was returning corn straw, at quantities of 0.64 g (C1) and 0 g (C0), and the secondary treatment was nitrogen fertilizer (urea) at the quantities of 0 g (N0), 0.015 g (N1) and 0.03 g (N2). The results showed that, firstly, with the extension of the incubation time, the nitrogen nitrification rate of saline soil in each treatment decreased gradually until it stabilized without straw. For Days 0–7 of incubation, the nitrogen mineralization rate of saline soil decreased rapidly, and the mineralization rates of C0N0, C0N1 and C0N2 decreased by 86.91%, 89.26% and 83.64%, respectively. The nitrification rate of nitrogen in saline soil was C0N0 > C0N1 > C0N2, which decreased by 68.01%, 67.42% and 60.52%, respectively. Secondly, under the condition of returning straw to the field, the nitrogen mineralization rate of saline soil in each treatment decreased gradually and became stable with the extension of the incubation time. The nitrogen mineralization rate of saline soil in each nitrogen application treatment was C1N2 > C1N1 > C1N0 within 0–3 days of incubation, which decreased by 87.46%, 87.20% and 81.83%, respectively. The nitrification rate of saline soil under different nitrogen treatments was C1N2 > C1N0 > C1N1, and the nitrification rates of C1N0, C1N1 and C1N2 decreased by 66.62%, 62.54% and 47.21%, respectively. Thirdly, during the incubation period, returning straw slowed down nitrogen mineralization and nitrification in saline soil under the reduced nitrogen and no-nitrogen fertilizer treatments, but it enhanced nitrogen mineralization and nitrification in saline soil under the high nitrogen treatment. In conclusion, returning straw and reducing the application of nitrogen fertilizer to saline soil can retain more ammonium nitrogen, thus inhibiting nitrification of the soil nitrogen, reducing the environmental pollution risk of nitrate leaching and reducing nitrogen losses, all of which are of great significance for environmental pollution.

Keywords: straw return; nitrogen application; fracture zone test; mineralization rate; nitrification

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1. Introduction

Soil nitrogen is an important material base for soil fertility, and its transport and transformation in the soil directly affect the utilization and loss of nitrogen [1]. Bioorganic matter such as straw and biochar will affect the nitrogen cycle of soil. Returning straw can improve the soil's physical and chemical properties, reduce the soil's bulk density, increase the soil organic matter content, improve the number of microorganisms and enzyme activity related to the soil nitrogen cycle and accelerate the decomposition of organic matter, thereby improving the mineralization rate of soil organic nitrogen and the level of soil nitrogen [2]. The combined application of nitrogen with straw and biomass carbon can improve the amount of nitrogen mineralized by the surface soil, the nitrogen mineralization rate of the upper soil [3] and the content of microbial biomass carbon [4,5], thereby increasing the assimilation of soil nitrogen. At the same time, the simultaneous use of straw and biomass carbon will also increase the loss of nitrogen through denitrification, and with an increase in the amount of straw added, the effect will be more obvious [6]. From the perspective of adding straw alone, returning straw to the field not only promotes the transformation and supply of nitrogen for crops, but it also improves the release and absorption of nitrogen [7]. Moreover, returning straw increases the total nitrogen content and nitrogen retention rate of the soil [8], changes the amount and activity of soil microorganisms [9] and, thus, affects soil nitrification. The nitrogen cycle of soil can also be affected by the amount of nitrogen applied. Some studies have shown that the application of nitrogen fertilizer significantly improves the mineralization and nitrification of nitrogen in the chernozem [10], and an increase in nitrogen fertilizer can also improve the mineralization rate of soil nitrogen [11]. Reducing nitrogen can slow down the potential of soil nitrification, prevent and control nitrate nitrogen leaching to deeper soils and reduce nitrogen losses [12].

The mineralization of soil nitrogen is also related to the soil's texture. Applying nitrogen to black soil can significantly inhibit nitrogen mineralization of farmland soil. The mineralization rate of soil net nitrogen decreases significantly with an increase in the application of nitrogen, whereas the net nitrification rate increases significantly with an increase in nitrogen [13], which will eventually encourage the nitrate nitrogen to move downward along the soil profile, increasing nitrogen losses [14]. Salinity in the soil has different effects on nitrogen's mineralization and nitrification. Some studies have shown that the amount of net nitrogen mineralized in coastal saline soil with 184 mg/kg nitrogen fertilizer was significantly lower than that under the 92 mg/kg nitrogen fertilizer treatment ($p < 0.05$). This phenomenon shows that excessive addition of nitrogen does not have a positive effect on the nitrogen supply capacity of the soil [15]. Different nitrogen application rates have different effects on the soil's mineralization and nitrification, whereas different soil types have different responses to nitrogen application rates.

Organic improvement materials have a significant effect on improving soil fertility and productivity. Straw has been used in soil to help minimize pollutants and to enrich the soil, and this approach is being encouraged in many countries. The incorporation of straw into the soil has a significant effect on soil and the atmosphere, for example, by increasing the content of soil organic carbon, improving the soil's structure and adjusting the pH of the soil [16]. Straw is composed of different organic contents, which are not easily transformed into the soil via microbial decomposition compared with other organic matter and humic and fulvic acids [17,18]. The incorporation of straw increases the soil nutrients via carbon cycling through microbial activities [19]. Similarly, the application of enriched compost has also been found to be an attractive option to increase the availability of various nutrients such as nitrogen, phosphorus and potassium [20–23].

To sum up, the transformation of nitrogen in the soil is affected by factors such as soil water, heat, salt environment, organic matter, nitrogen application and microorganisms. At present, the research on the transformation of nitrogen has generally been carried out from the perspective of returning straw and the application of nitrogen alone, and most of these studies have been aimed at non-saline soil. This present study assumed that returning straw to the field can slow down the mineralization and nitrification of nitrogen in saline soil and that excessive nitrogen application can enhance the mineralization and nitrification of nitrogen in saline soil. Through an experiment on the effect of returning straw and applying nitrogen on the mineralization and nitrification of nitrogen in saline soil, this study aimed to verify that returning straw slows down the mineralization and nitrification of nitrogen in saline soil under conditions of reduced nitrogen. The results of this study are of great significance for reducing the risk of environmental pollution caused by nitrate leaching in saline–alkaline farmland and reducing the loss of nitrogen to environmental pollution.

2. Materials and Methods

2.1. Overview of the Research Area

The saline soil samples were collected from Sandaoqiao Town, Hangjinhou Banner, Bayannur City, which belongs to the arid zone in the west of the Hetao Irrigation District, Inner Mongolia. The study area has a temperate continental monsoon climate, with an average annual temperature of 7.9 °C; annual average precipitation and evaporation of 136.5 mm and 1953.9 mm, respectively; an average wind speed of 2.2 m/s; 3200 h of sunshine and a frost-free period of 152 days.

2.2. Experimental Materials

The test soil was taken from the surface 0–20 cm soil from Chengni Village (40°49′34.463″ N, 106°54′29.463″ E), Sandaoqiao Town, Hangjinhou Banner, with a salt content of 0.4% (moderately saline soil). After collection, the saline–alkaline soil was first dried, then ground and passed through a 2 mm sieve for test using. The test straw was corn straw, in which the total carbon and total nitrogen contents were 444.69 g/kg and 6.19 g/kg, respectively, and the C/N ratio was 71.8. The physical and chemical properties of the saline soil are shown in Table 1.

Table 1. Physical and chemical properties of the saline soil.

Bulk Density/ kg/cm^3	pH	Conductivity/ dS/m	Ammonium Nitrogen/ mg/kg	Nitrate Nitrogen/ mg/kg	Inorganic Nitrogen/ mg/kg
1.45	8.0	2.40	13.79	18.88	32.67

2.3. Experimental Design

In this study, a method of culture with indoor ventilation and a constant temperature was adopted. A split-plot test design with the return of straw and different nitrogen application rates was adopted. The main treatment was returning corn straw, with straw application rates of 0 g (C0) and 0.64 g (C1), and the secondary treatment was nitrogen (urea) application, applying amounts of 0 g (N0), 0.015 g (N1) and 0.03 g (N2) urea, respectively. There were 6 treatments in total, including C0N0, C0N1, C0N2, C1N0, C1N1 and C1N2, as shown in Table 2. Three replicates were set for each treatment, and the average value of the three replicates was used for the experimental results.

Table 2. Design of the nitrogen transformation experiment on returning straw and applying nitrogen.

Treatment	C0N0	C0N1	C0N2	C1N0	C1N1	C1N2
Weight of saline soil/g	200	200	200	200	200	200
Weight of straw/g	0	0	0	0.64	0.64	0.64
Weight of urea/g	0	0.015	0.03	0	0.015	0.03

Each repeated treatment was tested in 250 mL plastic bottles (more than 300 g of soil could be placed into these bottles). The mouth of each bottle was tightly sealed with plastic wrap and a rubber band, and several small holes were made on the surface of the plastic wrap. Then, the bottles were placed in an incubator at 25 °C for culture. The saturated water content of the saline–alkaline soil used in the test was 36.4%, and the field water capacity was 30.0%. In order to simulate the soil water conditions after the irrigation of farmland, the test soil samples were replenished with water every day to keep the soil water content at 30% during the indoor cultivation process. The incubation test lasted for 35 days, and soil samples were collected on Days 1, 3, 7, 15, 25 and 35 of the test. The nitrate and ammonium nitrogen contents of the samples were measured.

2.4. Test Index and Method

The soil EC and pH were determined by the potentiometric method. The content of ammonium nitrogen (NH_4^+-N) in the soil was determined by 2 mol/L KCl extraction indophenol blue colorimetry. The content of soil nitrate nitrogen (NO_3^--N) was determined by dual wavelength ultraviolet spectrophotometry. Soil organic matter was determined by the potassium dichromate volumetric external heating method. The content of total nitrogen in soil was determined by the semi-micro-Kjeldahl method. The available phosphorus in the soil was determined by the 0.5 mol/L $NaHCO_3$ method. The formula used for calculating each index in this study was as follows:

$$N_x = \frac{[(NO_3^- \text{-} N)_t - (NO_3^- \text{-} N)_{t_0}]}{t - t_0} \tag{1}$$

where N_x is the net nitrification rate in mg $NO_3{}^-$-N·kg^{-1}·d^{-1}; $(NO_3{}^-$-$N)_t$ and $(NO_3{}^-$-$N)_{t0}$ are the $NO_3{}^-$-N content at t d and 0 d of culturing, respectively, in mg $NO_3{}^-$-N·kg^{-1}; and t is the day of culture the test, where t_0 indicates 0 d.

The soil net nitrogen mineralization rate N_m was calculated according to Equation (2):

$$N_m = \frac{[(NH_4^+ \text{-} N)_t + (NO_3^- \text{-} N)_t] - [(NH_4^+ \text{-} N)_{t0} + (NO_3^- \text{-} N)_{t_0}]}{t - t_0} \tag{2}$$

where N_m is the soil net nitrogen mineralization rate, in mg $(NH_4{}^+$-$N)$ + $(NO_3{}^-$-$N)$·kg^{-1}·d^{-1}; and $[(NH_4{}^+$-$N)_t$ + $(NO_3{}^-$-$N)_t]$ and $[(NH_4{}^+$-$N)_{t0}$ + $(NO_3{}^-$-$N)_{t0}]$ are the content of $NH_4{}^+$-N + $NO_3{}^-$-N at t d and 0 d of the culture, respectively, in mg $NH_4{}^+$-N + $NO_3{}^-$-N·kg^{-1}.

2.5. Data Analysis

Excel 2007 and SigmaPlot V12.5 were used to calculate the test data and plot the chart. SPSS 19.0 software was used for the statistical analysis, and Duncan's method was used for multiple comparisons.

3. Results

3.1. Effects of Different Treatments on the Mineralization Rate of Soil Nitrogen

The dynamic changes in the relationship between the mineralization rate of soil nitrogen and the incubation time were similar under the different treatments in saline soil (Figure 1). Under the conditions of not returning the straw, the nitrogen mineralization rate of the saline soil in each treatment gradually decreased to a stable level with the extension of the incubation time. The mineralization rate of soil nitrogen in each treatment was C0N2 > C0N1 > C0N0. For Days 0–7, the mineralization rate of nitrogen in the saline soil decreased rapidly, and the mineralization rate of C0N1 decreased the fastest. The mineralization rates of C0N0, C0N1 and C0N2 decreased by 86.91%, 89.26% and 83.64%, respectively.

Under the conditions of returning straw to the field, the nitrogen mineralization rate of the saline soil in each treatment decreased gradually and became stable with the extension of the incubation time. The nitrogen mineralization rate of the saline soil in each treatment was C1N2 > C1N1 > C1N0. Within Days 0–7, the mineralization rate decreased rapidly, and the mineralization rates of C1N0, C1N1 and C1N2 decreased by 87.46%, 87.20% and 81.83%, respectively. The reductions in the rates of C1N1 and C1N2 were very similar. In the process of cultivation, returning straw inhibited the mineralization of nitrogen in saline soil under the reduced nitrogen and no-nitrogen fertilizer treatments and promoted nitrogen mineralization in the saline soil under the high-nitrogen treatment.

During the whole incubation time, there were significant differences in the nitrogen mineralization rates of saline soil among the different nitrogen application treatments (Table 3). The nitrogen mineralization rate of saline soil under the different straw treatments was significantly different from 0 to 3 days of incubation, and there was no significant difference throughout the rest of the time. The nitrogen application rate had no significant difference in the effects on the nitrogen mineralization rate of saline soil when the incubation time was 0–1 days and 3–15 days. The interaction of returning straw and nitrogen application (C × N) had a significant effect on the nitrogen mineralization rate of the saline soil when the incubation time was 1–3 days and 15 days.

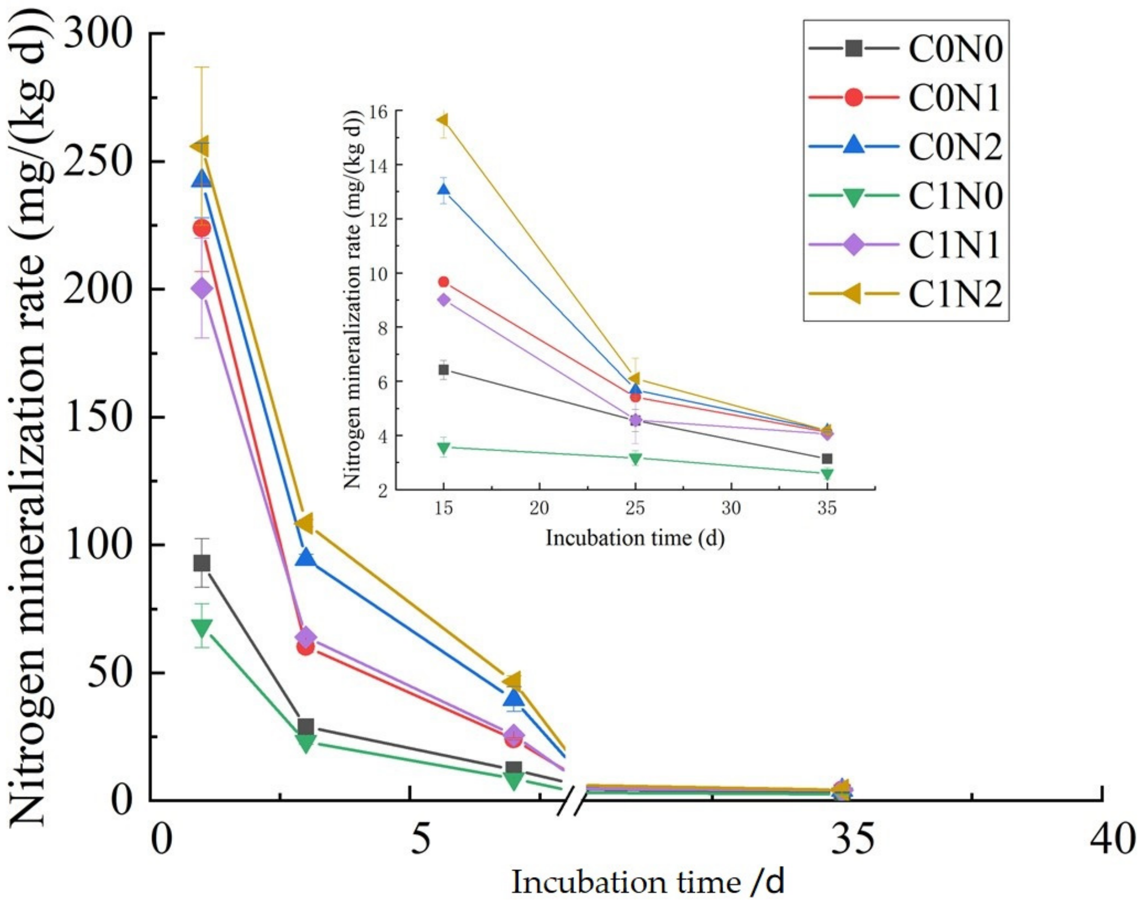

Figure 1. Dynamic changes in the nitrogen mineralization rate in saline soil during cultivation.

Table 3. ANOVA of the nitrogen mineralization rate of saline soil with the return of straw and the application of nitrogen.

Treatment	1 d		3 d		7 d		15 d		25 d		35 d	
	F	*p*	F	*p*	F	*p*	F	*p*	F	*p*	F	*p*
C	0.539	0.477	23.556	<0.001	2.148	0.168	2.391	0.148	6.289	0.028	11.336	0.006
N	41.966	<0.001	2814.437	<0.001	297.619	<0.001	787.073	<0.001	23.614	<0.001	205.053	<0.001
C × N	0.631	0.549	48.142	<0.001	7.539	0.008	67.871	<0.001	4.768	0.03	8.572	0.005

3.2. Effect of Different Treatments on the Nitrification Rate of Soil Nitrogen

The dynamic changes in the relationship between the nitrogen nitrification rate and the incubation time of each treatment in saline soil were similar (Figure 2). When no straw was returned to the field, the nitrogen nitrification rate of each nitrogen treatment in saline–alkaline soil decreased gradually throughout the incubation period until it became stable. At the beginning of incubation, the nitrogen nitrification rate of each treatment in saline soil was C0N0 > C0N1 > C0N2. At the early stage of the experiment, the application of nitrogen inhibited nitrification, and the intensity of this inhibition was different among different nitrogen application rates. The nitrification rate decreased rapidly in 0–3 days, and the nitrification rate of C0N0 decreased the fastest. The nitrification rates of C0N0, C0N1 and C0N2 decreased by 68.01%, 67.42% and 60.52%, respectively. However, after 3 days of indoor incubation, the nitrogen nitrification rate of the saline soil in each treatment was C0N0 < C0N1 < C0N2, which indicated that the nitrogen application rate gradually promoted nitrification.

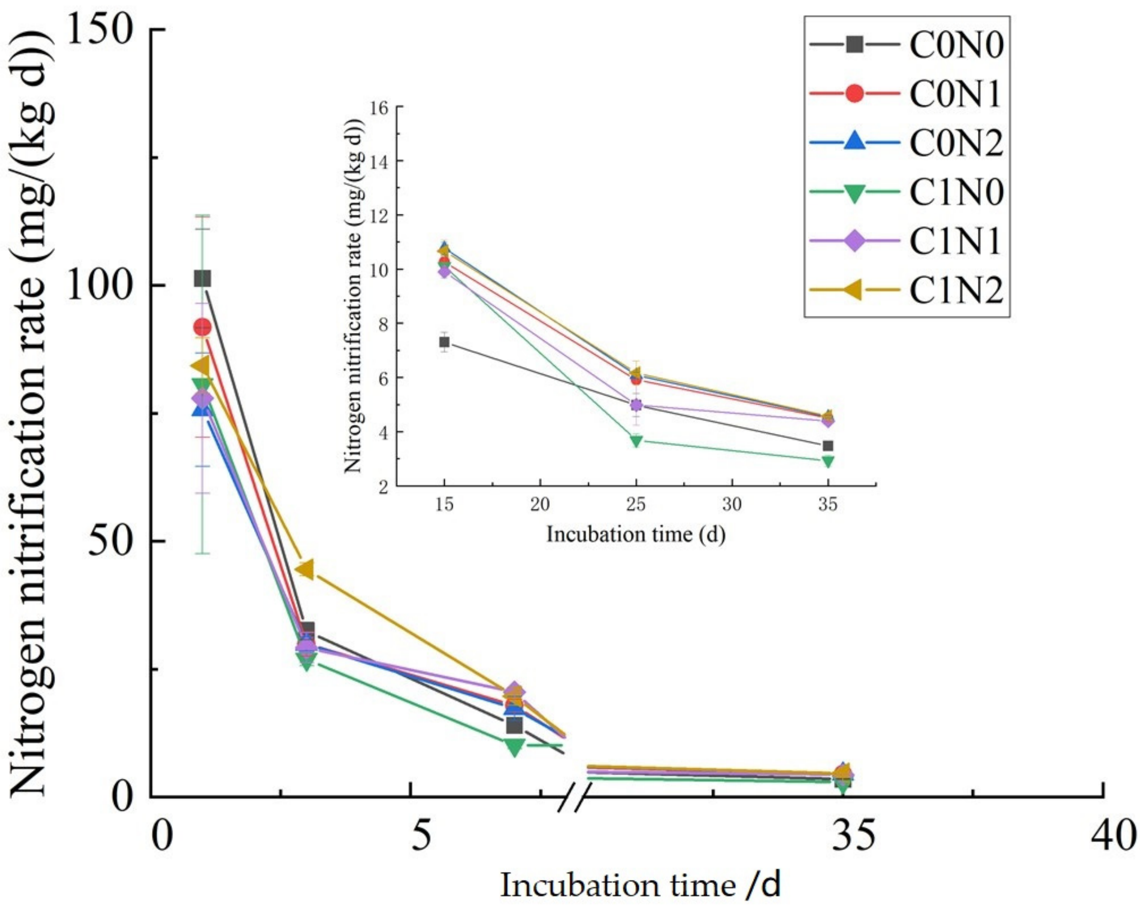

Figure 2. Dynamic changes in the nitrification rate of nitrogen in saline soil during incubation.

Under the conditions of returning straw to the field, the nitrogen mineralization rate of saline soil treated with nitrogen fertilizer decreased gradually until it stabilized during the incubation test. At the initial stage (0–3 d), the nitrification rate decreased rapidly. The nitrification rate of each nitrogen application treatment was C1N2 > C1N0 > C1N1. The nitrification rates of C1N0, C1N1 and C1N2 decreased by 66.62%, 62.54% and 47.21%, respectively, and the nitrification rate of C1N2 decreased the slowest. Therefore, compared with no nitrogen, the application of nitrogen (C1N2) will promote nitrification, whereas applying a small amount of nitrogen (C1N1) will inhibit nitrification. After 3 days of incubation, the nitrification rate of nitrogen in the saline soil under each treatment was C1N0 < C1N1 < C1N2, and the effect of the nitrogen application on the nitrification rate changed from the initial stage (0–3 d) and then reduced the nitrification rate. Returning straw slowed down the nitrification of nitrogen in saline soil under the reduced nitrogen and no-nitrogen fertilizer treatments, whereas the high-nitrogen treatment promoted the nitrification of nitrogen in saline soil.

After incubation for 0–7 days, there was no significant difference in the nitrification rate of soil nitrogen under different nitrogen application rates (as shown in Table 4), but after 7 days, there were significant differences in the nitrification rate of soil nitrogen under different nitrogen application rates. There was no significant difference in the nitrification rate between the treatments returning straw and not returning straw for 0–15 days. After 15 days, there was a significant difference in the nitrification rate of soil nitrogen between returning straw and not returning straw. The interaction between returning straw and the nitrogen application rate had a significant effect on the nitrification rate of nitrogen in the saline soil after 3 days of incubation.

Table 4. ANOVA of the effects of returning straw and the nitrogen application rate on the nitrification rate of nitrogen in saline–alkaline soil.

Treatment	1 d		3 d		7 d		15 d		25 d		35 d	
	F	*p*	F	*p*	F	*p*	F	*p*	F	*p*	F	*p*
C	0.515	0.487	9.485	0.01	0.331	0.575	2.391	0.148	13.818	0.003	15.675	0.002
N	0.274	0.764	31.38	<0.001	47.449	<0.001	787.073	<0.001	29.312	<0.001	265.892	<0.001
C × N	0.534	0.600	45.075	<0.001	10.598	0.002	67.871	<0.001	4.576	0.033	10.2	0.003

3.3. Effects of Different Treatments on the Soil Nitrogen Content

It can be seen from Figure 3 that the soil nitrate nitrogen content of each nitrogen application treatment increased slowly with the extension of the incubation time without straw and reached the peak value on Day 15 of incubation. The nitrate nitrogen content of saline soil under the C0N0, C0N1 and C0N2 treatments increased from 18.88 mg/kg on Day 0 to 140.44 mg/kg, 176.50 mg/kg and 178.08 mg/kg on Day 35 of incubation, respectively. The nitrate nitrogen content of the saline soil under each nitrogen application treatment was significantly higher than that under the no-nitrogen application treatment. From 0 to 3 days of incubation, the order of nitrate nitrogen content in the straw-free saline soil with the addition of nitrogen was C0N0 > C0N1 > C0N2. Seven days later, the order of nitrate nitrogen content in the straw-free saline soil with the addition of nitrogen at the same sampling time point was C0N0 < C0N1 < C0N2.

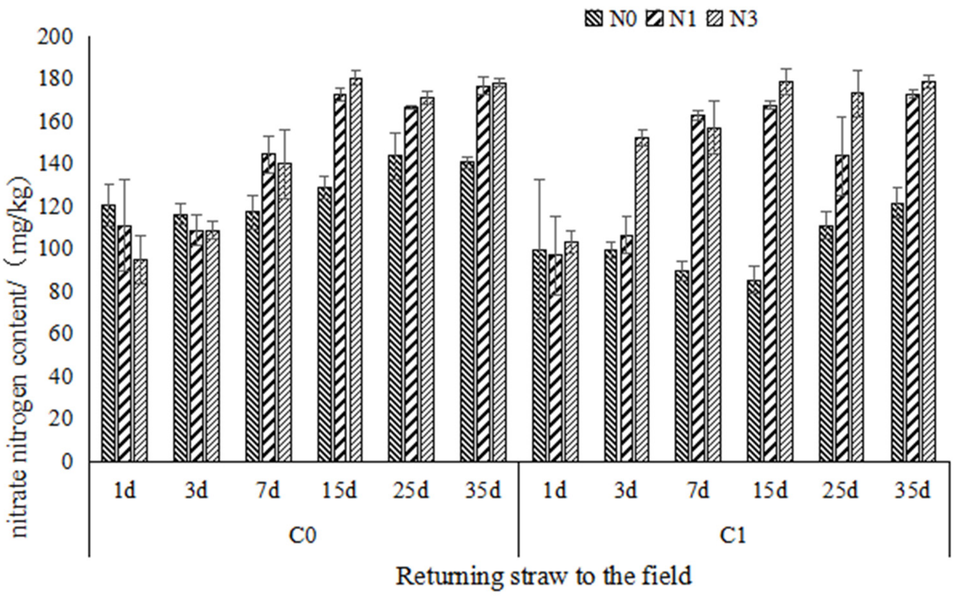

Figure 3. Dynamic changes in the nitrate nitrogen content of saline soil during cultivation.

Under the conditions of returning straw to the field, the soil nitrate nitrogen content of each nitrogen application treatment increased slowly with the extension of the incubation time and reached the peak value on Day 15 of incubation. The order of the nitrate nitrogen content of saline soil with the application of nitrogen and returning straw was C1N0 < C1N1 < C1N2 (except on the seventh day of cultivation). For Days 0–3 of the culture experiment, returning straw significantly reduced the nitrate nitrogen content.

According to the analysis of variance in Table 5, after 7 days of incubation, the amount of nitrogen applied had a very significant impact on the content of nitrate nitrogen in the saline soil under the addition of straw. In the incubation period from Days 15–25, returning straw had a significant effect on the nitrate nitrogen content in saline soil. After 3 days of incubation, the interaction of returning straw and the nitrogen application rate had a significant impact on the nitrate nitrogen content in the saline soil.

Table 5. ANOVA of the effect of returning straw and the nitrogen application rate on the nitrate nitrogen content in saline soil.

Treatment	1 d		3 d		7 d		15 d		25 d		35 d	
	F	*p*	F	*p*	F	*p*	F	*p*	F	*p*	F	*p*
C	0.515	0.487	1.747	0.211	0.327	0.578	57.910	<0.001	30.06	<0.001	8.368	0.014
N	0.275	0.764	5.771	0.018	47.474	<0.001	430.798	<0.001	64.309	<0.001	141.435	<0.001
C × N	0.533	0.600	8.288	0.005	10.612	0.002	36.764	<0.001	10.041	0.003	5.366	0.022

The dynamic changes in the ammonium nitrogen content of the saline soil are shown in Figure 4. When no straw was returned to the field, the content of ammonium nitrogen in the saline soil under the C0N0 treatment decreased slowly with an increase in the culture time, from 13.79 mg kg^{-1} on Day 0 of the culture to 2.23 mg kg^{-1} on Day 35. The ammonium nitrogen content of each nitrogen application treatment in the saline soil was significantly higher than that of the C0N0 treatment without the application of nitrogen. The content of ammonium nitrogen in the C0N1 soil decreased significantly with the incubation time, whereas the content of ammonium nitrogen under the C0N2 treatment increased first and then decreased. The order of ammonium nitrogen content in the nitrogen application treatments was C0N0 < C0N1 < C0N2. After culture, the content of ammonium nitrogen in the soil of each nitrogen application treatment was 2.23, 0.46 and 1.48 mg kg^{-1}, respectively, and there was no significant difference among the three treatments.

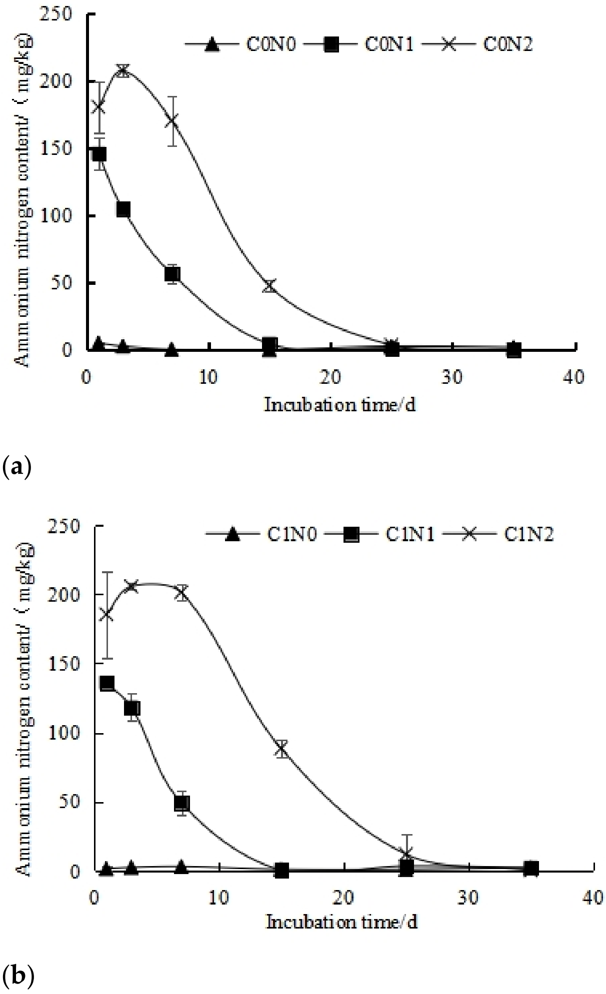

Figure 4. Changes in the ammonium nitrogen content in saline soil during cultivation. (**a**) Without straw returning. (**b**) Straw returning.

When straw was returned to the field, the content of ammonium nitrogen in the saline soil under the C1N0 treatment without the application of nitrogen was 13.79 mg/kg on Day 0 of the incubation, which continued to decrease with the incubation time until it reached 2.20 mg/kg on Day 35. The content of ammonium nitrogen in the saline soil under each nitrogen application treatment was significantly higher than that under the C1N0 treatment without the application of nitrogen. The content of ammonium nitrogen in the saline soil was significantly higher than that under the no-nitrogen treatment. During the whole incubation period, the content of ammonium nitrogen in the C1N1 soil decreased significantly with an increase in the incubation time, whereas that under the C1N2 treatment increased first and then decreased during the incubation period. Similar to soil without the return of straw, the order of the ammonium nitrogen content under each nitrogen application treatment in saline soil was C1N0 < C1N1 < C1N2. After the culture, the ammonium nitrogen content of each nitrogen application treatment was 2.20, 2.30 and 0.43 mg kg^{-1}, respectively, and there was no significant difference among the three treatments. Similar to the situation with no return of straw, the order of ammonium nitrogen in the saline soil under the different nitrogen application treatments was C1N0 < C1N1 < C1N2. After the culture, the content of ammonium nitrogen in the soil under the different nitrogen application treatments was 2.20, 2.30 and 0.43 mg/kg, respectively. There was no significant difference among the three treatments.

According to the analysis of variance in Table 6, for the incubation period of 0–7 d, the nitrogen application rate had a very significant impact on the ammonium nitrogen content of saline soil. For the incubation period of 7–25 days, returning straw alone, as well as the simultaneous effect of returning straw and the nitrogen application rate, had a significant impact on the content of ammonium nitrogen in the saline soil.

Table 6. ANOVA of the effects of returning straw and the nitrogen application rate on the ammonium nitrogen content in saline soil.

Treatment	1 d		3 d		7 d		15 d		25 d		35 d	
	F	*p*	F	*p*	F	*p*	F	*p*	F	*p*	F	*p*
C	0.884	0.366	0.857	0.373	6.928	0.022	215.712	<0.001	34.863	<0.001	0.0887	0.771
N	1235.051	<0.001	912.212	<0.001	528.741	<0.001	1519.48	<0.001	71.252	<0.001	0.741	0.497
C × N	1.917	0.190	1.566	0.249	10.465	0.002	279.308	<0.001	41.078	<0.001	0.966	0.408

4. Discussion

4.1. Effect of the Nitrogen Application Rate on the Nitrification and Mineralization of Nitrogen in Saline Soil

When inorganic nitrogen fertilizer was applied to the soil, it changed the C/N of the soil and significantly changed the intensity and time of the mineralization/assimilation process of nitrogen in the soil, thus affecting the dynamic changes in the soil inorganic nitrogen [24]. Generally speaking, an increase in the nitrogen application rate improves the mineralization of nitrogen in the soil [25] and also increases the mineralization rate of soil nitrogen, especially in red soil [26]. At the micro-level, the amount of nitrogen applied accelerated the mineralization rate of soil nitrogen in the rhizosphere soil [27]. Although the application of nitrogen has a positive effect on the maintenance of soil fertility, long-term application of high amounts of chemical fertilizer nitrogen significantly reduces the soil's mineralization ability [28].

In this study, the order of the mineralization rate was C0N2 > C0N1 > C0N1. When straw was not returned to the field, the nitrogen mineralization rate in saline soil decreased rapidly over Days 0–7, and the mineralization rates of C0N0, C0N1 and C0N2 decreased by 86.91%, 89.26% and 83.64%, respectively. Moreover, the mineralization rate of C0N1 decreased the fastest. The amount of nitrogen fertilizer promoted the mineralization rate of soil nitrogen within a certain range, but excessive amounts of nitrogen fertilizer inhibited the mineralization of nitrogen in the initial stage of cultivation (0–3 d), which was consistent with previous research results on non-saline soil. Soil nitrification is an important step in providing nitrogen for plant growth. The application of nitrogen fertilizers to the soil significantly increases the amount and activity of nitrifying bacteria and enhances the nitrification rate of soil [10]. The nitrification rate without nitrogen fertilizer was the highest at the initial stage (0–3 d), but there was no significant difference in the nitrification rate among the different nitrogen application rates. The nitrification rate of C0N1 was the highest when cultured for 1 week, and there was a significant difference between the nitrification rate of C0N1 and that of the no-fertilizer treatment. From Day 15 until the end of the incubation period, the nitrification rate of C0N2 was high, and the nitrification rates of N1 and N2 had no significant difference only on Day 35, whereas the nitrification rates of soil nitrogen at other time points had significant differences. The amount of nitrogen applied at the initial stage of culture (0–3 d) promoted nitrification, but an excessive amount of nitrogen had no significant effect on nitrification.

4.2. Effect of Returning Straw on the Nitrification and Mineralization of Nitrogen in Saline Soil

The mineralization of soil nitrogen is a biological process controlled by microorganisms, and the population size and activity of microorganisms are closely related to the soil nutrient status, temperature, humidity and other environmental factors. Therefore, when the environmental factors were the same, the mineralization of soil nitrogen was affected mainly by the soil nutrient status. When different amounts of external carbon were added to the soil, this increased the soil C/N ratio, affected the population size and activity of soil microorganisms, and changed the mineralization process of soil organic nitrogen. In this research, the mineralization rate of saline soil decreased with an increase in the C/N ratio under the treatments with no nitrogen application and reduced nitrogen under the conditions of returning straw to the field. Especially in the first 3 days of the incubation test, the mineralization rate decreased rapidly. Under the conditions of the high-nitrogen treatment, the C/N ratio of saline soil could be less than 30, and returning straw to the field promoted mineralization. It is generally believed that when the C/N ratio is greater than 30, the microbial fixation of inorganic nitrogen is greater than the mineralization of organic nitrogen, which is manifested as the net assimilation of inorganic nitrogen. When the C/N ratio is less than 30, the mineralization of organic nitrogen is greater than the biological fixation of inorganic nitrogen [10], which is manifested by the increase in the mineralization rate of soil organic chlorine. The input of a large amount of carbon and nitrogen sources improves the aeration of the soil [29]; such an input not only stimulates the activities of microorganisms in the soil, but it also increases the ability of the soil microorganisms to mineralize and decompose organic nitrogen, thus slowing down the rate of consuming ammonia nitrogen [30–32].

Compared with the high nitrogen application rate, the treatment of returning straw to the field combined with the reduced application of nitrogen fertilizer in this study reduced the nitrification rate of saline soil and slowed down the formation rate of nitrate nitrogen. This phenomenon showed that the increase in the NH_4^+ content did not promote soil nitrification, and returning straw to the field slowed down the nitrification of saline soil [33,34]. This was caused mainly by the high C/N ratio of the straw of the crop, so when the straw was returned to the field, a large number of carbon sources entered the soil, significantly increasing the C/N ratio of the soil and promoting the biological fixation of NH_4^+ by soil microorganisms or clay particles. To sum up, previous studies have shown that returning straw to the field can improve the physical and chemical properties of saline soil, increase the amount of soil microorganisms and enhance the ability of the microorganisms to mineralize and decompose organic nitrogen. The research in this article showed that returning straw to the field can not only improve the soil mineralization rate but also slow down nitrification and reduce the risk of NO_3^--N losses through leaching. Therefore, returning straw to the field is an effective way to reduce the salinization barrier and improve the nutrient utilization efficiency.

5. Conclusions

Under the conditions of not returning the straw, the application of nitrogen slowed down the nitrification rate and accelerated mineralization for Days 0–3 of incubation, whereas the nitrification and mineralization of soil nitrogen were significantly enhanced for Days 3–35 of the culture period.

After 7–35 days of incubation, the treatment of returning straw had a significant impact on the mineralization and nitrification of nitrogen in the saline soil, in which the reduced nitrogen and no-nitrogen fertilizer treatments slowed down the mineralization and nitrification of nitrogen in the saline soil, whereas the high-nitrogen treatment enhanced the mineralization and nitrification of nitrogen in the saline soil.

Returning straw and reducing the nitrogen fertilizer can retain more ammonium nitrogen, thus inhibiting the nitrification of soil nitrogen, reducing the environmental pollution risk of nitrate leaching and reducing soil nitrogen losses in saline soil. From the perspective of the transformation of soil nitrogen, returning straw and reducing the application of nitrogen fertilizer are more effective and environmentally friendly measures for improving saline soils.

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References

1. Zhang, C.; Che, Y.; Li, Z. Migration and transformation of fertilizer nitrogen in a simulated black soil column. *Chin. J. Eco-Agric.* **2010**, *18*, 683–688. [CrossRef]
2. Shi, Z.; Wang, F.; Zhang, C.; Gu, D.; Gu, K.; Yang, S.; Zhang, S. Effects of nitrogen applications on soil phosphorus balance of winter wheat in a rice-wheat rotation. *Acta Agric. Boreali-Sin.* **2014**, *29*, 187–192.
3. Wang, Y.; Wu, J.; He, Y.; Cai, L.; Zhang, R. Effects of Straw and Biochar Addition on Soil Nitrogen Mineralization in Dryland Iarmland of the Loess Plateau. *J. Soil Water Conserv.* **2021**, *35*, 186–193.
4. Liu, Z.; Lu, H.; Zhao, H.; Wang, J.; He, J.; Wang, Y.; Huang, Z.; Zhao, H.; Wei, D. Effects of Methods for Spring Maize Straw-returning to Field on Soil Microbial Biomass C, N, P and Enzyme Activities in Dry Farming Area. *Acta Agric. Boreali-Occident. Sin.* **2022**, *32*, 183–192.
5. Zhou, M.; Gao, H.; Liu, S.; Li, H.; Liu, F.; Jiang, G.; Zhao, Y. Effects of Combined Application of Straw and Nitrogen Fertilizer on Microbial Activity and Aggregate Distribution in Fluvo Aguic Soil. *J. Soil Water Conserv.* **2022**, *36*, 340–345.
6. Zou, C.; Ding, H.; Wang, Y.; Zhang, Y.; Yu, J.; Zheng, X. Effect of Straw on Urea Nitrogen Transforration in Soil. *Ecol. Environ. Sci.* **2021**, *30*, 1213–1219.
7. Gao, Y.; Liang, A.; Zhang, Y.; McLaughlin, N.; Zhang, S.; Chen, X.; Zheng, H.; Fan, R. Dynamics of Microbial Biomass, Nitrogen Mineralization and Crop Uptake in Response to Placement of Maize Residue Returned to Chinese Mollisols over the Maize Growing Season. *Atmosphere* **2021**, *12*, 1166. [CrossRef]

8. Meng, X. *Effects of Nitrogen Fertilizer and Straw Returning on Carbon and Nitrogen Fixation and Greenhouse Gas Emission Reduction in Wheat-Maize Double Cropping System*; Northwest A & F University: Xianyang, China, 2021.
9. Cheng, Y.; Huang, Q.; Wu, L.; Huang, S.; Zhong, Y.; Sun, Y.; Zhang, K.; Zhang, X. Efects of Straw Mulching and Vetiver Grass Hedgerows on Soil Enzyme Activities and Soil Microbial Community Structure in Red Soil Sloping Land. *Sci. Agric. Sin.* **2017**, *50*, 4602–4612.
10. Guo, C.; Li, Y.; Guo, Y.; Cao, X.; Zhao, X.; Wang, H. Effect of straw and nitrogen fertilizers application on nitrogen mineralization and nitrification of cherno. *J. Northeast. Agrieultural Univ.* **2021**, *52*, 17–24.
11. Shang, F.; Ren, S.; Yang, P. Effects of Different Fertilizer and Irrigation Water Types, and Dissolved Organic Matter on Soil C and N Mineralization in Crop Rotation Farmland. *Water Air Soil Pollut.* **2015**, *226*, 396. [CrossRef]
12. Fu, H.; Duan, Y.; Zhu, P. Potential N mineralization and availability to maize in black soils in response to soil fertility improvement in Northeast China. *J. Soils Sediments* **2021**, *21*, 905–913. [CrossRef]
13. Li, P.; Lang, M.; Wei, W. Effects of Nitrogen Application Amounts on Net Nitrogen Transformation Rates in Forest and Agricultural Black Soils. *Chin. J. Soil Sci.* **2020**, *51*, 694–701.
14. Yin, F.; Fu, B.; Mao, R. Effects of Nitrogen Fertilizer Application Rates on Nitrate Nitrogen Distribution in Saline Soil in the Hai River Basin, China. *J Soils Sediments* **2007**, *7*, 136–142. [CrossRef]
15. Yang, R.; Zhang, H.; Hu, L.; Fan, Z. Effects of AMF inoculation and nitrogen application on nitrogen mineralization of coastal saline soil. *J. Nanjing For. Univ. (Nat. Sci. Ed.)* **2021**, *45*, 145–152.
16. Wang, Y.; Liang, H.; Li, S.; Zhang, Z.; Liao, Y.; Lu, Y.; Zhou, G.; Gao, S.; Nie, J.; Cao, W. Co-utilizing milk vetch, rice straw, and lime reduces the Cd accumulation of rice grain in two paddy soils in south China. *Sci. Total Environ.* **2022**, *806*, 150622. [CrossRef]
17. Su, Y.; Kwong, R.W.; Tang, W.; Yang, Y.; Zhong, H. Straw return enhances the risks of metals in soil? *Ecotoxicol. Environ. Saf.* **2021**, *207*, 111201. [CrossRef] [PubMed]
18. 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] [PubMed]
19. Mohamed, I.; Bassouny, M.A.; Abbas, M.H.; Ming, Z.; Cougui, C.; Fahad, S.; Saud, S.; Khattak, J.Z.K.; Ali, S.; Salem, H.M.; et al. Rice straw application with different water regimes stimulate enzymes activity and improve aggregates and their organic carbon contents in paddy soil. *Chemosphere* **2021**, *274*, 129971. [CrossRef] [PubMed]
20. Ditta, A.; Arshad, M.; Zahir, Z.; Jamil, A. Comparative efficacy of rock phosphate enriched organic fertilizer vs. mineral phosphatic fertilizer for nodulation, growth and yield of lentil. *Int. J. Agric. Biol.* **2015**, *17*, 589–595. [CrossRef]
21. Ditta, A.; Muhammad, J.; Imtiaz, M.; Mehmood, S.; Qian, Z.; Tu, S. Application of rock phosphate enriched composts increases nodulation, growth and yield of chickpea. *Int. J. Recycl. Org. Waste Agric.* **2018**, *7*, 3–40. [CrossRef]
22. Farooq, N.; Kanwal, S.; Ditta, A.; Hussain, A.; Naveed, M.; Jamshaid, M.; Iqbal, M. Comparative efficacy of KCl blended composts vs. sole application of KCl or K2SO4 in improving K nutrition, photosynthetic capacity and growth of maize. *Soil Environ.* **2018**, *37*, 68–74. [CrossRef]
23. Zeb, H.; Hussain, A.; Naveed, M.; Ditta, A.; Ahmad, S.; Jamshaid, M.U.; Ahmad, H.T.; Hussain, M.B.; Aziz, R.; Haider, M.S. Compost enriched with ZnO and Zn-solubilising bacteria improves yield and Zn-fortification in flooded rice. *Ital. J. Agron.* **2018**, *13*, 310–316. [CrossRef]
24. Said-Pullicino, D.; Cucu, M.A.; Sodanoa, M.; Birk, J.J.; Glaser, B.; Celia, L. Nitrogen immobilization in paddy soils as affected by redox conditions and rice straw incorporation. *Geoderma* **2014**, *228*, 44–53. [CrossRef]
25. Wang, X.; Xu, J.; Long, C.; Zhu, S.; Lu, M.; Yang, W. Effect of nitrogen rates and soil water contents on soil nitrogen mineralization under ryegrass returning into red soil. *J. Plant Nutr. Fertil.* **2018**, *24*, 365–374.
26. Ali, S.; Liu, K.; Ahmed, W.; Jing, H.; Qaswar, M.; Kofi Anthonio, C.; Maitlo, A.A.; Lu, Z.; Liu, L.; Zhang, H. Nitrogen Mineralization, Soil Microbial Biomass and Extracellular Enzyme Activities Regulated by Long-Term N Fertilizer Inputs: A Comparison Study from Upland and Paddy Soils in a Red Soil Region of China. *Agronomy* **2021**, *11*, 2057. [CrossRef]
27. Yuan, L.; Bao, D.; Jin, Y.; Yang, Y.; Huang, J. Influence of fertilizers on nitrogen mineralization and utilization in the rhizosphere of wheat. *Plant Soil* **2011**, *343*, 187–193. [CrossRef]
28. Wu, X.; Shi, W.; Xu, Y.; Min, J. Effects of Long-term Different Chemical Nitrogen Rates on Soil Nitrogen Mineralization and Nitrification in Greenhouse Vegetable Field. *Soils* **2021**, *53*, 1160–1166.
29. Xi, K.; Yang, S.; Xi, J.; Li, Y.; Zhang, J.; Wu, X. Effects of long-term cotton straw incorporation and manure application on soil characters and cotton yield. *Soil Fertil. Sci. China* **2022**, *303*, 82–90.
30. Chen, L.; Du, H.; Liu, Q.; Li, T.; Zhang, X.; Li, J.; Chen, X.; Sui, P.; Liu, J.; Chen, Y. Effects of organic materials returning on the form, transformation and utilization of soil nitrogen in summer maize field. *J. China Agric. Univ.* **2022**, *27*, 1–11.
31. Huo, H.; Li, J.; Yuan, L.; Xie, H.; Zhu, T.; Christoph, M.; He, H.; Zhang, X. Effects of different straw returning amount on the potential gross nitrogen transformation rates of fertilized Mollisol. *Chin. J. Appl. Ecol.* **2020**, *31*, 4109–4116.
32. Wang, D.; Guo, L.; Zheng, L.; Zhang, Y.; Yang, R.; Li, M.; Ma, F.; Zhang, X.; Li, Y. Effects of nitrogen fertilizer and water management practices on nitrogen leaching from a typical open field used for vegetable planting in northern China. *Agric. Water Manag.* **2019**, *213*, 913–921. [CrossRef]

33. Wu, C.; Xiong, C.; Han, Y.; Zhang, Q.; Li, P.; Zhang, L. Mechanism of combination of nitrogen fertilizer reduction and straw returning in regulating dryland nitrification intensity and keeping stable crop yield in long run. *J. Plant Nutr. Fertil.* **2020**, *26*, 1782–1793.
34. Guo, R.; Qian, R.; Han, F.; Khaliq, A.; Hussain, S.; Yang, L.; Zhang, P.; Chen, X.; Ren, X. Managing straw and nitrogen fertilizer based on nitrate threshold for balancing nitrogen requirement of maize and nitrate residue. *J. Environ. Manag.* **2023**, *329*, 117084. [CrossRef] [PubMed]