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ORIGINAL ARTICLE

Different behaviors in nitrogen leaching between soil types following the substitution of synthetic fertilizers by manure

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Abstract The substituting chemical nitrogen (N) fertilizer with organic forms such as livestock manure in agroecosystems improves crop yields while reducing nutrient losses. However, the effects of such management practices in China on different soil types and cropping systems are widely unknown. The present lysimeter study investigated the different chemical fertilizer replacement rates on crop yields and N leaching rates for two spring maize systems on a Luvisol (the typical soil type in the North China Plain) and the other on a Chernozem (the typical soil in the Northeast China Plain). The results achieved herein indicated that manure substitution gave higher crop yields in the Luvisol, except for the treatment with 100% manure N replacement, which showed a slight yield reduction in the short term. For the Chernozem, manure substitution showed a significantly negative effect on crop yield in the short term, but the yield gradually increased and, over longer periods, even surpassed the yields found under baseline conditions. Manure substitution significantly reduced total N (TN) leaching by 57–76% in the Luvisol, while it increased TN leaching by 15–21% in the Chernozem. Results showed that soil properties, including water-holding capacity and clay and organic carbon contents are the main factors that can explain the contrasting effects of manure substitution on N leaching and crop yields for the two selected regions. Such information will enable more bespoke nutrient management

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measures in these two regions achieving agronomic and environmental benefits.

Keywords Maize yield · Manure substitution · N leaching · Non-point source pollution

Introduction

China faces one of the most severe groundwater pollution crises (Han et al. 2016; Ma et al. 2020; Ouyang et al. 2014), with diffuse source pollution from agriculture as the dominant source. More than 70% of the monitored water aquifers are severely contaminated classified at level IV–V, where nitrate-nitrogen (NO_3^-–N) concentrations in groundwater are higher than the World Health Organization's (WHO's) permissible limit of 11.3 mg L^{-1} (MEEPRC 2018). Various studies have shown that nitrogen (N) leaching from farmland associated with excessive N fertilizer applications (organic and inorganic forms) is the primary source of groundwater nitrate, especially in Northern China (Gu et al. 2013; Wang et al. 2018). For example, it is documented that only 33% of the N excreted by livestock is effectively recycled back to the croplands (Bai et al. 2017), and it is estimated that livestock production generates about 3.0×10^9 t of manure each year in China, which continues to grow (Chadwick et al. 2015). To mitigate the agricultural diffuse source pollution, policymakers in China have recently introduced various policies, such as the 'zero fertilizer increase action plan,' the 'livestock manure recycling action plan', and the 'fruit, vegetable, or tea organic fertilizer replacement action plan' (MARAPRC 2015, 2017). These plans aim to reduce the use of organic and inorganic fertilization with agroecosystems, thereby minimizing environmental losses. However, such plans are implemented without considering differences in soil, cropping and climatic conditions across China. This can lead to ad-hoc agronomic and environmental outcomes.

The N leaching from cropland can be partially controlled by implementing better agricultural management practices such as optimization of fertilization rate and timing, land use pattern and cropping system and pattern, and the choice of irrigation system type (Min et al. 2021; Farneselli et al. 2018; Ju and Zhang 2017; Karimi and Akinremi 2018). However, some key factors affecting N leaching, such as inherent soil properties, climate, and hydrological conditions, are not controlled by agricultural management practices (Gao et al. 2016; Lu et al. 2019). Many experimental trials have investigated the effects of manure incorporation on N leaching and crop yields (Guo et al. 2020; Yang et al. 2017a, b). Yet, many uncertainties are identified or remain unsolved in these studies due to variations in field management practices and environmental factors. A global meta-analysis of 141 studies concluded that substituting manures for chemical N fertilizer (with an equivalent N rate) would increase crop yield by 4.4% and significantly reduce N leaching by 28.9% on average (Xia et al. 2017). When the manure N substitution rate was 40%, compared with conventional treatment, total N (TN) leaching was reduced by 43.1% and crop yield was increased by 10.3% (Zhou et al. 2016). However, Gai et al. (2019) identified a high amount of nitrate accumulation in deeper soil due to surplus manure application that could lead to a greater N leaching risk. Moreover, it was found that crop yield could decrease when the manure N substitution rates increase by up to 75% (Xia et al. 2017). Therefore, understanding the N leaching patterns and implementing sources control measures are critical in mitigating groundwater nitrate pollution.

The North China and Northeast China Plains are two important grain-producing regions, where N leaching to groundwater is identified as the main pathway of diffuse point pollution (Wang et al. 2018). The application of livestock manure in agroecosystems to substitute synthetic fertilizer N is recommended to improve crop yield and alleviate environmental impacts. However, previous studies that focused on the effects of manure substitution on N leaching were mostly based on meta-analysis, short-term, and simulation experiments. Very few studies have evaluated N leaching during long term experimental set ups in different soil types with the same crop production systems. It is not well documented how the mitigation potential of manure substitution on N leaching responds to different soil types. Therefore, a thorough understanding of the effects of substitution on crop yield and N leaching based on local conditions is needed. This can be achieved using long-term stable positioning experiments. To fill the gaps mentioned above, N leaching from two long-term typical spring maize systems on a Luvisol (typical soil type in the North China Plain, 2009–2019) and a Chernozem (the typical soil in the Northeast China Plain, 2008–2019), respectively, were investigated. The objectives for the present study were to: (i) identify the effects of manure application with different substitution rates on the crop yield for the Luvisol and Chernozem; (ii) clarify the N leaching risks and the mitigation capacity of manure N replacement for the two typical soil type regions; (iii) provide suggestions for manure application in croplands for the North China Plain and the Northeast China Plain.

Materials and methods

Study areas

The first study area with the Luvisol was located at the "Beijing Changping Soil Quality National Field Science Observation Research Station" (40.22°N, 116.23°E) in the North China Plain. This area has an altitude of 43.5 m, an average annual temperature of 11.5 °C, and annual precipitation of 625 mm. More than 80% of the precipitation in this area occurs from June to October each year. The typical cropping pattern in the North China Plain is double-cropping summer maize with winter wheat. Maize is rainfed with supplemental irrigation in the region. The Luvisol is the major soil type in the region, which produces about 35–40% of maize in China (Kong et al. 2014). The second study area with the Chernozem was located in the Northeast China Plain in "Kemao Street, Gongzhuling City, Jilin Province" (43.53°N, 124.80°E). This area has an altitude of 210 m, an annual average temperature of 5.6 °C, and annual precipitation of 595 mm. About 80% of the precipitation occurs from April to October each year. The Northeast China Plain is an important commodity grain production area in China, with the Chernozem as the major soil type. Maize is mainly rainfed and single cropping in the region.

Experimental design

The long-term field monitoring experiments in both study sites began in 2007. The size of each plot (lysimeter) was 1 m width, 2 m length and 1.2 m depth (Fig. S1). The bottom and sides of the lysimeter were encased with concrete to seal them off from the surrounding soil. A PVC pipe was installed at the bottom of the lysimeter, and the leachate was continuously collected using a water bucket during rainfall or irrigation events. The basic soil characteristics of the 0–0.2 m soil layer at the start of the two trials are presented in Table 1.

Spring maize monoculture production systems were imposed for the Luvisol lysimeter (2009–2019) and the Chernozem lysimeter (2008–2019). Three different fertilization treatments were used: NPK (100% chemical N fertilizer application, 240 kg N ha^{-1} in the Luvisol and 180 kg N ha^{-1} in the Chernozem), MNR_{50} (50% manure N replacement), and MNR_{100} (100% manure N replacement with no chemical fertilizer component). The manure was collected once, homogenized, and applied each year to the surface soil layer (0–0.2 m) before sowing. The total N applications, including chemical fertilizer and manure for two different soil types were 240 kg/ha and 180 kg/ha, respectively, based on the commonly used application rates in the two regions. The detailed fertilization of each N treatment and planting management practices are presented in Table S1 and Table S2.

Crop and leachate collection and analysis

The crop was harvested at maturity, and the maize grains were weighted to determine the yield. The volume of irrigation water was recorded after each irrigation event. The leachate was collected and measured in the buckets, which were emptied and washed after each sampling event to avoid mixing with the next leachate event (Zhang et al. 2015). After the

Table 1 The basic soil characteristics of 0–0.2 m soil layer at the beginning of experiments

Soil type	TN (g kg^{-1})	SOM (g kg^{-1})	BD (g cm^{-3})	NO- 3-N (mg kg^{-1})	NH+4-N (mg kg^{-1})	pH
Luvisol	0.76	7.9	1.32	0.89	0.15	8.3
Chernozem	1.2	29.9	1.39	10.6	11.1	7.5

TN total nitrogen, *SOM* soil organic matter, *BD* bulk density, NO – 3–N nitrate-nitrogen, NH + 4–N ammonium nitrogen water samples were delivered to the laboratory, the potassium persulfate-ultraviolet spectrophotometer (UV-1780, SHIMADZU, China) was used to measure the TN concentration in the leachate samples. Equation (1) and (2) were used to calculate the leaching probability (LP) and leaching loss (Carneiro et al. 2012):

$$LP = {}^{n}/_{R} \times 100\% \tag{1}$$

$$TN(\text{kg ha}^{-1}) = \sum_{i=1}^{n} \frac{TN_{ci} \times V_i}{1 \times 2} \times 0.01 \tag{2}$$

where n is the number of leaching events; R is the number of rainfall events; TN_{ci} is the concentration of TN in the leachate collected each time (mg/L), V_i is the volume of the leachate collected each time (L), while 1 and 2 are lysimeter's length (m) and width (m), respectively.

The formula for calculating the annual TN leaching factor (ANLF) was as follows:

$$ANLF(\%) = \frac{TN_{leach}}{F_N} \times 100\% \tag{3}$$

where TN_{leach} is annual TN leaching losses in the treatment with applied N fertilizer rate (kg/ha), and F_N is the amount of N fertilizer applied (kg), including synthetic fertilizer and manure.

To evaluate the impact of manure substitution on N leaching, the leaching reduction rates (LRR) of two manure substitution treatments were calculated using Eq. 4 as follows:

$$LRR(\%) = \frac{TN_{leach,NPK-TN_{leach,MNR}}}{TN_{leach,NPK}} \times 100\% \tag{4}$$

where $TN_{leach,NPK}$ is the annual TN leaching loss for the chemical fertilizer treatment (kg/ha) for each soil type and $TN_{leach,MNR}$ is the annual TN leaching loss for manure substitution treatments (kg/ha) for each soil type.

In order to investigate the impact of rainfall events on N leaching, the rainfall events during the study period were divided into six classes based on the daily rainfall amount (mm). The six classes of rainfall events include light rain (< 9.9 mm), moderate rain (10.0 ~ 24.9 mm), heavy rain (25.0 ~ 49.9 mm), rainstorm (50.0 ~ 99.9 mm), heavy rainstorm (100.0 ~ 249.9 mm), and extreme rainstorm (≥ 250.0 mm). In addition, the leaching probability of rainfall events with different magnitudes were also calculated.

Statistical analysis

Data were presented as means ± standard errors of the three replicates. Statistical analyses were performed with General Linear Model (GLM) using SPSS software (version 19.0). The significant differences between the treatments were determined using one-way ANOVA with Tukey's test for multiple comparisons at the P-value of 0.05.

Results

Economic yields and N balances of the two regions

The average crop yields from 2008 to 2019 were used to illustrate the differences among the different treatments (Fig. 1). The results of the present study showed that the effects of manure substitution on crop yield were closely related to the manure N substitution rate and the duration of the experiment, while their effects were found to be dramatically different for the two different regions. For cropland with the Luvisol, the results indicated that long-term application of manure results in as higher increase in crop yield for the duration of the experiment. Moreover, the yield increase rate under the MNR_{100} treatment was slightly higher than that of the MNR_{50} treatment. Compared with the yield of the NPK treatment, the yield was significantly higher in the MNR_{50} (10%) and decreased in the MNR_{100} (2%) treatments when the application period was less than five years. The yield was enhanced by 21% (MNR_{50}) and 23% (MNR_{50}), respectively, when the application period was over ten years. For cropland with the Chernozem, the MNR_{50} treatment presented a substantial reduction in crop yield within the short-term (< 5 years) period, while the crop yield showed a considerable increase after long-term manure application (> 10 years). The MNR_{50} treatment increased the yield by 13.1% ($P < 0.05$) after ten years of application. However, the 100% manure N substitution (MNR_{100}) decreased the crop yield within short-term (< 5 years) application, although it was not significant in the medium term (5–10 years). Thus, the MNR_{100}

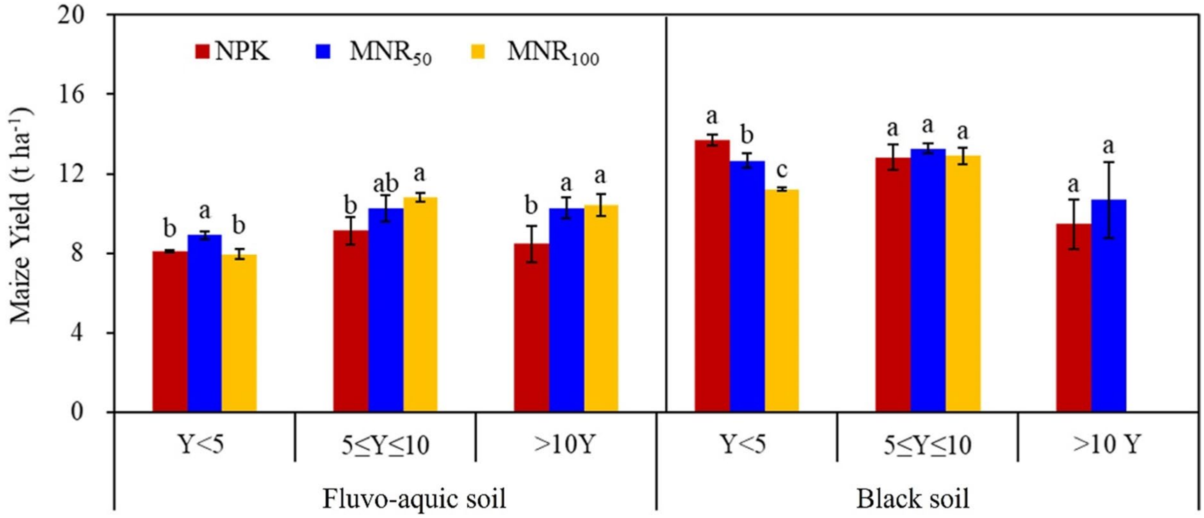

Fig. 1 The average spring maize yields with different treatments during various application years in the Luvisol and Chernozem. NPK: conventional treatment, MNR_{50}: 50% manure N replacement, MNR_{100}: 100% manure N replacement, Y: years. The vertical bars indicate standard deviations, and the different lower case letters indicate significant differences among three treatments at $P < 0.05$

treatment was ended after a 10-year experiment for Chernozem. The maize system's N balances, including N uptake by crop, N leaching losses and unaccounted N during the experiment period in the two regions, were analyzed and presented in Table S2. The results indicated that the manure substitution increased N accumulation in the soil and decreased N uptake by the crop, especially for the 100% manure substitution treatments for the two different regions.

The response of leaching characteristics to rainfall pattern

During the study period, the cumulative rainfall amounts of the six classes of rainfall events contributed about 16%, 30%, 24%, 15% and 15% of the total rainfall amounts in the Luvisol, respectively. While in the Chernozem, the cumulative rainfall amounts of the six classes of rainfall events accounted for 11%, 25%, 39%, 23% and 2% of the total rainfall amounts during the study period, respectively. The characteristics of rainfall, irrigation, and leaching water monitored in the Luvisol and the Chernozem are shown in Figs. 2 and 3. These two figures show that not all rainfall events resulted in leaching and that the leaching water amount generally increased with the magnitude of the rainfall events. The Luvisol's leaching probability of the six classes of rainfall events were calculated as 6%, 17%, 42%, 67%, and 100%, respectively. For the Chernozem, the leaching probability was calculated as 17%, 26%, 45%, 53% and 100% for rainfall events with different magnitudes, respectively. The results showed moderate and heavy rainfall events were the leading causes of leaching losses during the maize growth period. However, light rainfall could also lead to leaching losses because of high precedent soil moisture and previous rainfall amounts (Fig. S2).

Variations of TN concentrations in leachate

The results of this study indicated that there were noticeable inter-annual variations in TN leaching concentrations in the Luvisol (Fig. 4) and the Chernozem (Fig. 5). In the Luvisol, TN leaching concentrations ranged from 3.5 to 112.6 mg L^{-1} with an average of 48.7 mg L^{-1}, for MNR_{50} leaching concentrations ranged from 2.9 to 66.9 mg L^{-1} with an average of 20.7 mg L^{-1}, and for MNR_{100}, it ranged from 1.0 to 73.5 mg L^{-1} with an average of 17.4 mg L^{-1}. In comparison, the NPK, MNR_{50} and MNR_{100} treatments have reduced leaching TN concentrations by 57% (19–78%) and 64% (− 7 to

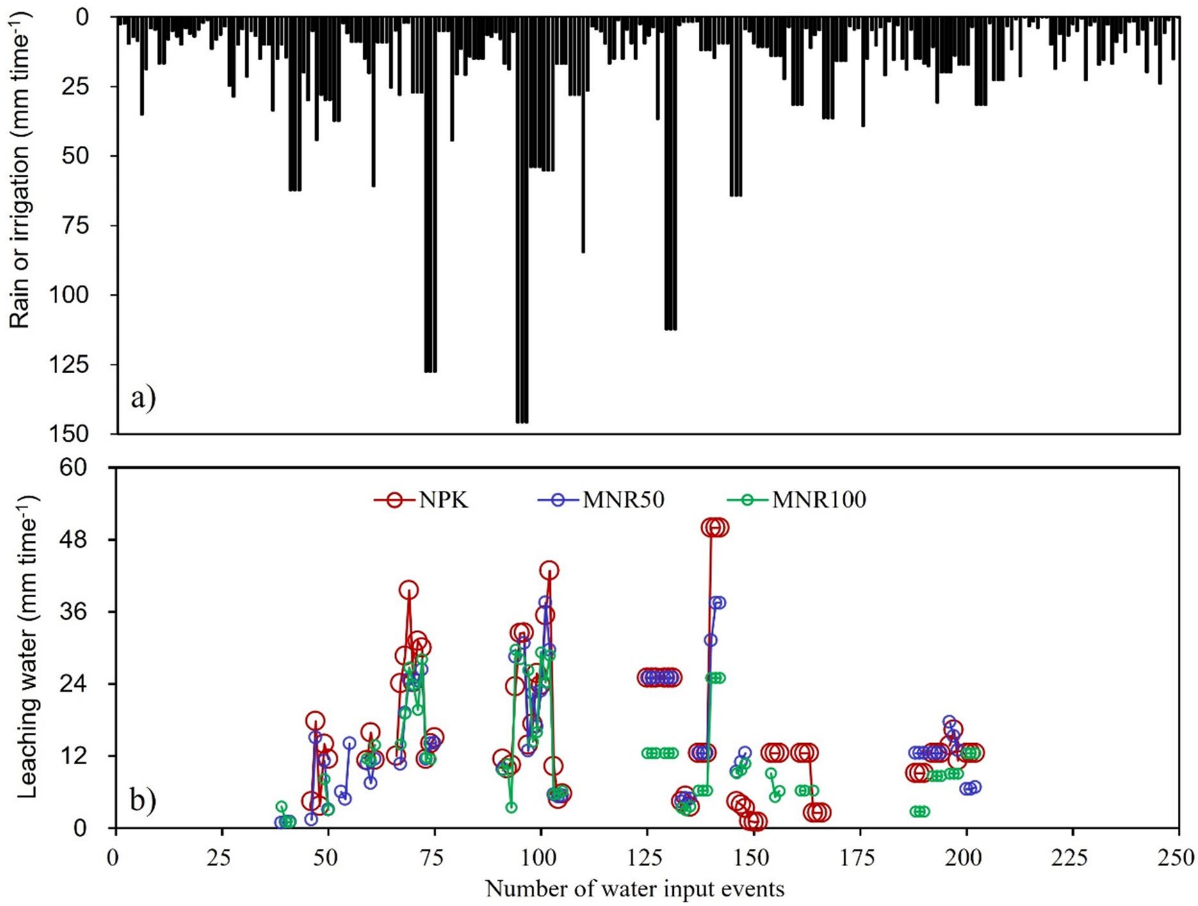

Fig. 2 Characteristics of water inputs including rainfall and irrigation and leaching water in the Luvisol. NPK: conventional treatment; MNR50: 50% manure N replacement; MNR100: 100% manure N replacement

93%), respectively. In the Chernozem, leaching TN concentrations decreased during the first few years of manure substitution, but leaching TN concentrations began to increase as the manure rate increased. Leaching TN concentrations in NPK ranged from 0.6 to 62.0 mg L^{-1} with an average of 13.4 mg L^{-1}, for $MNR_{50,}$ the concentrations ranged from 0.8 to 69.0 mg L^{-1} with an average of 15.0 mg L^{-1}, and for MNR_{100} they ranged from 8.6 to 64.5 mg L^{-1} with an average of 22.2 mg L^{-1}. The leaching concentrations increased by 12% (− 44% ~ 75%) and 66% (− 52% ~ 43%), in the MNR_{50} and MNR_{100} treatments, respectively, compared to the NPK treatment. These results indicated that leachate N concentrations showed contrasting characteristics under manure substitution, which decreased in the Luvisol and increased in the Chernozem.

TN leaching loss of different fertilization treatments

The annual TN leaching losses (ANLL) and the annual TN leaching factor (ANLF) for three different fertilization treatments in the two regions are presented in Table 2. Compared to NPK, the average ANLL in the Luvisol was significantly reduced in the MNR_{50} (57%) and MNR_{100} (76%) treatments, respectively. The ANLF of the two manure substitution treatments also significantly decreased compared with the chemical fertilizer treatment. The average ANLL in the Chernozem was significantly increased for the MNR_{50} (15%) and MNR_{100} (21%) treatments, respectively, compared to the chemical fertilizer

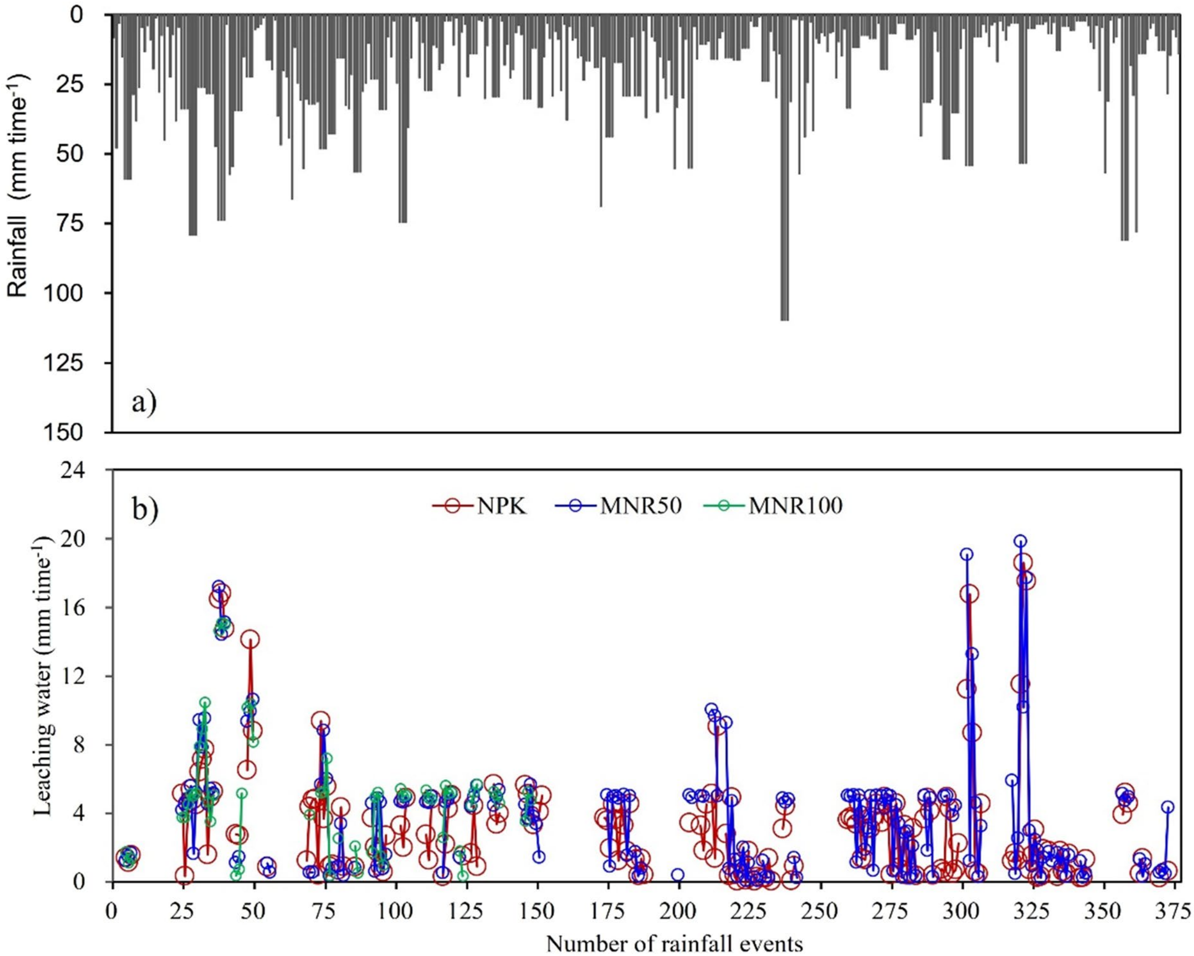

Fig. 3 Characteristics of rainfall and leaching water in the Chernozem. NPK: conventional treatment; MNR50: 50% manure N replacement; MNR100: 100% manure N replacement

treatment. While the ANLF of the three treatments in the Chernozem were close to 2% and did not show apparent changes among the different treatments. These results indicated that the Luvisol has a high TN leaching risk, and manure substitution could greatly decrease N leaching. While for the Chernozem, the TN leaching risk is relatively low, and manure substitution could slightly increase it. This implies that manure application could be encouraged in the North China Plain and should be cautiously implemented in the Northeast China Plain, considering the impact on N leaching. The detailed analysis revealed that the leaching reduction rate of the MNR_{50} and MNR_{100} treatments increased initially and then decreased with the increase of annual precipitation in the Luvisol (Fig. S3a). On the contrary, the leaching reduction rate of the MNR_{50} and MNR_{100} treatments decreased initially but increased with the increase in annual precipitation in the Chernozem. This showed that leaching could increase after manure application when annual precipitation exceeds 300 mm (Fig. S3b).

Discussion

The effects of replacing fertilizer N with manure N on maize yields change over time

This study showed that the effects on crop yield by substituting chemical fertilizer N with manure were specific; therefore, different management regimes would be needed for the Luvisol and Chernozem

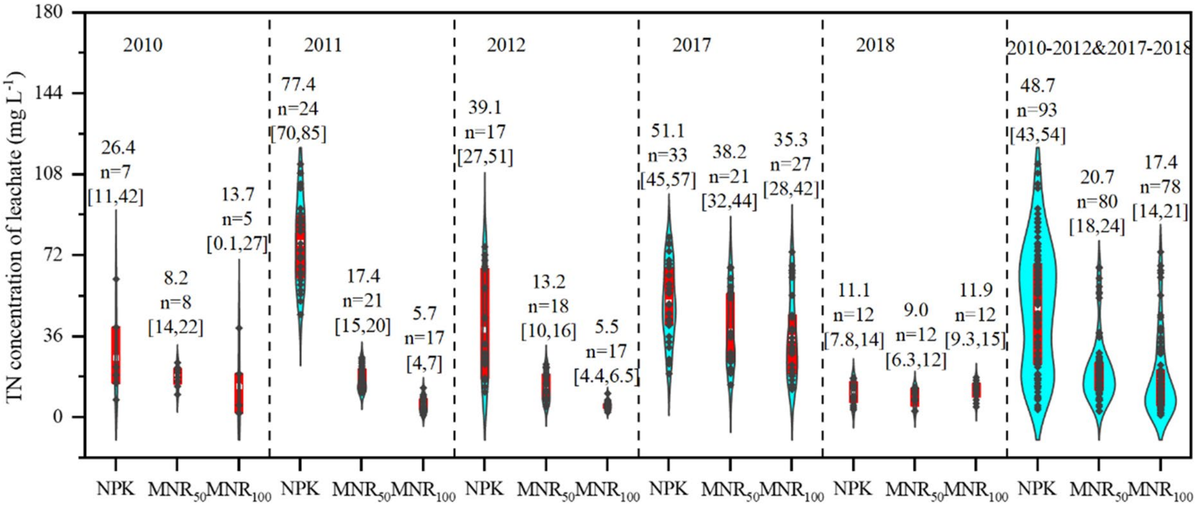

Fig. 4 Total nitrogen (TN) concentration of leachates in the Luvisol for different years. The value on each violin is the average, n represents the number of data, and the data in brace represents the 95% confidence interval. NPK: conventional treatment; MNR_{50}: 50% manure N replacement; MNR_{100}: 100% manure N replacement

regions. For the Luvisol, manure substitution resulted in higher yield (9.8–22.9%) except for the MNR_{100} treatment, which resulted in a slight yield reduction for short term application. This is consistent with previous studies, where 40%–60% substitution with organic inputs tends to be the optimal substitution rate for maize production yield (Wei et al. 2020; Zhang et al. 2020). This is mainly because manure substitution could improve soil properties, such as soil structure, water holding capacity, and microbial activity, which consequently promotes the maize yield (Bashir et al. 2019; Shepherd and Newell-Price 2016; Zhang et al. 2016). It should be noted that manure substitution significantly reduced yield in a short time on the Chernozem site. This indicated that chemical N as a quick N source is insufficient for maize crop yield increase in the Chernozem region when the manure substitution rate reached 50% during the initial phase. Thus, manure substitution is not always beneficial for crop yields, and it is necessary to consider local conditions while implementing manure N substitution in specific regions.

The results from the current study indicated that the spring maize yield was closely related to the duration of manure application. The positive effects of partial manure substitution on the maize yield increased over time, while there were almost no adverse effects of complete substitution on yield results after long-term manure application (Fig. 1). This is an important finding as it indicates that the yield reduction caused by complete manure substitution application can be recovered over time. The appropriate manure substitution could be explored in future studies using varying substitution rates based on a similar long-term experiment used in this study.

Impacts of rainfall characteristics and antecedent conditions on N leaching

Rainfall is a primary factor affecting N leaching in addition to the N application rate (He et al. 2016; Li et al. 2019; Liu et al. 2019). The present results indicate that N leaching was positively correlated with the rainfall amount, which is consistent with previous studies (Li et al. 2020; Jiao et al. 2021). It should be noted that N leaching was affected by the annual rainfall amount and the intensity of the storm events (Huang et al. 2017). Moderate and heavy rainfall events accounted for most of the precipitation during the growth period of spring maize, although the probability of leaching was not 100%. Extreme rainfall events increased the probability of leaching, as described previously (Zheng et al. 2020). Seasonal variations of rainfall are considered as one of the most critical factors controlling N leaching (Li et al. 2020). The rainfall in the two areas of this study was

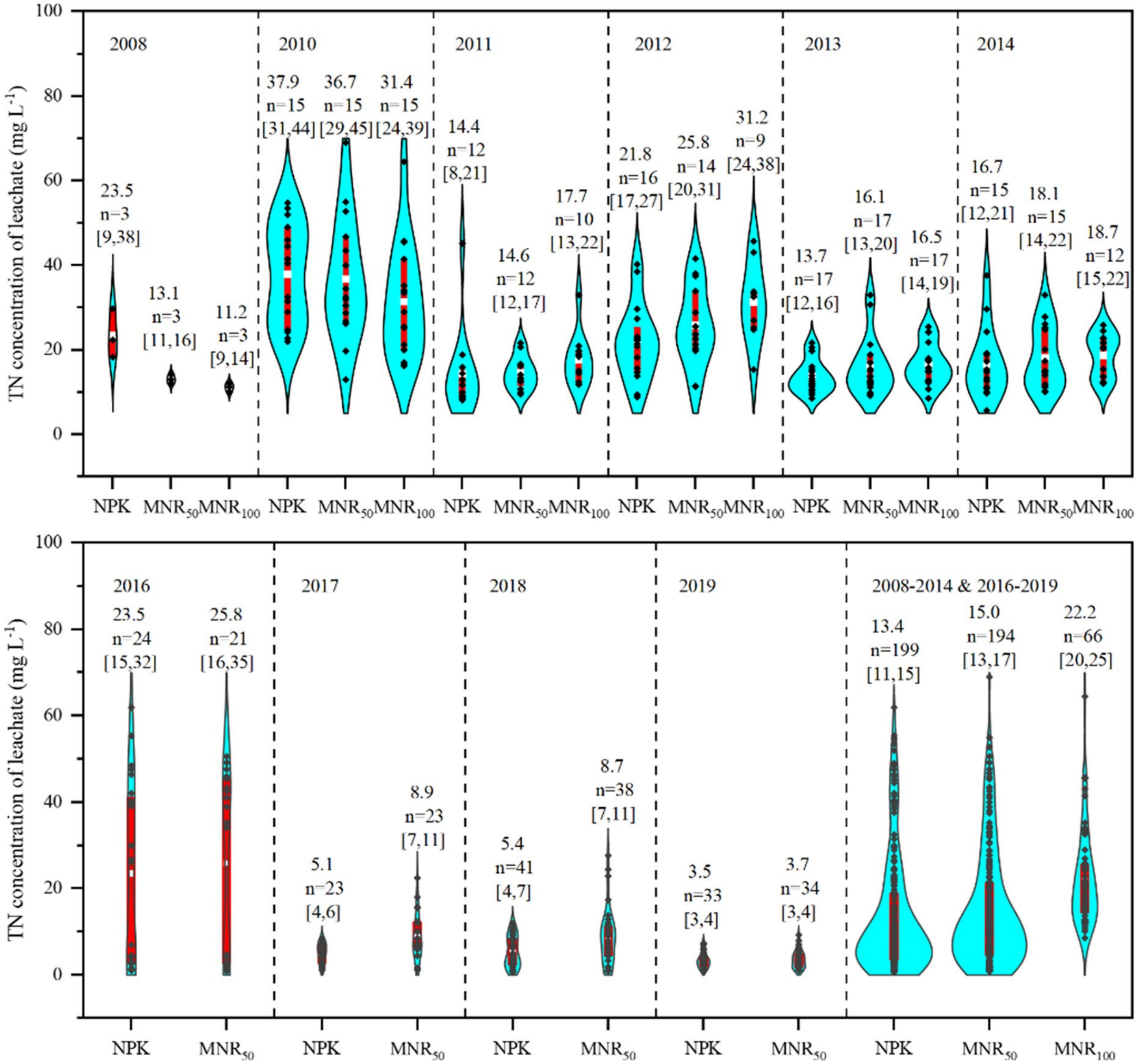

Fig. 5 Total nitrogen (TN) concentration of leachates in the Chernozem for different years. The value on each violin is the average, n represents the number of data, and the data in brace represents the 95% confidence interval. NPK: conventional treatment; MNR_{50}: 50% manure N replacement; MNR_{100}: 100% manure N replacement.

concentrated during the summer flood season, which overlaps with the maize growing season. This implies that summer is the critical period for N leaching in maize fields.

The present results also showed that a certain amount of accumulated rainfall is required for the first leaching event during a year (Niu et al. 2021). This can be attributed to the low soil moisture content at the beginning of the flood season. For example, there were no leaching events caused by rainfall events in 2019 in the Luvisol. However, the rainfall amount of the first leaching event in 2012 was only 1.8 mm with the antecedent rainfall amounts of 260 mm. These results were supported by field measurements (Jia et al. 2014; Li et al. 2016) and other modelling results (Fang et al. 2013; Zhang et al. 2015).

Table 2 The annual TN leaching amount and leaching factor of each treatment in the Luvisol and Chernozem

Region	Years	NPK		MNR_{50}		MNR_{100}	
		Leaching amount (kg/ha)	Leaching factor (%)	Leaching amount (kg/ha)	Leaching factor (%)	Leaching amount (kg/ha)	Leaching factor (%)
Luvisol	2009	–	–	–	–	–	–
	2010	4.03	1.68	3.11	1.30	0.98	0.41
	2011	63.64	26.5	14.91	6.21	3.48	1.45
	2012	30.76	12.8	12.83	5.35	4.32	1.80
	2017	76.25	31.8	41.98	17.5	30.18	12.6
	2018	5.07	2.11	4.52	1.88	3.72	1.55
	2019	–	–	–	–	–	–
	Average	43.66	15.0	18.21	6.45	9.74	3.56
Chernozem	2008	0.31	0.17	0.19	0.11	0.16	0.09
	2009	–	–	–	–	–	–
	2010	12.86	7.15	13.22	7.34	11.08	6.16
	2011	1.25	0.69	1.85	1.03	1.93	1.07
	2012	3.30	1.84	2.49	1.38	2.70	1.50
	2013	2.14	1.19	3.31	1.84	3.67	2.04
	2014	3.46	1.92	3.69	2.05	3.54	1.97
	2015	–	–	–	–	–	–
	2016	4.99	2.77	5.53	3.07	–	–
	2017	0.32	0.18	0.98	0.55	–	–
	2018	2.23	1.24	4.06	2.26	–	–
	2019	0.97	0.54	1.23	0.68	–	–
	Average	3.18	1.77	3.66	2.03	3.85	2.14

The annual TN leaching factor (ANLF, %) is annual TN leaching losses divided by the amount of N fertilizer applied; NPK: conventional treatment; MNR_{50}: 50% manure N replacement; MNR_{100}: 100% manure N replacement

Contrasting effects of manure substitution on N leaching for the two soil types

The long-term experiments in this study revealed that the average ANLF of NPK were 15% in the Luvisol and 2% in the Chernozem. The ANLFs of the NPK treatments were consistent with the results of previous studies; for example, 13% of the fertilizer N inputs were lost to leaching in a study based on data compiled from a survey of 2.89 million farmers between 2005 and 2014 (Ying et al. 2020). The ANLF was calculated at 22% and 15% by Cui et al. (2014) and Zhou and Butterbach-Bahl (2014), respectively. These results suggest that the high ANLF (30%) recommended by the IPCC guidelines (IPCC 2006) overestimates N leaching for spring maize.

The present study indicated that manure substitution has the capacity to reduce N leaching significantly, and the reduction rate was elevated as substitution rates increased in the North China Plain. Compared with the NPK treatment, the average reduction rates of N leaching in the manure substitution treatment were 57–76% in the Luvisol similar to previous studies. This is summarized in a meta-analysis of 133 studies that evaluated the impacts of organic N substitutions on maize yield and environmental risks worldwide (Wei et al. 2020). The water-holding capacity (Feng et al. 2019; Oldfield et al. 2019) and soil aggregation (Li 2009) can be improved after long-term organic substitution. The significant N leaching abatements for manure substitution in the Luvisol were mainly caused by increased water-holding capacity. Improved water-holding capacity is an important factor in reducing N leaching (Li et al. 2018), as reduced water leaching will also reduce N losses. However, the complete manure substitution in the Chernozem showed a weak mitigation ability for N leaching and even slightly increased N leaching, which may be due to the higher SOC and clay contents of Chernozem. Although the addition of manure may increase the soil N pool, the holding capacity of SOC to N is limited (Ying et al. 2020). It was found that manure can accelerate soil organic matter (SOM) mineralization and N leaching (Gai et al. 2019; Wang et al. 2019). In addition to soil type and properties, the N application rates and the amount of water inputs including rainfall and irrigation also have impacts on N leaching under manure substitution condition. In particular, higher N application rates in the Luvisol led to high N leaching amounts. Previous studies have shown that the leaching amount increased with the N application rate, but the leaching factor was not affected by the application rates (Wang et al. 2018). In addition, the Luvisol also received more water inputs because of higher rainfall amounts with supplementary irrigation, which is another cause for higher N leaching amounts and the leaching factor.

The quantitative evaluation of the effects of replacing synthetic N fertilizer with manure found in this present study could be helpful for policy decisions, such as the “the zero growth in fertilizer policy” to reduce environmental risks caused by N losses. It was found that the North China Plain is the main area of N losses in China (Wang et al. 2018). Considering crop yield enhancement and N leaching abatements caused by manure substitution, manure can be applied in cropland in the North China Plain. However, due to the possible adverse effect of manure N substitution on crop yield and N leaching, manure application should be carefully observed in the Northeast China Plain. These results imply that the distribution of livestock and poultry breeding should fully consider the capacity of manure utilization in cropland in different areas (Bai et al. 2019).

Conclusions

The impact of replacing different proportions of chemical fertilizer with manure on crop yield and N leaching in two typical spring maize systems with a Luvisol in the North China Plain and a Chernozem in the Northeast China Plain were investigated using a long-term lysimeter monitoring method. The results indicated that the manure substitution could decrease the crop yield in the initial period after substitution but, over longer periods, does not affect yields. The associated N leaching amount is related to soil type, N application rate and water inputs (sum of rainfall and irrigation). Soil types and properties were the main causes for contrasting effects of manure substitution on N leaching for the two different regions. The significant N leaching abatement achieved after manure substitution in the Luvisol treatment was mainly caused by the increased water-holding capacity. In contrast, the Chernozem treatment showed low mitigation potential due to higher SOC and clay contents. This study shows that generic advice pertaining to manure substitution must consider soil types across China if agronomic and environmental goals are to be achieved.

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Data availability statement The data used in this study can be requested by contacting the corresponding author.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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