Plant Soil
https://doi.org/10.1007/s11104-024-06496-y

RESEARCH ARTICLE

Straw retention and inhibitor application reduce the leaching risk of mineral N in no-tillage systems of Northeast China

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Received: 10 September 2023 / Accepted: 10 January 2024

Abstract

Purpose To clarify the effects of maize straw retention combined with reduced fertilization and urease/nitrification inhibitors on the accumulation and leaching potential of mineral N in the deep soil profile of no-tillage agroecosystem.

Methods A ^{15}N-tracing micro-plot experiment was conducted with four treatments (**NPK**, traditional NPK fertilization; **NPKS**, NPK with maize straw retention; **RNPKS**, NPKS with 20% fertilizer-N reduction; and **RNPKSI**, RNPKS with inhibitors application) in the Mollisol of Northeast China. We analyzed fertilizer-N transformation dynamics in different soil N pools, quantified the fertilizer N use efficiency in crops, and evaluated fertilizer-derived nitrate leaching losses throughout the complete maize growing period.

Results Our analyses revealed that, compared to the NPK treatment, NPKS, RNPKS, and RNPKSI remarkably reduced the accumulation of urea-derived mineral-N during maize seedling stage by enhancing the transformation of urea-N into fixed NH_4^+-N and organic-N pools, both of which could be quickly released for maize uptake following the extension of crop growth periods. At the maize ripening stage, soil NO_3^--N and ^{15}N-labeled urea-derived NO_3^--N, which migrated vertically to a depth of 80–100 cm, were significantly reduced by treatments of RNPKS and RNPKSI without minimizing crop yields when compared with NPK.

Responsible Editor: Jorge Durán.

Lei Yuan and Yanyu Hu contributed equally to this study.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11104-024-06496-y.

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Conclusion Our results suggest that combining maize straw retention with reduced fertilization and the application of urease/nitrification inhibitors can be efficient management practices for lowering urea N leaching risk, improving N use efficiency, and maintaining or even increasing crop yields by enhancing soil N retention and supply in the croplands of Northeast China.

Keywords ^{15}N labeling · Mineral N accumulation · Leaching risk · Long-term no-tillage · Straw retention

Introduction

Global food security issues greatly increase the use of nitrogen (N) fertilizers, resulting in increased losses of active N forms (available NH_4^+-N and NO_3^--N) to the environment and leading to adverse ecological consequences (Galloway et al. 2008; Quan et al. 2016). While mineral N provides extractable N for crop uptake, excessive N application can lead to significant N losses in soil and water systems, primarily via soil mineral N runoff and leaching following fertilizer application (Ma et al. 2022). Thus, soil mineral N becomes the main N loss pathway in agricultural soils (Martens and Bremner 1989), potentially reducing agricultural productivity and posing a severe threat to agroecosystem sustainability in the absence of optimized management strategies (Zhang et al. 2015). Generally, an appropriate concentration of available mineral N is required for crop uptake and subsequent food production, however, excessive accumulation in the soil, particularly in the deep soil profile, heightens the risk of N leaching and environmental pollution in soil and water systems (Zhu and Chen 2002). Therefore, the application of optimized agricultural management practices is urgently needed to help mitigate excessive mineral N accumulation in the soil profile, which is an important pathway for soil N retention and reduce N leaching to water, thus improving the quantity and quality of agricultural production in an environmentally friendly ecosystem approach to sustainable agriculture (Deng et al. 2022; Elrys et al. 2022).

Conservation management practices, including minimum or no-tillage (NT) without soil disturbances, combined with crop residue retention, fertilization reduction, or urease/nitrification inhibitor application, have been proposed as potential sustainable management strategies for low-input agricultural systems (Kassam et al. 2019; Gu et al. 2023). Specifically, NT combined with straw retention offers numerous advantages, including reducing soil erosion (Blanco-Canqui and Ruis 2018), improving soil structure, water retention, and infiltration (Zhao et al. 2017), promoting microbial abundance and activity (Jiang et al. 2018), and enhancing soil carbon (C) sequestration (Li et al. 2023) in comparison with traditional ridge tillage (RT). Moreover, NT with straw retention can enhance available nutrient levels for crop growth by reducing N loss in runoff and leaching, thereby promoting crop yields (Soane et al. 2012). With reduced soil disturbance and increased organic C and N, NT with straw retention could decrease soil organic N mineralization while simultaneously enhancing microbial mineral N immobilization. This could lead to reduced soil mineral N accumulation and lower N leaching potential compared to RT (Yuan et al. 2022). However, under conservation management, soil mineral N, especially extractable NO_3^--N, may leach to the deeper soil profile due to the increase of soil moisture and water infiltration in the NT agroecosystem (Oorts et al. 2007). Thus, urease/nitrification inhibitors, such as N-(n-butyl) thiophosphoric triamide (NBPT) and 3,4-Dimethyl-1H-pyrazolium dihydrogen phosphate (DMPP), are often recommended to slow urea hydrolysis and the subsequent microbial autotrophic oxidation of NH_4^+-N to NO_3^--N (Afshar et al. 2018; Klimczyk et al. 2021), potentially resulting in a significant decrease in N leaching losses as NO_3^--N to the deeper soil layers (Turner et al. 2010; Soares et al. 2012). Therefore, despite the advantages of NT combined with straw retention in agroecosystems with high N leaching potential, questions remain regarding the long-term effects of combining NT with straw retention, reduced fertilization, and inhibitor application on the vertical transport of mineral N, particularly NO_3^--N, in the deep soil profile.

The black soil (Mollisol) region is a major agricultural production base in Northeast China, where the yields of maize, as key cereal crop, accounts for two-thirds of local food products and one-quarter of national maize production (Wang et al. 2021). However, traditional intensive cultivation practices, such as the removal and burning of crop residues, have led to significant organic C loss in the topsoil of this region (Zhao et al. 2018), posing a significant threat to soil health and food production in China. Therefore, applying optimal management practices is crucial for promoting soil C sequestration, maintaining or increasing crop productivity, and reducing N loss in NT agroecosystems. Nevertheless, the dynamics of NH_4^+-N and NO_3^--N accumulation and leaching risk in responses to maize straw retention associated with fertilization practices and inhibitors application in long-term NT cropping systems of Northeast China have not been fully elucidated. We used a ^{15}N tracer technique to evaluate the effects of maize straw retention, reduced fertilization, and urease/nitrification inhibitor application on the accumulation, vertical transport, and leaching risk of mineral N in a long-term (9-year) NT agroecosystem with continuous maize cropping in Northeast China. We hypothesized that 1) compared with traditional NPK, maize straw retention (NPKS) would significantly reduce the accumulation of fertilizer-derived NO_3^--N and its contribution to the seasonally applied fertilizer N and mineral N pool, particularly in deeper soil layers; 2) compared to NPKS, reduced fertilization and urease/nitrification inhibitor application would further diminish the accumulation and transport of both available NH_4^+-N and NO_3^--N to deeper soil layers.

Materials and methods

Study site

This investigation was conducted in Siping, Jilin, China (43°19’N, 124°14’E), where the mean annual temperature (MAT) and precipitation (MAP) are 6.9 °C and 614 mm, respectively (Zhu et al. 2023), and the soil was classified as Mollisol according to the USDA Soil Taxonomy (Soil Survey Staff 2014). The basic characteristics of the topsoil (0–20 cm), collected before the adoption of no-tillage practice in 2007 are listed in Table 1. Continuous spring maize, with a planting density of 60,000 ha^{-1}, has been the dominant crop cultivated in this area.

Field plots

An *in-situ* conservation management experiment, characterized by a randomized block design, was established in 2007. Each plot measured 8.7 m × 30 m and included four replicates. Three treatments were applied in no-tillage systems: (1) NPK, traditional NPK application with 0% maize straw retention as a control, (2) NPKS, NPK application with 100% (7.5 t ha^{-1}) maize straw retention, and (3) RNPKS, a reduction of 20% NPK application with 100% (7.5 t ha^{-1}) maize straw retention. The no-tillage treatments were left undisturbed until the spring sowing of maize, during which maize straw was evenly distributed on the surface as mulch after each annual fall harvest. Table S1 provides the basic properties (0–20 cm) under the different management practices after 9 consecutive years prior to ^{15}N-labeling. In 2016, a ^{15}N-labeled micro-plot field experiment was established within the 12 aforementioned plots to investigate the accumulation and vertical transport of N from fertilizers in the deep soil profile. For each treatment, a 2 m × 2 m micro-plot was created, enclosed by PVC fencing, which was inserted 60 cm into the ground and extended 10 cm above ground. Four additional micro-plots of the same size were established in each RNPKS block for the application of NBPT and DMPP (RNPKSI), resulting in four ^{15}N-tracing treatments across 16 micro-plots in this study.

On 10 May 2016, the following synthetic fertilizers were applied according to local practices: urea (240 kg N ha^{-1}), concentrated super-phosphate (110 kg P_2O_5

Table 1 Basic properties of the tested soil (0–20 cm) prior to no-tillage management in 2007

Chemical properties				Physical properties			
Total (g kg^{-1})		Available (mg kg^{-1})		Texture (%)		Clay Mineral (< 2 μm, %)	
SOC	11.3	Alkaline N	90.1	Sand	28.5	Chlorite	30.0
TN	1.2	Available P	6.9	Silt	38.6	Montmorillonite	24.2
TP	0.38	Available K	143.6	Clay	32.9	Illite	14.5
TK	24.3					Vermiculite	2.7
						Kaolinite	23.3
						Quartz	5.0
						Feldspar	0.3

Note: Sand: 2–0.05 mm; Silt: 0.05–0.002 mm; Clay: < 0.002 mm

ha^{-1}), and KCl (110 kg K_2O ha^{-1}). Simultaneously, ^{15}N-labeled urea with a 9.80% abundance was used in the above-mentioned micro-plots, in which NBPT and DMPP, with 1% of the applied urea, served as basal fertilizers. Twenty-four maize plants, spaced 65 cm apart, were planted in each of the 16 micro-plots, maintaining a crop density of 60,000 ha^{-1}.

Sample collection

Soil cores were collected from random locations using a stainless-steel soil auger (2 cm diameter) at depths of 0–40 cm (with 20 cm intervals) at the maize seedling (27 May 2016) and tasseling (20 July 2016) stage, as well as at 0–100 cm (with 20 cm intervals) at the ripening stage (13 October 2016). Five core samples were combined into a composite sample, which was subsequently sieved (2-mm mesh) and homogenized. Soil characteristics were analyzed following the Soil Agro-Chemical Analysis Procedures proposed by Lu (2000). Soil total nitrogen (TN) was determined using the combustion method using an Elemental Analyzer (Elementar vario MACRO cube, Germany), and fixed NH_4^+-N was measured using the KOBr-KOH method. Exchangeable concentrations of mineral N, including NH_4^+-N and NO_3^--N, were measured after extraction with 2 M potassium chloride, and the filtrate was analyzed using a continuous chemical analyzer (SmartChem200, Roma, Italy). The ^{15}N abundances of TN, fixed NH_4^+-N, and exchangeable mineral N were determined using a stable isotope-ratio mass spectrometer (Thermo Finnigan Delta plus XP, USA). At the same time, all maize plants at the ripening stage from each micro-plot were air-dried, weighed and analyzed for TN and associated ^{15}N abundance.

Calculations and analysis

Labeled urea-derived NH_4^+-N ($N_{F\text{-}NH4}$), NO_3^--N ($N_{F\text{-}NO3}$), mineral N ($N_{F\text{-}m}$), fixed NH_4^+-N ($N_{F\text{-}f}$), organic N ($N_{F\text{-}o}$) and total residual N ($N_{F\text{-}s}$) were estimated as follows (Lu et al. 2018):

$$N_{F-NH4,}N_{F-NO3,}N_{F-f}\mathrm{or}N_{F-s} = N_x \times \frac{b-c}{a-c} \tag{1}$$

$$N_{F-m} = N_{F-NH4} + N_{F-NO3} \tag{2}$$

$$N_{F-o} = N_{F-s} - \left(N_{F-m} + N_{F-f}\right) \tag{3}$$

where N_x is the content of soil total NH_4^+-N, NO_3^--N, fixed NH_4^+-N and TN (kg N ha^{-1}); a represents the ^{15}N abundance of applied urea (9.80%); b is the ^{15}N abundance of extractable NH_4^+-N, NO_3^--N, fixed NH_4^+-N or TN (%); and c represents the ^{15}N natural abundance of 0.366%.

The renewal of $N_{F\text{-}NH4}$ and $N_{F\text{-}NO3}$ to total soil mineral N ($N_{F\text{-}NH4}$-P_m, or $N_{F\text{-}NO3}$-P_m, %), the transformation of applied urea N to specific soil N pools ($N_{F\text{-}m}$-P_f, $N_{F\text{-}f}$-P_f or $N_{F\text{-}o}$-P_f, %) and fertilizer nitrogen use efficiency (NUE, %) were calculated as follows:

$$N_{F-NH4-}P_{m,}\mathrm{or}N_{F-NO3-}P_m = \frac{N_i}{N_m} \times 100 \tag{4}$$

$$N_{F-m-}P_{f,}N_{F-f-}P_f\mathrm{or}N_{F-o-}P_f = \frac{N_j}{N_{fertilizer}} \times 100 \tag{5}$$

$$NUE = \frac{N_c \times (d-c)}{N_{fertilizer \times (a-c)}} \times 100 \tag{6}$$

where N_i is the content of NH_4^+-N ($N_{F\text{-}NH4}$) or NO_3^--N ($N_{F\text{-}NO3}$) derived from ^{15}N- labeled urea (kg N ha^{-1}); N_m is the total available NH_4^+-N (N_{NH4}) and NO_3^--N (N_{NO3}) in the studied Mollisol (kg N ha^{-1}); N_j is the mineral N ($N_{F\text{-}m}$), fixed NH_4^+-N ($N_{F\text{-}f}$) and organic N ($N_{F\text{-}o}$) derived from ^{15}N-labeled urea (kg N ha^{-1}); $N_{fertilizer}$ is applied urea N (240 kg N ha^{-1}); N_c is the TN content in maize plant (kg N ha^{-1}); and d is the ^{15}N abundance of TN in maize plants (%).

We used a linear mixed-effect model (R package 'nlme') to investigate the main individual and interactive effects of the management practices on the accumulation and vertical transport of extractable mineral N in the studied Mollisol, with the soil sampling date and depth used as two fixed factors, and the block as a random factor. A three-way analysis of variance (ANOVA) was conducted to assess the significance of the different fertilization treatments, sampling dates, and depths, as well as their interactions. Differences at $P < 0.05$ among the fertilization treatments were considered to be statistically significant.

Results

Renewal of fertilizer-derived NH_4^+-N and NO_3^--N in total soil mineral N across different maize growth stages

Soil NH_4^+-N (N_{NH4}), urea-derived NH_4^+-N ($N_{F\text{-}NH4}$) and the proportions of urea-derived NH_4^+-N to total soil mineral N ($N_{F\text{-}NH4}$-P_m) were remarkably affected by the management practices, soil sampling dates and depths, as well as significant interactions among the fixed factors ($P < 0.05$, Fig. 1, Table 2). N_{NH4} and $N_{F\text{-}NH4}$ decreased as the maize growth stage progressed under all the treatments at both soil depths. Compared with NPK, NPKS, and RNPKS, urease/nitrification inhibitors in RNPKSI treatment significantly increased the N_{NH4} and $N_{F\text{-}NH4}$ at both depths during maize seedling stage and those at the 20–40 cm soil layer during maize tasseling stage. However, NPKS, RNPKS, and RNPKSI significantly decreased N_{NH4} and $N_{F\text{-}NH4}$ at both soil depths when compared to NPK during the ripening stage of maize (Fig. 1A, B, D, E). Across the three maize growing stages, the proportions of urea-derived NH_4^+-N in soil total mineral N ($N_{F\text{-}NH4}$-P_m) for all treatments decreased over the growth period, from an average of 3.5% to

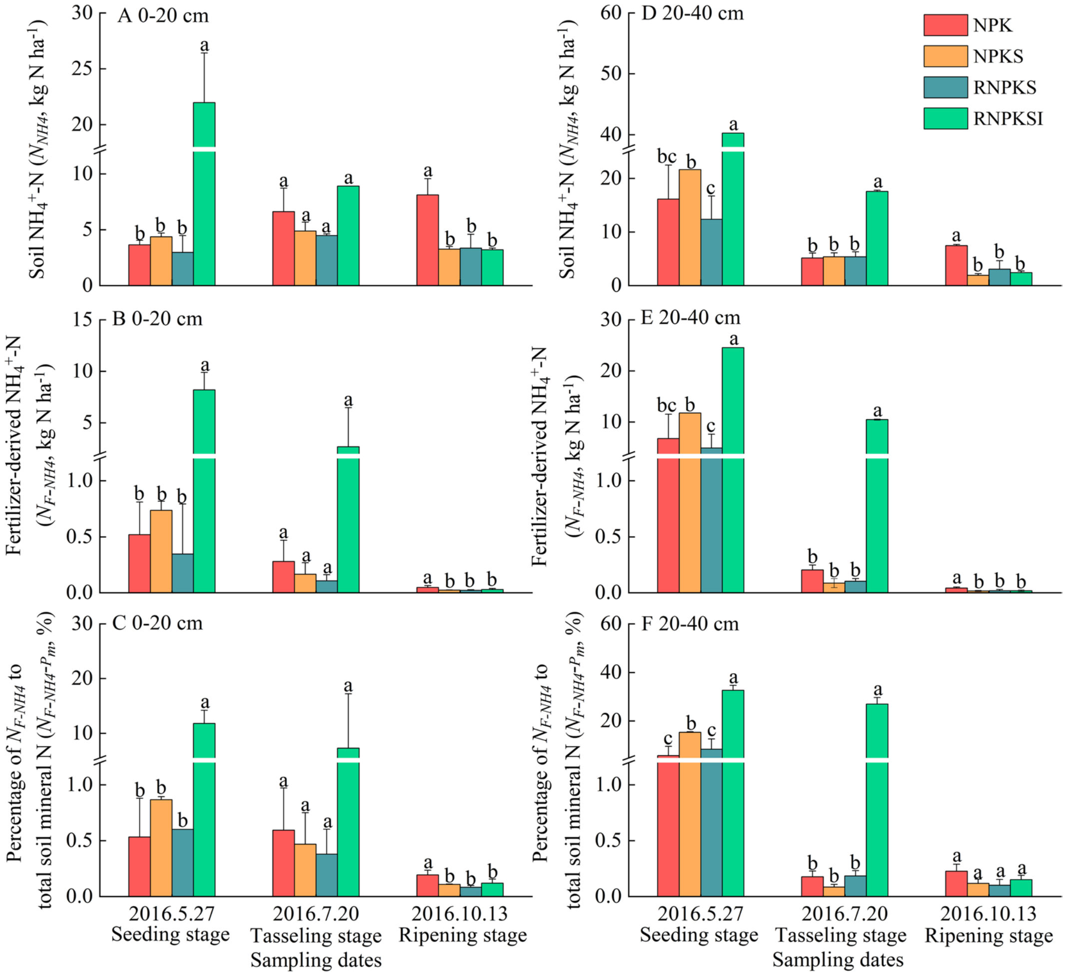

Fig. 1 Effects of varied management practices on soil NH_4^+-N (N_{NH4}, kg N ha^{-1}), urea-derived NH_4^+-N ($N_{F\text{-}NH4}$, kg N ha^{-1}) and the renewal of urea-derived NH_4^+-N to soil total mineral N at the 0–20 cm and 20–40 cm soil layers among maize growing stages. NPK: traditional NPK fertilization; NPKS: NPK with maize straw retention; RNPKS: 20% reduced NPK with maize straw retention; RNPKSI: RNPKS with urease/nitrification inhibitors. Different letters indicate significant differences at $\alpha = 0.05$. Error bars indicate standard deviations ($n = 4$)

Table 2 Results of linear mixed effect model testing of the effects of management treatment (Tr), sampling time (Ti), soil depth (D), and their interactions on the contents and percentages of total mineral N and urea-derived mineral N

	P-values						
	Tr	Ti	D	Tr × Ti	Tr × D	Ti × D	Tr × Ti × D
N_{NH4}	< 0.001	< 0.001	< 0.001	< 0.001	ns	< 0.001	ns
N_{NO3}	< 0.001	< 0.001	0.040	< 0.001	0.002	ns	ns
$N_{F\text{-}NH4}$	< 0.001	< 0.001	< 0.001	< 0.001	0.010	< 0.001	ns
$N_{F\text{-}NO3}$	< 0.001	< 0.001	0.003	< 0.001	0.025	ns	ns
$N_{F\text{-}NH4}$-P_m	< 0.001	< 0.001	< 0.001	< 0.001	0.001	< 0.001	ns
$N_{F\text{-}NO3}$-P_m	< 0.001	< 0.001	0.015	0.006	ns	0.042	ns

ns represents not significant

N_{NH4}: Total NH_4^+-N; N_{NO3}: Total NO_3^--N; $N_{F\text{-}NH4}$: labeled urea-derived NH_4^+-N; $N_{F\text{-}NO3}$: labeled urea-derived NO_3^--N; $N_{F\text{-}NH4}$-P_m: proportions of labeled urea-derived NH_4^+-N to total mineral N; $N_{F\text{-}NO3}$-P_m: proportions of labeled urea-derived NO_3^--N to total mineral N

0.1% at the 0–20 cm depth and from 15.5% to 0.1% at the 20–40 cm depth. In comparison with NPK, NPKS, and RNPKS, urease/nitrification inhibitors in RNPKSI treatment significantly increased $N_{F\text{-}NH4}$-P_m at both depths during the maize seedling stage and at the 20–40 cm soil layer during maize tasseling stages (Fig. 1C, F).

In contrast to N_{NH4} and $N_{F\text{-}NH4}$, soil NO_3^--N (N_{NO3}) and urea-derived NO_3^--N ($N_{F\text{-}NO3}$) significantly increased in all four treatments at both soil depths and during all three maize growth stages ($P < 0.05$, Fig. 2). At the depth of 0–20 cm, soil N_{NO3} and $N_{F\text{-}NO3}$ decreased significantly with the extension of maize growth stage under all treatments (Fig. 2A, B). However, at the depth of 20–40 cm, soil N_{NO3} and $N_{F\text{-}NO3}$ in all the treatments were greatest during the tasseling stage of maize (Fig. 2D, E). Compared with NPK, both N_{NO3} and $N_{F\text{-}NO3}$ in the NPKS treatment significantly decreased at both depths during the maize seedling stage and at the 0–20 cm soil layer during the tasseling stage of maize. Compared to NPKS, soil N_{NO3} and $N_{F\text{-}NO3}$ in the RNPKS and RNPKSI treatments also reduced significantly at both depths during the seedling stage of maize and at 20–40 cm soil layer during the tasseling stage of maize. The average proportions of urea-derived NO_3^--N to total mineral N ($N_{F\text{-}NO3}$-P_m) during three maize growing stages for all treatments were 49.6%, 17.0% and 4.7% in the 0–20 cm soil layer, and the corresponding percentages were 35.8%, 51.3%, and 5.1%, respectively, at a depth of 20–40 cm (Fig. 2C, F). RNPKS and/or RNPKSI significantly reduced $N_{F\text{-}NO3}$-P_m at both soil depths during the maize seedling and tasseling stages when compared with NPK plot.

Both management treatments and/or soil depth significantly affected the vertical transformation of soil mineral N and ^{15}N-labelled urea-derived mineral N in the 0–100 cm soil layer during the maize ripening stage ($P < 0.05$, Fig. 3). In comparison with NPK, NPKS, RNPKS and RNPKSI exhibited a significant decrease in N_{NH4} at depths of 0–100 cm soil layer (Fig. 3A). Similar to N_{NH4}, urea-derived $N_{F\text{-}NH4}$ in NPKS, RNPKS, and RNPKSI were significantly lower than NPK in the 0–100 cm soil profile except for the 40–60 cm soil layer (Fig. 3B). NPKS, RNPKS and RNPKSI obviously reduced soil $N_{F\text{-}NH4}$-P_m in the 0–100 cm soil layer in comparison to NPK plot (Fig. 3C). Generally, soil N_{NO3} was significantly greater than N_{NH4} in the 0–100 cm soil layer. Across all the treatments, soil N_{NO3} decreased gradually from 0–20 cm to 60–80 cm soil depth, but rapidly increased in the 80–100 cm soil profile. Specifically, soil N_{NO3} in RNPKSI treatment was markedly lower than that in the other three treatments at depths of 40–80 cm and that in the NPK and NPKS treatments at the depth of 80–100 cm (Fig. 3D). Urea-derived $N_{F\text{-}NO3}$, which mainly accumulated at the depth of 80–100 cm, was greater than $N_{F\text{-}NH4}$, and RNPKS and RNPKSI treatments caused significant decreases in the $N_{F\text{-}NO3}$ at depths of 60–80 cm and 80–100 cm, respectively, in comparison with the NPK and NPKS treatments (Fig. 3E). Soil $N_{F\text{-}NO3}$-P_m were greatest in the 80–100 cm soil than other depths, and significantly lower in the treatments of RNPKS and RNPKSI than NPK and NPKS treatments at the depth of 80–100 cm soil layer (Fig. 3F).

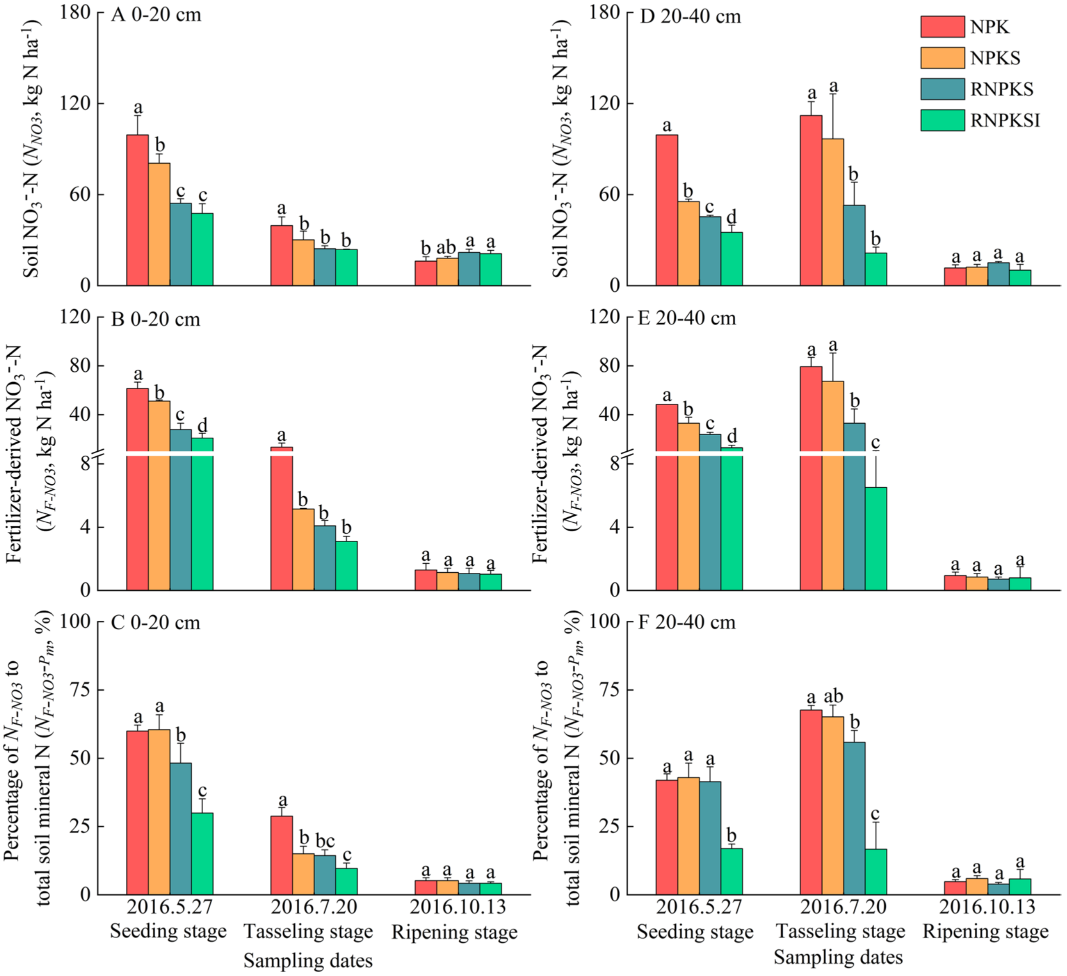

Fig. 2 Effects of varied management practices on soil NO_3^--N (N_{NO3}, kg N ha^{-1}), urea-derived NO_3^--N ($N_{F\text{-}NO3}$, kg N ha^{-1}) and the renewal of urea-derived NO_3^--N to soil total mineral N at the 0–20 cm and 20–40 cm soil layers among maize growing stages. Different letters indicate significant differences at $\alpha = 0.05$. Error bars indicate standard deviations (n = 4)

The transformation dynamics and utilization of ^{15}N-labeled Urea-N among different management practices

The transformation dynamics of applied urea-derived N into specific soil N pools were significantly influenced by the adoption of various management practices (Fig. 4). During the maize seeding stage, ^{15}N-labeled urea-N was primarily transformed into mineral-N pool (38.3%), followed by fixed NH_4^+-N (36.5%) and organic-N (18.5%) in the 0–40 cm soil layer. NPKS, RNPKS and RNPKSI treatments significantly increased the conversion of applied urea-N into fixed NH_4^+-N by an average of 51.9%. The RNPKS treatment also led to a 56.2% increase in urea-N conversion into organic-N, while the corresponding conversion into mineral-N decreased by an average of 28.7% compared to the NPK treatment. As the crop growth period extended, the average proportions of fertilizer-derived N converted into mineral-N and fixed NH_4^+-N both decreased to less than 2% at the maize ripening stage, with the majority (14.9%) transforming into the organic-N pool. In the RNPKSI treatment, this percentage was significantly higher by 15.2% compared to the NPK plot. After a complete maize growth stage, an average of 51.4% of the applied urea-N was recovered from the crop.

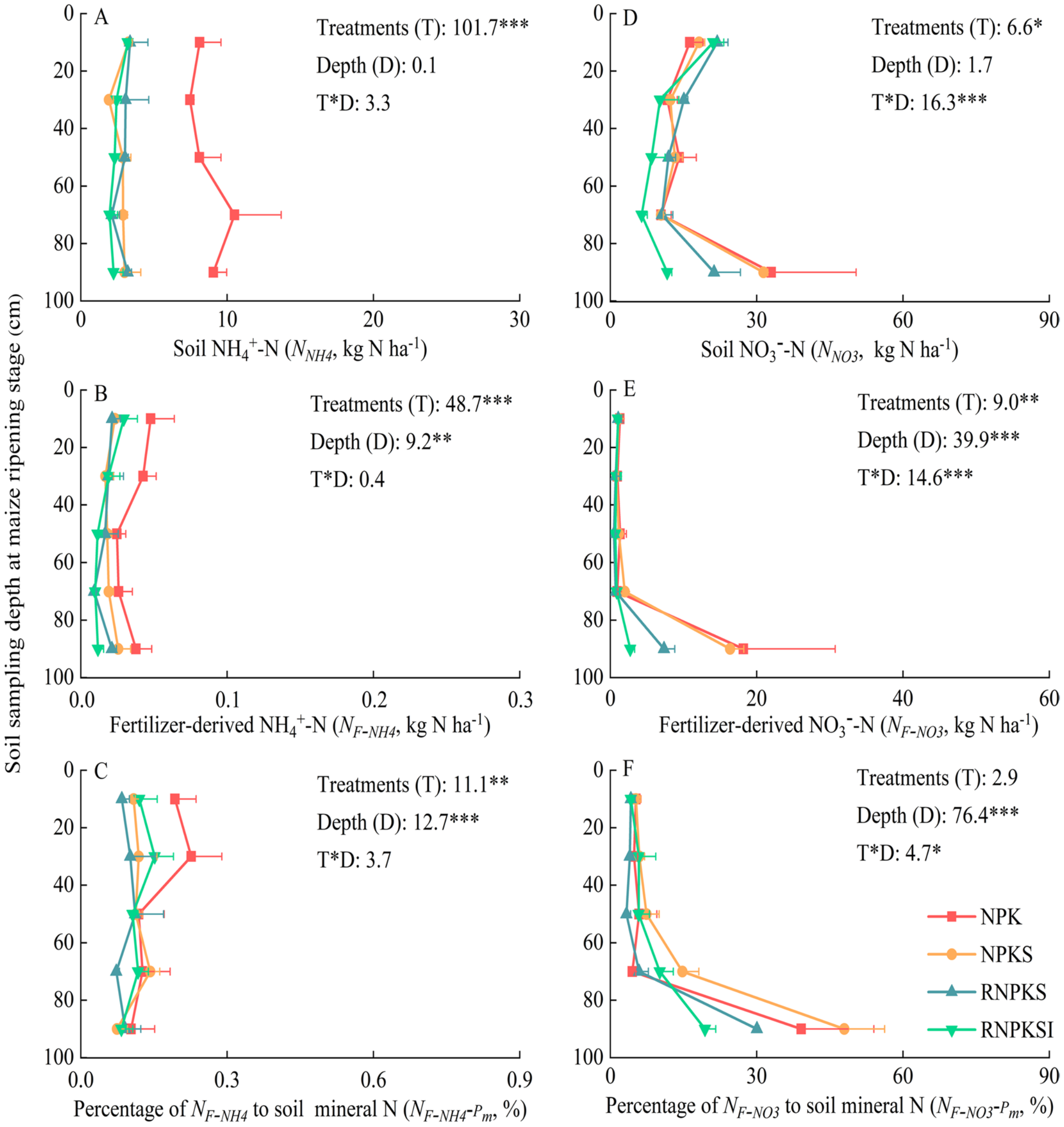

Fig. 3 Effects of varied management practices on vertical transfer of exchangeable mineral N at 0–100 cm soil layers in the maize ripening stages. Different letters indicate significant differences at α = 0.05. Error bars indicate standard deviations (n = 4)

The NPKS, RNPKS, and RNPKSI treatments notably enhanced fertilizer N use efficiency by 14.7%, 19.3%, and 14.4%, respectively, compared to the NPK plot (Fig. 5A). In addition, crop yields under different management practices ranged from 1.26 to 1.42 t ha^{-1} in the studied Mollisol. Compared to the conventional NPK treatment, the application of NPKS, RNPKS, and RNPKSI led to significant increases in crop yield by 9.9%, 11.3%, and 12.8%, respectively (Fig. 5B).

Discussion

Effects of no-tillage with straw retention on the leaching dynamics of fertilizer-derived mineral-N

A key prerequisite for selecting effective NT with straw retention practices is ensuring that they lead to a reduction in the potential for reactive N leaching, particularly for extractable NO$_3^-$-N over NH$_4^+$-N, to prevent environmental pollution. Both organic and

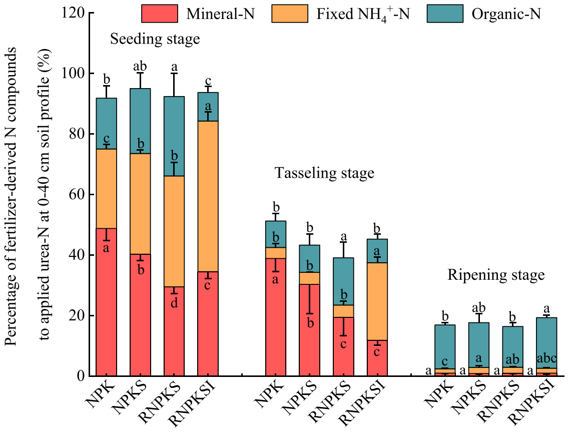

Fig. 4 Effects of varied management practices on the transformation dynamics of labeled urea-N in 0–40 cm soil layers among maize growing stages. Different letters indicate significant differences at α = 0.05. Error bars indicate standard deviations (n = 4)

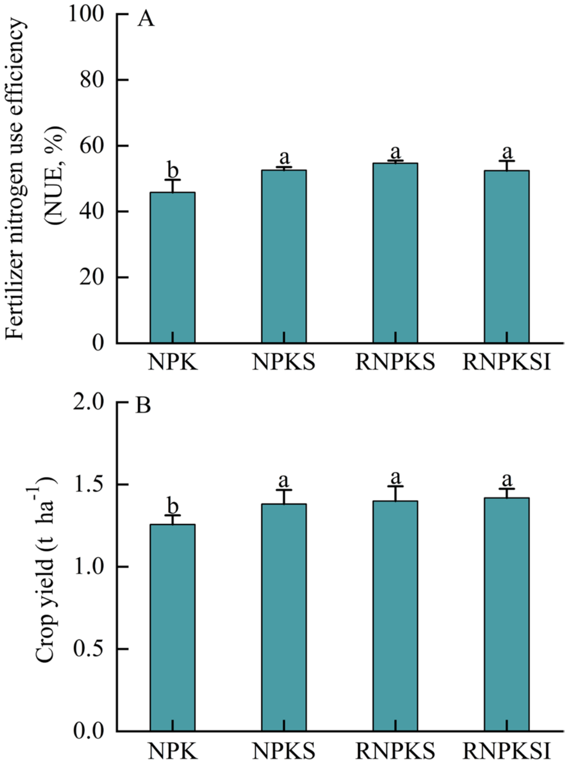

Fig. 5 Effects of varied management practices on fertilizer N use efficiency and crop yield in the maize ripening stages. Different letters indicate significant differences at α = 0.05. Error bars indicate standard deviations (n = 4)

inorganic N serve as substrates for microbial and plant uptake, indicating that the transformation of fertilizer N following application is predominantly controlled by biological processes (Geisseler et al. 2010). With traditional N application rates, NH_4^+-N and NO_3^--N from applied fertilizer can exceed the microbial immobilization capacity, leading to a significant loss potential of mineral N, particularly soil NO_3^--N, to deeper soil layers (Dai et al. 2021; Zhang et al. 2021). Our results showed that the proportions of urea-derived NO_3^--N in soil mineral N ranged from 41–43% in the 0–20 cm and 20–40 cm soil layers during maize seedling and tasseling stages (Fig. 2), suggesting the high contribution potential of seasonally applied fertilizer N to N leaching risk of NO_3^--N in the deep soil layer. Furthermore, considering the minimal N demand during the maize seedling stage and the use of labeled urea N as basal fertilizer in the 10–15 cm soil layer, the accumulated soil mineral N, particularly NO_3^--N in the 20–40 cm layer, was comparable to or even exceeded that in the 0–20 cm layer. This indicates the rapid vertical migration of applied urea N as NO_3^--N into the deeper soil profile.

Additionally, the rapid migration of fertilizer N into deeper soil layers reduced the availability of fertilizer-derived mineral N in the topsoil (Fig. 3), requiring the amendment of organic substrates, such as maize straw retention, to the topsoil to compensate for the lack of fertilizer-derived nutrients. Several studies have shown that reducing the excessive accumulation of mineral N in the soil through straw retention is crucial for promoting N use efficiency and minimizing N loss (Xu et al. 2005; Chaves et al. 2006; Quan et al. 2016). Our results suggest that maize straw retention significantly reduced the conversion of applied urea N to soil mineral N pools, particularly extractable NO_3^--N, at both soil depths during the maize seeding and tasseling stages, aligning with findings from our previous wheat-buckwheat-wheat ^{15}N-labeled pot experiment (Lu et al. 2010). It has been shown that returning rice straw or cereal straw to the soil can reduce the levels of soil mineral N (Cheng et al. 2017), likely because the quality and quantity of exogenous organic C from straw retention enhances NO_3^--N immobilization by soil microorganisms (Yuan et al. 2022). A study by Chen et al. (2022) was the first to quantify the relationships between the quality and quantity of organic amendments and the soil NO_3^--N immobilization rate, which enabled more accurate predictions of the NO_3^--N immobilization process, aiding in the regulation of soil NO_3^--N content and the development of strategies to mitigate NO_3^--N accumulation.

Regulating the conversion of applied urea N into mineral N pools is crucial for temporarily retaining fertilizer N in the soil, supplying N to crops, and reducing N losses in the form of NO_3^--N. Fertilizer-derived NH_4^+-N and mineral N can be rapidly fixed by clay minerals and immobilized by soil microorganisms, thus forming two vital temporary pools for urea N retention in the soil and for subsequent crop N uptake (Figs. 4 and 5), aligning with the findings proposed by Lu et al. (2018) and Pan et al. (2017). This study indicated that conservation management practices involving NT combined with straw retention can significantly reduce the accumulation and conversion of urea N into mineral N pools, particularly NO_3^--N. This finding suggested that long-term maize straw retention in NT agroecosystems may be a beneficial and practical approach in Northeast China, leading to comparatively lower N loss potentials than traditional management practices.

Effects of reduced fertilization and urease/nitrification inhibitor on the leaching dynamics of fertilizer-derived mineral-N

Excessive fertilization can lead to significant accumulation of N in the soil, exceeding plant uptake limits, primarily as NO_3^--N. This surplus is problematic for N leaching due to the high nitrification potential and relatively low NO_3^--N immobilization rates in agricultural soils (Zhang et al. 2013; Wang et al. 2015). In a 120-day incubation experiment using a ^{15}N tracer technique, we previously found that 87–92% of the applied fertilizer N was rapidly converted to NO_3^--N, while only 2–4% became part of the soil organic matter (Quan et al. 2016), suggesting an urgent need to enhance the immobilization of applied fertilizer N into more stable N pools, thereby reducing NO_3^--N accumulation and subsequent leaching losses (Chen et al. 2021).

Under the influence of urease/nitrification inhibitors, the hydrolysis rate of applied fertilizer N is slowed, and the oxidation of NH_4^+-N to NO_3^--N is inhibited (Barth et al. 2001). This favors the retention of extractable NH_4^+-N in the soil, leading to substantial accumulation of both inorganic and organic N in the 0–20 cm and 20–40 cm soil layers, which are available for microbial immobilization of substrate C and N. Our study also showed that the application of urease/nitrification inhibitors can increase the conversion of fertilizer-derived N to soil-fixed NH_4^+-N. This was largely due to the high clay content (33% of the soil particle size composition, with more than 70% being 2:1 clay minerals, as shown in Table 1) in the studied Mollisol (Cao et al. 2020).

The role of urease/nitrification inhibitors is mainly to slow the urea hydrolysis rate and subsequently nitrification/denitrification processes by prolonging the retention of NH_4^+-N in the soil (Kim et al. 2012). Our study demonstrated that the combination of reduced fertilization and inhibitor application increased the accumulation and transformation of ^{15}N-labeled fertilizer N to NH_4^+-N at the maize seedling stage (Fig. 1). Consequently, in the long-term NT system tested, urease/nitrification inhibitors significantly extended the duration of NH_4^+-N retention in the soil and its rapid absorption by soil particles, thereby reducing the potential for N leaching as NO_3^--N (Gioacchini et al. 2002).

Additionally, our study showed that applying urease/nitrification inhibitors in a long-term NT agroecosystem improved fertilizer N use efficiency by 14.4%, while maintaining crop yields by regulating the conversion of reactive N into more stable N pools (Figs. 4 and 5). The findings of a meta-analysis also suggested that urease inhibitors, nitrification inhibitors, and double inhibitors markedly increased crop utilization and soil retention of applied fertilizer N by an average of 27.4% and 10.4%, respectively, and further reduced N loss by 28.3%, with the double inhibitors exhibiting the greatest inhibitory effect (Sha et al. 2020). Other studies have shown that combining urease/nitrification inhibitors with other management strategies can balance plant nutrient uptake and reduce total N losses through leaching (Thapa et al. 2015) and runoff (Kim et al. 2012), when compared to the application of a single management practice (Afshar et al. 2018). Thus, our study underscores that the combined application of urease and nitrification inhibitors in NT and straw retention agroecosystems could be the most effective management approach for sustainable agriculture in the NT maize cropping systems of Northeast China. While urease/nitrification inhibitor application favors the retention of available NH_4^+-N and decreases the potential for N loss as NO_3^--N from maize seedling to the tasseling stage, urea-derived NH_4^+-N and NO_3^--N are rapidly released from maize tasseling to the ripening stage as the inhibitory effect diminishes. At the ripening stage, both urease/nitrification inhibitors and other tested management practices significantly reduced soil NH_4^+-N and ^{15}N-labelled NH_4^+-N throughout the 0–100 cm soil layer. However, urease/nitrification inhibitors still significantly inhibited soil NO_3^--N and ^{15}N-labeled fertilizer-derived NO_3^--N, which mainly accumulated in the 80–100 cm soil layer (Fig. 3). We thus provided evidence that the application of urease/nitrification inhibitors with reduced fertilization could be the optimum management practice for reducing N inputs and potentially controlling the environmental pollution throughout the maize growth period in maize cropping systems with long-term NT and straw retention practices.

Conclusions

Our results indicated that urea-derived NO_3^--N primarily accumulated in the 80–100 cm soil layer after the complete maize growing season, suggesting a high risk of NO_3^--N leaching in the croplands of Northeast China. In addition, a high proportion of urea-derived NO_3^--N to total soil mineral N was observed across various management practice agroecosystems, indicating that reducing soil mineral N leaching potential hinges on regulating the internal transformation dynamics of urea-N. Compared to traditional NPK treatment, maize straw retention, reduced fertilization, and urease/nitrification inhibitor application effectively enhanced soil N retention and supply by promoting the conversion of fertilizer N into fixed NH_4^+-N and the organic-N pool, thereby reducing the accumulation of urea-derived NO_3^--N in the deeper soil layers. Furthermore, during the maize ripening stage, all optimized management strategies improved fertilizer N use efficiency while increasing crop yields in the no-tillage agroecosystem. Therefore, we provide evidence that conservation practices involving maize straw retention, reduced fertilization, and urease/nitrification inhibitor application could be effective and practical in Northeast China. These practices aim to balance the potential for N leaching with crop uptake, offering an alternative to traditional soil management strategies.

Acknowledgements We thank the editor Jorge Durán and two anonymous reviewers for valuable contributions to the manuscript. This research was supported by the National Key R&D Program of China (grant numbers 2021YFD1500100, 2022YFD1500305, 2022YFD1500302), the National Natural Science Foundation of China (grant number 42177005 and 32201373), the Strategic Priority Research Program of the Chinese Academy of Sciences (grant number XDA28090400), the Science and Technology Program of Shenyang (22-317-2-01), Innovation team for research, development and application of conservation tillage in Liaoning Province (XLYC2008015), the National Key Technology Support Program for Foreign Experts (ZCNC2022001L), the Postdoctoral Science Foundation of China (2022M713295), and the Special Research Assistant Project of Chinese Academy of Sciences (2022000137).

Author contributions Lei Yuan: Investigation, Data Curation, Writing-Review & Editing. Yanyu Hu: Writing-Original Draft Preparation, Funding acquisition. Miaoyin Yang: Methodology, Software. Ningbo Lei: Validation, Formal analysis. Huaihai Chen: Resources, Writing-Review & Editing. Jian Ma: Methodology, Software. Xin Chen: Resources, Writing-Review & Editing. Hongtu Xie: Investigation, Resources. Hongbo He: Visualization, Supervision, Funding acquisition. Xudong Zhang: Conceptualization, Supervision. Caiyan Lu: Conceptualization, Writing-Review & Editing, Funding acquisition.

Data Availability Data will be made available on request.

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