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Effects of Reduced Nitrogen Fertilizer Rates on Its Fate in Maize Fields in Mollisols in Northeast China: A ^{15}N Tracing Study

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Abstract: A large amount of nitrogen fertilizer is applied in maize planting in Northeast China, but the recovery rate is low, causing a series of water and soil environmental problems in farmland areas. Thus, based on isotope tracing technology and combining a field plot test with an in situ microzone test, we carried out an experiment under reduced nitrogen fertilizer conditions. Five different nitrogen application levels were set: conventional nitrogen application (N1: 250 kg ha^{-1}), 10%-reduced nitrogen fertilizer (N-10: 225 kg ha^{-1}), 20%-reduced nitrogen fertilizer (N-20: 200 kg ha^{-1}), 30%-reduced nitrogen fertilizer (N-30: 175 kg ha^{-1}), and nitrogen-free (N0: 0 kg ha^{-1}) treatments. Yield, nitrogen accumulation in maize and nitrogen fertilizer fates were studied. The results showed that reducing nitrogen application rates improved the recovery rates of basal fertilizer and topdressing. Specifically, the recovery rate of basal fertilizer was 19.81–26.20%, and the recovery rate of topdressing was 40.24–47.71%. The loss rate of basal fertilizer was 19.96–39.18%, and nitrogen reduction decreased the loss rate of basal fertilizer. The loss rate of topdressing ranged from 36.46 to 41.76%. The residual rates of basal fertilizer and topdressing in the 0–100 cm soil layer were 41.01–53.84% and 12.22–22.30%, respectively. As the nitrogen application rate decreased, corn yield and nitrogen accumulation in maize decreased. Reductions of 20% and 30% in nitrogen fertilizer had a negative influence on plant nitrogen accumulation. This experiment revealed the effect of reducing nitrogen fertilizer application rates on the fate of nitrogen fertilizer, maize yield and nitrogen accumulation in Northeast China. In Northeast China, reducing the nitrogen fertilizer application rate could increase the nitrogen fertilizer recovery rate and reduce nitrogen fertilizer loss amounts and the risk of environmental pollution, but reduce maize yield.

Keywords: maize; mollisols; ^{15}N-labeled; nitrogen fate; yield; nitrogen accumulation

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1. Introduction

At present, corn is the crop with the largest sown area in the Mollisols area of Northeast China, accounting for about a third of the national corn yield [1,2]. To ensure that the yield remains stable or increases, the nitrogen application rate has been maintained at a high level for a long time. Increasing crop yields by increasing nitrogen application rates has become a common practice in the local agricultural planting process [3,4]. Studies have shown that excess nitrogen application and a low nitrogen fertilizer utilization rate cause fertilizer nitrogen to be lost through leaching in the form of nitrate, ammonia volatilization and gaseous nitrogen (N_2O, NO, N_2) emissions [5,6]. Recently, the "Agricultural and Rural Pollution Control Action Plan (2021–2025)" was issued by five ministries and commissions in China, which stated that it is necessary to promote the reduction and efficiency of chemical fertilizers, improve the efficiency of fertilizer utilization rates, ensure food security, and reduce pollution from chemical fertilizer. This puts forward higher requirements for the efficient use of chemical fertilizers.

The fate of nitrogen fertilizer in farmland ecosystems has received extensive attention because it is closely related to the fertilizer recovery rate and environmental issues [7,8]. Nitrogen fertilizer is an important form of nitrogen supplementation in soil. The fate of nitrogen fertilizer may change depending on the management practices and planting region. Additionally, the nitrogen fertilizer recovery rate for major cereal crops in China is significantly lower than that in America and in Europe [7,8]. A global analysis of field ^{15}N tracer data showed that the nitrogen fertilizer recovery rate by maize aboveground is 33% in China, which was significantly lower than that in North America (42%) and the European Union (54%), and reducing the nitrogen fertilizer rate could increase the nitrogen fertilizer recovery rate but presents risks of yield reductions in some regions [9]. Jun-Zhong found that the overapplication of N in high-yield fields did not further increase the yield, and the nitrogen recovery rate was low; with the increase in the nitrogen application rate, the nitrogen recovery rate decreased in the middle-yield field [10]. ^{15}N tracing technology can quantitatively analyze the absorption of nitrogen fertilizer and its effect on the environment [11]. Although the fate of nitrogen fertilizer has been investigated in many experiments, few studies have labeled base and topdressing fertilizers with ^{15}N. In particular, there is a lack of research on the fate of basal fertilizer and topdressing under the condition of reduced nitrogen. Therefore, we carried out experiments using ^{15}N tracer technology to quantitatively analyze the nitrogen recovery rate, residual amounts in the soil system and nitrogen fertilizer loss following basal fertilizer and topdressing applications.

An appropriate nitrogen application rate can improve crop yield, nitrogen-use efficiency and soil nutrient contents, and reduce the risk of environmental pollution caused by nitrogen fertilizer loss [12]. Peng found that reducing the nitrogen application rate by 30% at the reproductive growth stage can double the nitrogen agronomic utilization efficiency and slightly improve yield [13]. Zhao found that increasing nitrogen application significantly promoted the total nitrogen accumulation of wheat aboveground; the grain nitrogen accumulation was the highest when the nitrogen application rate was 180 kg ha^{-1}, and the grain nitrogen accumulation decreased when the nitrogen application rate continued to increase [14]. Tong showed that the excessive application of N fertilizer had no significant effect on grain yield, and N recovery rates slightly decreased with the increase in the N application rate [15]. After evaluating the impacts of reducing nitrogen application rates on rice yields, environmental effects and other factors, the researchers proposed that reducing nitrogen fertilizer application rates is feasible, but the sustainability of yield still needs to be further verified [16]. Many experimental results have also shown that as long as the balance between the nitrogen supply of the soil and the demand of crops at different growth stages is satisfied, the goal of improving fertilizer efficiency and increasing crop yield can be achieved [17,18]. However, the results regarding crop nitrogen reduction experiments differ among different experimental areas [19,20]. Therefore, we carried out a nitrogen fertilizer reduction experiment to explore the specific effect of nitrogen fertilizer reduction on maize yield and nitrogen accumulation in Northeast China.

We used ^{15}N isotope tracing technology to carry out maize planting experiments under reduced nitrogen fertilizer conditions. We quantitatively studied the fate of basal fertilizer and topdressing under different nitrogen application rates and explored the effects of reducing the nitrogen fertilizer application rate on the fate of nitrogen fertilizer, maize yield and nitrogen accumulation.

2. Materials and Methods

2.1. Experimental Site

The field experiment was conducted at the Hei Long Jiang Province Hydraulic Research Institute (45°43″ N, 126°36″ E), which has an average altitude of 137 m. The experimental site was located in a mid-tropical continental monsoon climate zone with four distinct seasons, concentrated precipitation and susceptibility to spring drought. The multi-year average temperatures at the experimental station are −4–5 °C, the frost-free period lasts 130–140 days, the average annual precipitation is 400–650 mm, rainfall from July to September accounts for 70% of the annual precipitation, and the multi-year average evaporation is 796 mm. The temperature and rainfall during the growing period in 2021 are shown in Figure 1. The experimental area was located in the typical black soil zone in Northeast China. The soil was classified as Mollisols. The basic soil fertility is shown in Table 1.

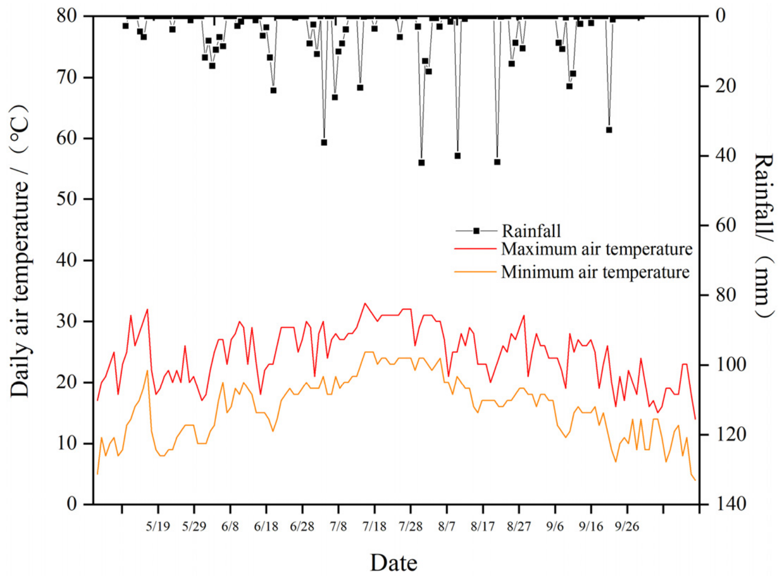

Figure 1. Temperature and rainfall.

Table 1. Basic fertility of 0–40 cm soil in the experimental field.

Soil Layers/(cm)	Available N/(mg kg^{-1})	Available P/(mg kg^{-1})	Available K/(mg kg^{-1})	SOM/(g kg^{-1})	pH
0–20	154.4	40.1	376.8	25.07	7.27
20–40	150.1	36.8	356.3	22.37	7.25

2.2. Experimental Design

The maize was sown on 11 May 2021. Five nitrogen application levels were set in the experiment: a treatment of conventional N fertilizer application rate (N1: 250 kg ha^{-1}), a 10% reduction in N fertilizer application rate treatment (N-10: 225 kg ha^{-1}), a 10% reduction in N fertilizer application rate treatment (N-20: 200 kg ha^{-1}), a 30% reduction in N fertilizer application rate treatment (N-30: 175 kg ha^{-1}) and a treatment without nitrogen fertilizer application (N0: 0 kg ha^{-1}) (Table 2). Each treatment was repeated 3 times, and 15 plots were set in total. A total of 67,500 seedlings were grown per hectare. Large-ridge double-row planting was adopted in each plot. The experimental plot area was 64 m^2 (8 m × 8 m), and the plant spacing was 23.0 cm. The width of the protection area was 5 m, and the width of the protection row was 1 m. Two microzones were established in the center of each plot. The two microzones were used to apply ^{15}N-labeled urea when applying basal fertilizer and topdressing. The two microzones were 2 m apart and established by using a bottomless PVC rectangular frame with a length of 1.2 m, a width of 1.0 m and a height of 0.4 m. The microzone frames extended into the soil to a depth of 0.35 m and 5 cm above the surface. ^{15}N-labeled urea was produced at the research institute in Shanghai. In one microzone, ^{15}N-labeled urea was applied as basal fertilizer, while ordinary urea was applied as topdressing, and the opposite was adopted in the other microzone. The nitrogen application ratio of basal fertilizer and topdressing in plots and microzones was 1:1. Topdressing was applied at the jointing stage. The amounts of phosphorus and potassium fertilizer in each treatment were the same. P_2O_5 90 kg ha^{-1} and K_2O 90 kg ha^{-1} were simultaneously applied as basal fertilizers.

Table 2. Experimental treatment design.

Treatment	N/(kg ha^{-1})	P_2O_5/(kg ha^{-1})	K_2O/(kg ha^{-1})
N0	0	90	90
N1	250	90	90
N-10	225	90	90
N-20	200	90	90
N-30	175	90	90

2.3. Sampling and Analytical Methods

At the mature stage, three maize plants were collected from each microzone. After being dried and weighed, samples of different organs from mature plants were ground, screened through an 80-mesh filter and mixed well. After digestion of the samples in a mixture of concentrated H_2SO_4 and H_2O_2, an Autoanalyzer-iii flow analyzer (SEAL Analytical, Germany) was used to determine the nitrogen content in each plant organ. An elemental analyzer (Flash 2000 HT, Thermo Fisher Scientific, Waltham, MA, USA) and isotope mass spectrometer (DELTA V Advantage, Thermo Fisher Scientific, Waltham, MA, USA) were used to determine the ^{15}N abundance in each plant organ.

At the mature stage, soil samples from the 0–100 cm layer (with one layer every 20 cm) were collected by a soil drill according to a five-point sampling method, and stones and roots were removed. The soil samples were air-dried, ground and sieved to measure the soil total nitrogen content and isotopic abundance.

Production was tested on 2 October 2021. The ears of corn were air-dried to a constant weight, after which they were threshed and weighed. The yield was converted into the grain yield based on 14% water content.

2.4. Formulas for Calculating Related Indicators

The nitrogen accumulation in plant organs (N_{AA}, kg ha^{-1}) was calculated as follows:

$$N_{AA} = D_m \times N_c \tag{1}$$

where D_m is the plant dry matter weight in kg ha^{-1} and N_c is the nitrogen content of the plant expressed as a percentage.

The percentage of nitrogen in plants derived from basal fertilizer and topdressing (Ndff $_{(b,t)}$, %) was calculated as follows:

$$\text{Ndff}_{(b,t)} = (N_P - N_c)/(N_f - N_c) \times 100 \tag{2}$$

where N_p is the ^{15}N abundance in the plant sample from the microregion, N_c is the standard natural ^{15}N abundance value (0.3663% ^{15}N), and N_f is the ^{15}N abundance in urea (10.22% ^{15}N).

The accumulation of basal fertilizer and topdressing ($^{15}N_{(b,t)}$, kg ha^{-1}) was determined as follows:

$$^{15}N_{(b,t)} = N_{AA} \times \text{Ndff}_{(b,t)} \tag{3}$$

The percentage of plant nitrogen derived from soil nitrogen (Ndfs, %) was calculated as follows:

$$\text{Ndfs} = 100 - \text{Ndff} \tag{4}$$

The accumulation of soil nitrogen in plants (N_{soil}, kg ha^{-1}) was determined follows:

$$N_{soil} = \text{Ndfs} \times N_{AA} \tag{5}$$

The residual amount of ^{15}N ($^{15}N_{S\,(b,t)}$, kg ha^{-1}) in the soil was calculated by the following formula:

$$^{15}N_{S\,(b,t)} = N_i \times (a - N_c)/(N_f - N_c) \quad (6)$$

where N_i is the total nitrogen amount in soil, a is the ^{15}N abundance in soil samples from the microzone.

The proportion of the total ^{15}N residues in the 0–100 cm soil layer ($^{15}N_{Si(b,t)} - P$, %) was accounted for by the ^{15}N residues in each soil layer ($^{15}N_{Si(b,t)}$, kg ha^{-1}), and was calculated as follows:

$$^{15}N_{Si(b,t)} - P = {^{15}N_{Si(b,t)}}/{^{15}N_{S(b,t)}} \times 100 \quad (7)$$

Nitrogen fertilizer loss ($^{15}N_{L(b,t)}$, kg ha^{-1}) was calculated by the following formula:

$$^{15}N_{L(b,t)} = N_{APP} - {^{15}N_{S(b,t)}} - {^{15}N_{(b,t)}} \quad (8)$$

where N_{APP} is the basal fertilizer or topdressing applied (kg ha^{-1}).

The recovery rates of basal fertilizer and topdressing ($^{15}N_{(b,t)} - P$, %), the residual rates of basal fertilizer and topdressing ($^{15}N_{S(b,t)} - P$, %) and the loss rates of basal fertilizer and topdressing ($^{15}N_{L(b,t)} - P$, %) were calculated by the following formula:

$$^{15}N_{(b,t)} - P, {^{15}N_{S(b,t)}} - P, {^{15}N_{L(b,t)}} - P = {^{15}N_{(b,t)}}, {^{15}N_{S(b,t)}}, {^{15}N_{L(b,t)}}/N_{APP} \times 100 \quad (9)$$

2.5. Data Management and Analysis

Microsoft Excel 2019 was used to record the data, and SPSS 2019 was used for data analysis. The data are expressed as the mean ± standard error, and the least significant difference (LSD) method was used to test for significance at the 5% level. Origin 9.0 was used to produce graphs.

3. Results

3.1. Maize Yield and Nitrogen Accumulation

Under different nitrogen application rates, the grain yields ranged from 8053 to 12,805 kg ha^{-1}, and there were significant differences between the nitrogen-application treatments and the N0 treatment ($p < 0.05$) (Figure 2a). The grain yield showed a decreasing trend with decreasing nitrogen application rates. The grain yields of the N1 and N-10 treatments were significantly higher than that of the N-30 treatment ($p < 0.05$), and there were no significant differences between the N1, N-10 and N-20 treatments ($p > 0.05$).

The nitrogen accumulation in maize is shown in Figure 2b. The total N accumulation in maize was between 170 and 304 kg ha^{-1}. The total N accumulation for the N1, N-10, N-20 and N-30 treatments was 45.29–78.82% higher than that under the N0 treatment. The total N accumulation in the N1 treatment was 23.27 and 11.42% higher those in the N-20 and N-30 treatments, respectively, ($p < 0.05$). As shown in Figure 2a,b, the total N accumulation in maize decreased with decreasing nitrogen application rates. There was no significant difference in nitrogen accumulation between the 250 and 225 kg ha^{-1} treatments ($p > 0.05$).

As shown in Figure 2d, soil nitrogen accounted for more than 70% of the total N accumulation in maize and was the main source of the total N of maize. As the nitrogen application rates decreased, the soil nitrogen accumulation in maize showed a decreasing trend (Figure 2c). The accumulation and proportion of soil nitrogen in each organ decreased in the order of grain > leaf > stem. The accumulation of soil nitrogen in grain accounted for 59.69–64.42% of the total accumulation of soil nitrogen in plants.

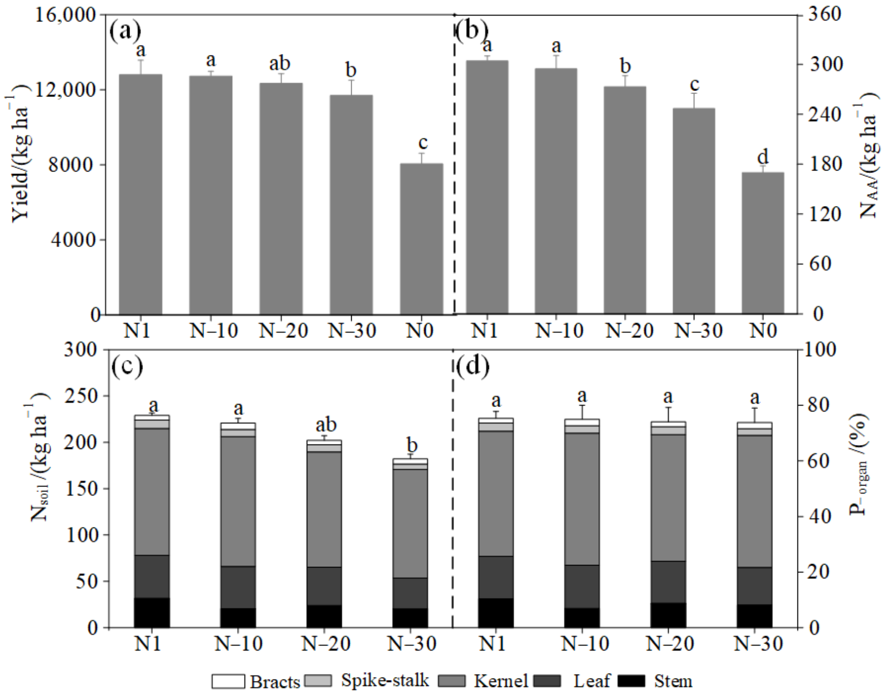

Figure 2. Corn yields (**a**), nitrogen accumulation (**b**), soil nitrogen accumulation (**c**), and ratios of soil nitrogen accumulation to plant nitrogen accumulation under the different treatments (**d**). Note: different letters indicate significant differences ($p < 0.05$). N0, N1, N-10, N-20 and N-30 represent the five fertilization treatments.

3.2. The Nitrogen Absorption and Utilization of Maize from Fertilizer

The accumulation of basal fertilizer increased first and then decreased as nitrogen application decreased (Figure 3a). The recovery rates of the basal fertilizer ranged from 19.81 to 26.20% (Figure 3b) and increased as the nitrogen application rates decreased. The recovery rates of basal fertilizer under the reduced nitrogen fertilizer treatments were 23.42–32.22% higher than those under the N1 treatment. The basal fertilizer recovery rate under the N1 treatment was significantly different from that under the N-30 treatment ($p < 0.05$).

The accumulation of topdressing in maize decreased as nitrogen application decreased (Figure 3c). The accumulations from topdressing under the N-10 and N-20 treatments were similar. The accumulation in the N1 treatment was 50.30 kg ha^{-1}, which was 8.94, 9.30 and 20.48% higher than that in the N-10, N-20 and N-30 treatments, respectively. The recovery rates of basal fertilizer and topdressing increased as nitrogen application decreased (Figure 3b, d). Approximately 40.24–47.71% of the topdressing was recovered to the above-ground parts of the plant. Compared with N1 treatment, the recovery rates of topdressing in the N-10, N-20 and N-30 treatments increased by 1.99, 14.36 and 18.58%, respectively.

The accumulation of basal fertilizer in maize organs decreased in the order of grain > leaf > stem > cob and bracts (Figure 3b). With the increase in N application rates, the accumulation of basal fertilizer in grain first increased and then decreased. The accumulation of topdressing in maize organs showed the same trend as that of basal fertilizer (Figure 3a,c), following the order of grain > leaf > stem. A total of 9.10–11.23% of the topdressing was distributed in stems, 24.70–30.08% was distributed in leaves, and 52.61–60.61% was distributed in grains. The accumulation of topdressing in individual organs was higher than that under basal fertilizer.

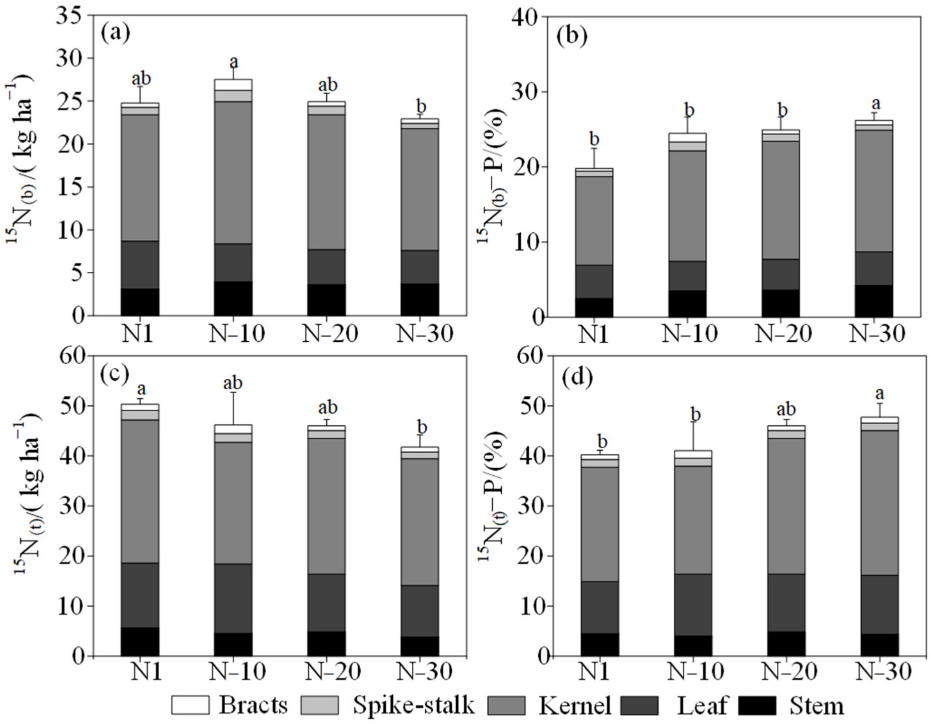

Figure 3. Accumulation and recovery rate of basal fertilizer (**a**,**b**) and topdressing (**c**,**d**) in different maize organs. Note: different letters in the same column indicate that the differences in $^{15}N_{(b,t)}$ and $^{15}N_{(b,t)} - P$ in the whole maize plant reached a significant level ($p < 0.05$). N0, N1, N-10, N-20 and N-30 represent the five fertilization treatments.

3.3. Residual Basal Fertilizer and Topdressing in the Soil

The residual amount of basal fertilizer in the 0–100 cm soil layer was 47.11–52.81 kg ha^{-1}, and there were no significant differences between treatments ($p > 0.05$) (Figure 4a). The residual amounts of basal fertilizer in the 0–20 cm soil layer was higher than other soil layers (Figure 4a). The residual amount in the 0–20 cm soil layer was 18.18–22.20 kg ha^{-1}, accounting for 36.18–43.27% of the total residue (Figure 4b).

The residual amount of topdressing in the 0–100 cm soil layer ranged from 12.22 to 29.13 kg ha^{-1}. Similarly, larger amounts of topdressing residue were found in the surface soil layer (0–20 cm soil layer) (Figure 4c), accounting for 40.80–63.15% of the total residues of topdressing (Figure 4d). With decreasing nitrogen application rates, the residual amounts of topdressing followed the order of N1 > N-10 > N-20 and N-30, and there were significant differences between the reduced nitrogen application treatments and N1 treatment ($p < 0.05$).

3.4. Loss of Basal Fertilizer and Topdressing

The loss of basal fertilizer ranged from 17.47 to 48.97 kg ha^{-1}. As the nitrogen application rates decreased, the loss of basal fertilizer showed a decreasing trend (Figure 5a). Compared with the N1 treatment, the loss of basal fertilizer under the nitrogen reduction treatments decreased by 29.07–64.32%, representing significant differences ($p < 0.05$). Basal fertilizer loss could be significantly reduced by reducing nitrogen application rates.

As shown in Figure 5b, the loss of topdressing decreased after nitrogen was reduced. There were no significant differences between the N1, N-10 and N-20 treatments ($p > 0.05$). The loss of topdressing in the N-30 treatment was 26.55% lower than N1 treatment, representing significant differences ($p < 0.05$).

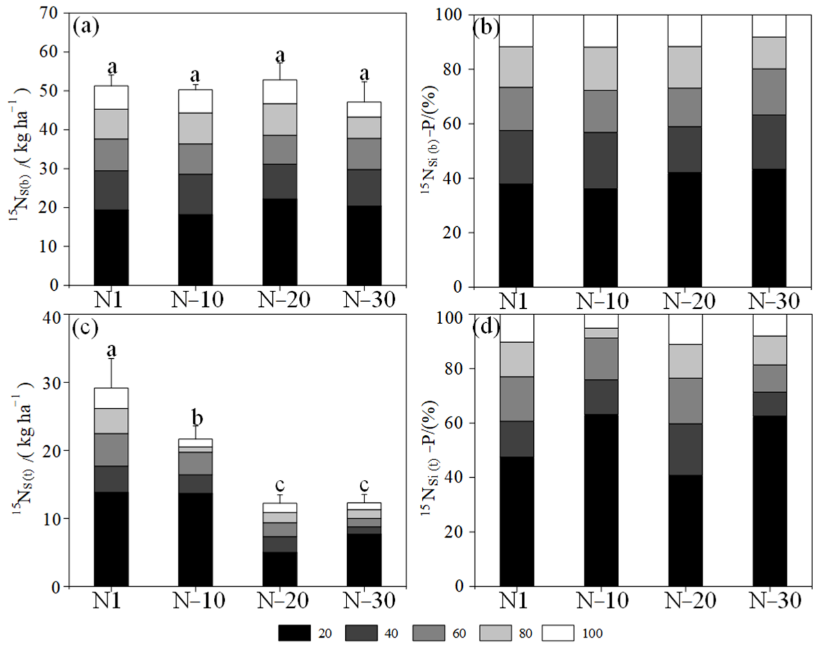

Figure 4. Nitrogen residues from the basal fertilizer and topdressing fertilizer in the 0–100 cm soil layer (**a**,**c**) and the proportion of residues in each soil layer relative to the total residues in the 0–20 cm, 20–40 cm, 40–60 cm and 80–100 cm soil layer (**b**,**d**). Note: different letters indicate significant differences ($p < 0.05$). N0, N1, N-10, N-20 and N-30 represent the five fertilization treatments.

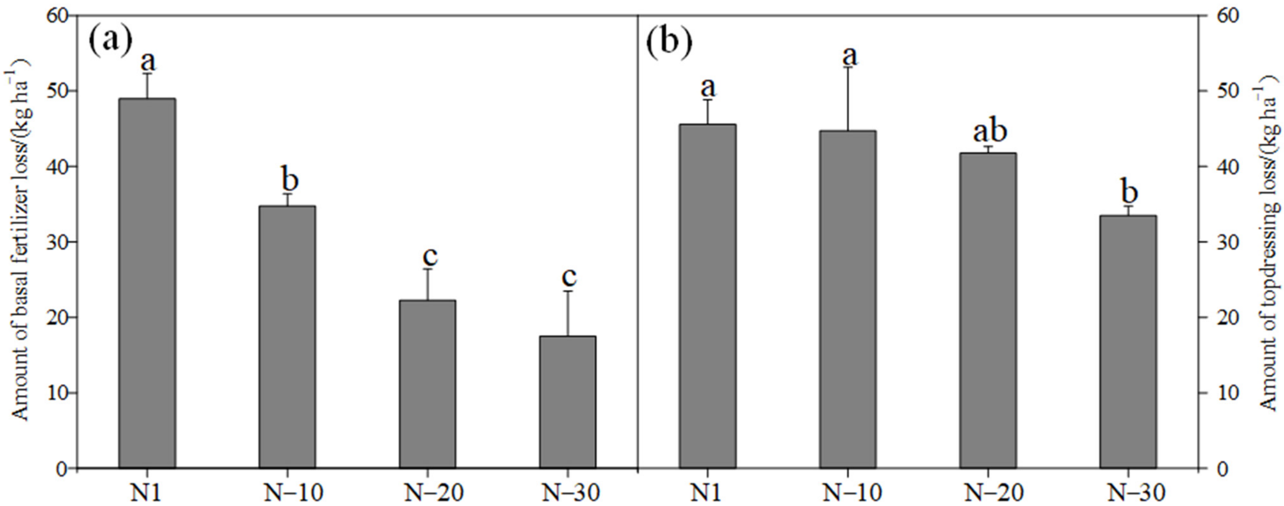

Figure 5. Nitrogen loss from basal fertilizer (**a**) and topdressing fertilizer (**b**). Note: different letters indicate significant differences ($p < 0.05$). N0, N1, N-10, N-20 and N-30 represent the five fertilization treatments.

As shown in Figure 6, with the reduction in nitrogen application rates, the basal fertilizer recovery rates were improved, and the loss rates were reduced. With the reduction in nitrogen application rates, the recovery rates of topdressing improved, and the loss rates tended to increase first and then decrease. At the same time, although the basal fertilizer recovery rate of the N-20 treatment increased by 25.80% compared with the N1 treatment, the basal fertilizer recovery rate of the N-30 treatment increased by only 5.14% compared with the N-20 treatment. Similarly, the topdressing recovery rate of the N-20 treatment increased by 14.36% compared with the N1 treatment, while that of the N-30 treatment increased by only 3.67% compared with that of the N-20 treatment. This phenomenon showed that when the nitrogen application rate was reduced to 200 kg ha^{-1}, continuing to reduce the nitrogen application rate had a limited effect on the improvement of nitrogen fertilizer recovery rates.

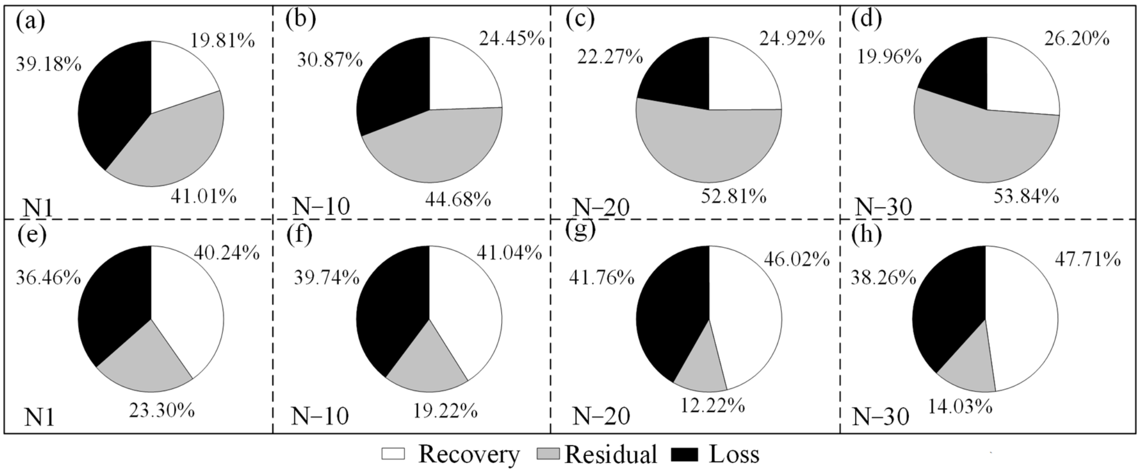

Figure 6. Proportions of nitrogen meeting the three fates for basal fertilizer (**a**–**d**) and topdressing fertilizer (**e**–**h**). Note: N0, N1, N-10, N-20 and N-30 represent the five fertilization treatments.

4. Discussion

4.1. Effects of Nitrogen Reduction on Nitrogen Uptake and Yield

Huang investigated nitrogen reduction in a single-cropped rice field, and their findings showed that there was no significant difference in yield between nitrogen application rates of 150 and 90 kg ha^{-1} [21]. In our study, the grain yields of the N-10 and N-20 treatments showed no significant decrease compared with that of N1 ($p > 0.05$), which may be because black soil has higher soil fertility [22]. Wang highlighted that the effect of the nitrogen application rates on nitrogen accumulation and maize yield were also affected by the initial soil nitrogen content, and soils with a high initial nitrogen content can reduce the impact of nitrogen fertilizer on crop yield [23]. Other study had shown that an appropriate nitrogen application rate can promote the root dry weight, specific surface area, root length density and root-shoot ratio of crops, and provide sufficient nutrients and water for maize and ensure a high yield [24]. However, our results also showed that 20% and 30% reductions in nitrogen fertilizer had a great negative influence on plant nitrogen accumulation.

4.2. Effects of Nitrogen Reduction on the Fate of Nitrogen Fertilizer

^{15}N isotope tracer technology can accurately and quantitatively present the fates of nitrogen in basal fertilizer and topdressing. This approach overcomes the disadvantage that the traditional method only represents the NUE of crops [8]. The results of this experiment showed that reducing nitrogen application can improve the recovery rates of basal and topdressing fertilizers. However, continuing to reduce nitrogen application rates has a limited effect on the improvement of nitrogen fertilizer recovery rates. The reason for this phenomenon is that crops mainly absorb nitrogen through the root system—a fertilizer nitrogen application amount that is either too high or too low has adverse effects on nitrogen absorption by roots [25,26]. Excessive nitrogen application may inhibit root growth due to the high nitrate concentration in the soil, particularly inhibiting crop lateral root growth [27]. Chen also confirmed that increasing the nitrogen application rates could increase the soil residual nitrate nitrogen concentration, promote N_2O emissions and reduce the nitrogen-use efficiency [28]. Other studies showed that the synchronization of the nitrogen supply with the crop demand is essential to ensuring nitrogen uptake, use and yield maximization [29]. The peak of maize nitrogen demand occurs at the jointing stage, and high nitrogen-use efficiency can be achieved by providing a sufficient nitrogen supply at this stage [7]. Combined with the effects of nitrogen reduction on crop yield and nitrogen fertilizer recovery rates, we believe that the N-20 treatment can meet the nitrogen demands of maize. A study showed that high N application did not result in high NUE, and low N application with high NUE led to soil N deficits [30].

Wang showed that the loss rates of fertilizer nitrogen were 11.2–22.2% [7]. Quan showed that 23% of fertilizer N was lost at harvest [31]. However, the loss rate under each treatment in this experiment was above the present range, which may have been caused by a higher loss of topdressing. Ammonia volatilization and nitrate leaching from soil are two main pathways of fertilizer nitrogen loss [32,33]. In our study, the leaching of fertilizer nitrogen into deeper soil in the form of mineral nitrogen or NO_3^--^{15}N may have occurred. Liu also reported that in a semi-arid area, as the nitrogen application rate increased, the soil residual nitrate and apparent nitrogen loss increased significantly after harvest [34]. And 18% of applied nitrogen was lost through ammonia volatilization worldwide, which was the main pathway of nitrogen loss in field trials [35]. More frequent irrigation is beneficial for reducing NH_3 emissions. Since no irrigation was used in our study, ammonia volatilization was an important cause of fertilizer nitrogen loss [36].

In our experiment, the residual amount of basal fertilizer was the main source of fertilizer residue. As the nitrogen application rates decreased, the loss amounts and loss rates of basal fertilizer decreased. The reduction in basal fertilizer loss rates may be related to the improvement in basal fertilizer recovery and residue rates. The residual rates of topdressing under the N reduction treatments were lower than those under the N1 treatment. This difference may be related to the higher recovery rates of topdressing. Studies have shown that residual fertilizer nitrogen is mainly organic nitrogen. The fixation process of soil organic nitrogen is a biological process mediated by soil microorganisms [37]. The production of soil microorganisms requires a supply of nitrogen, while plant growth also requires a supply of nitrogen fertilizer, resulting in competition for nitrogen fertilizer [38].

The ^{15}N tracer technology was used to explore the fates of nitrogen fertilizer in our study in order to provide references for improving the nitrogen fertilizer recovery rate, reducing nitrogen fertilizer loss and achieving the coordination between fertilizer utilization and environmental effects. Compared with other methods, ^{15}N tracer technology can reveal the fates of nitrogen fertilizer more directly. Generally, the nitrogen fertilizer utilization experiment, which is based on ^{15}N tracer technology, cannot be tested in the same plots for two consecutive years. Many experiments based on the ^{15}N tracer technology were carried out for only one year [39–41] because the residual ^{15}N in soil in the first year of the experiment would affect observations in other years. This was also the major limitation of our experiment, as the results of our study were based on a single year of data. More experiments are needed to further verify the results of this study.

5. Conclusions

In the maize planting process in the black soil of Northeast China, reducing the application of nitrogen fertilizer can increase the absorption and utilization of nitrogen fertilizer, reduce the loss of nitrogen fertilizer and play a role in reducing the risk of environmental pollution. Compared with the 250 kg ha^{-1} treatment, with rates of 10% and 20% lower, the yield was not lower ($p > 0.05$). The recovery rates of basal fertilizer and topdressing were 19.81–26.20% and 40.24–47.71%, respectively. The loss rates of basal fertilizer and topdressing were 19.96–39.18% and 36.46–41.76%, respectively. The residual rates of basal fertilizer and topdressing were 40.01–53.84% and 12.22–23.30%, respectively. Reducing nitrogen application rates can improve the recovery rates of basal fertilizer and topdressing and reduce the loss rates of basal fertilizer. Considering the nitrogen-use efficiency and corn yield in the current season under the conditions of reduced nitrogen fertilizer application and reduced risk of environmental pollution, we suggest that the nitrogen fertilizer application amount should be reduced by 20% in the process of corn planting in the black soil area of Northeast China; that is, an application rate of 200 kg N ha^{-1} should be used in this area. However, we found that the loss rate of topdressing is high and the residual rate of topdressing is low in this experiment. Whether nitrogen fertilizer reduction can be combined with other agronomic measures to reduce the loss rate and improve the residual rate of topdressing or further improve the utilization rate of topdressing represents a future research direction. Additionally, we should clearly state that the implications of our results were limited because the results were based on a single year of data from a single site. In future studies, we will continue to carry out tests to verify the applicability in different plots and environments.

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