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Patterns of crop-specific fertilizer-nitrogen losses and opportunities for sustainable mitigation: A quantitative overview of ^{15}N-tracing studies

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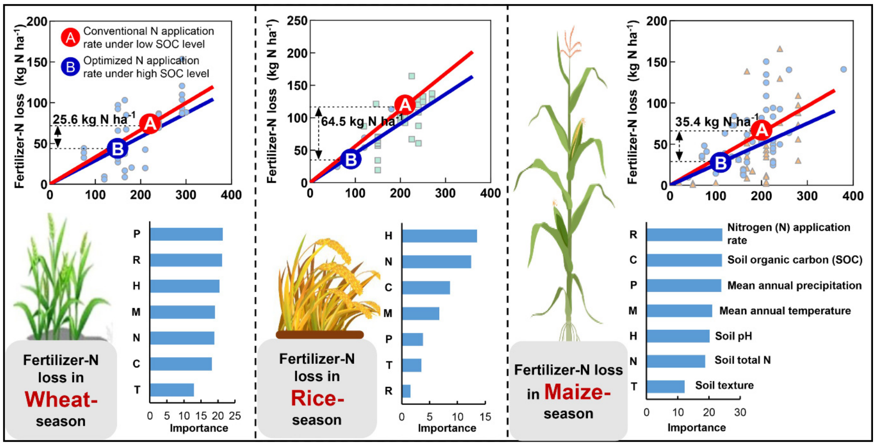
ABSTRACT



- Pattern and mitigation potential of crop-specific fertilizer-N losses were assessed.
- China showed high fertilizer-N losses due to high N application rates and low SOC.
- MAP, SOC, and soil pH are key parameters affecting fertilizer-N losses.
- At a given application rate, soils with higher SOC have lower fertilizer-N losses.
- Optimal N rate combined with SOC improvement could cut 34.8%−59.6% of N losses.

Understanding crop-specific fertilizer-nitrogen (N) loss patterns, driving factors, and mitigation potentials is vital for developing efficient mitigation strategies. However, analyses based on the gross magnitude of fertilizer-N losses within a growing season remain fragmented and inconclusive at a global scale. To address this gap, we conducted a global meta-analysis using 940 observations from 79 published ^{15}N-tracing studies to assess the effects of natural factors, soil parameters, and N application rates on gross fertilizer-N losses in cereal-cropped soils. We found that China had the highest conventional fertilizer-N application and loss rates (230−255 and 75.9−114 kg N ha^{-1} season^{-1}, respectively) and the lowest soil organic carbon (SOC) contents (10.6 g kg^{-1}) among the countries examined. Mean annual precipitation, SOC content, and soil pH were key parameters affecting fertilizer-N losses in wheat-, maize-, and rice-cropped soils, respectively. Fertilizer-N application rates were positively correlated with N loss amounts, while higher SOC levels led to lower losses. Adopting optimized N application rates combined with improving SOC levels could potentially mitigate 34.8%−59.6% of N losses without compromising crop yields compared with conventional practices. This study underscores the critical role of SOC in reducing N losses and suggests that future research should focus on innovative strategies and efficient organic amendments for enhanced SOC sequestration.

Keywords fertilizer-nitrogen loss, crop-specific, ^{15}N tracing, soil organic carbon, meta-analysis

1 Introduction

Nitrogen (N) fertilizers play an essential role in ensuring global food security (Guo et al., 2010; Poffenbarger et al., 2018; Suter et al., 2020). However, numerous studies have shown that the applied fertilizer-N, particularly that exceeding crop demand and soil N retention capacity, can potentially escape into the environment via the pathways of nitrate (NO_3^-) leaching and runoff (Liu et al., 2020b; Teixeira et al., 2021), ammonia (NH_3) volatilization (Rochette et al., 2009; Huddell et al., 2020), and nitrous oxide (N_2O) emissions (Tian et al., 2020; Maaz et al., 2021), which have led to a variety of negative environmental impacts (Wang et al.,

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2014). Therefore, it is urgently pertinent to propose practices aimed at mitigating fertilizer-N losses (Tilman et al., 2011).

Fertilizer-N losses can be influenced by various factors, such as fertilizer-N application rates, natural factors, and soil parameters (Wang et al., 2014; Huang et al., 2017; Teixeira et al., 2021). For example, Ma et al. (2019) indicated that NH_3 volatilization and NO_3^- leaching increased with higher fertilizer-N application rates in rice-cropped soils; Hansen et al. (2019) observed diverse features of soil N_2O emissions and NO_3^- leaching in croplands with different SOC levels and precipitation rates. Quantitatively elucidating the main driving factors of fertilizer-N losses would help to establish specific mitigation strategies. However, obtaining this information from existing studies is still a challenge. On the one hand, the significant spatial heterogeneity of natural factors and management practices across different regions makes it difficult to draw up mitigation guidelines at regional or broader scales (Templer et al., 2012; Schutz et al., 2017; Pan et al., 2022). On the other hand, there is a lack of reports that account for the variation in fertilizer-N losses in soils cultivated with different crops (Cui et al., 2022), which hinders our understanding of crop-specific characteristics of fertilizer-N losses. Accordingly, synthesis studies are needed to clarify the spatial patterns and driving factors of crop-specific fertilizer-N losses (Gurevitch et al., 2001).

The stable isotope tracing (^{15}N) approach, which facilitates the direct determination of the fates of fertilizer-N, could provide a more robust understanding of the magnitude and proportion of fertilizer-N losses compared to conventional methods (Goodale, 2016; Zhao et al., 2016; Bhattacharyya et al., 2019). Nevertheless, available synthesis studies of ^{15}N tracing research are fragmented and inconclusive. For instance, a meta-analysis conducted by Gardner and Drinkwater (2009) did not consider the impacts of soil parameters on the losses of ^{15}N fertilizers; a recent study investigated the fates of applied ^{15}N as affected by natural factors and management practices (Quan et al., 2021), but the study only focused on maize-cropped systems, and did not provide a quantitative conclusion on the main drivers of fertilizer-N losses, which led to uncertainties in developing management strategies in current seasons.

Here, we conducted a global meta-analysis to provide a critical overview of current research efforts on quantifying fertilizer-N losses. We aimed to 1) investigate the heterogeneity of fertilizer-N loss proportions and magnitudes across different regions; 2) quantify the relationship of natural factors and soil parameters with fertilizer-N losses and identify the driving factors of fertilizer-N losses; and 3) propose possible solutions for achieving sustainable mitigation of fertilizer-N losses.

2 Materials and methods

2.1 Data collection

We based the meta-analysis on a literature survey of peer-reviewed studies published before September 2022. The data were obtained from the China National Knowledge Infrastructure and Web of Science. A preliminary search was conducted using the keywords “^{15}N,” “^{15}N tracing,” “^{15}N label,” “^{15}N fate,” “wheat,” “maize,” and “rice,” which collected 560 published studies. These preliminarily searched studies were further scrutinized and selected if they met the following criteria: 1) The experiment should be carried out under field conditions; 2) the magnitude and proportion of ^{15}N losses were directly reported or could be calculated; 3) the soil depth of ^{15}N sampling should exceed 60 cm; and 4) the period from ^{15}N labeling to sampling should cover the entire growing seasons of wheat, maize, and rice. The final database consisted of 940 observations derived from 79 publications, of which 15 were conducted in European Union and North America, 51 were conducted in China, and 13 were conducted in other countries (Fig. S1). Detailed information on the collected publications is listed in the Supplement.

We extracted ^{15}N application rates, natural factors (mean annual temperature [MAT] and mean annual precipitation [MAP]), soil parameters (soil organic carbon [SOC] content, soil total N [TN] content, soil pH value, and soil texture), and ^{15}N losses based on the database.

2.2 Calculation and analysis

The fates of ^{15}N-labeled fertilizer are assigned to the pathways of crop uptake, soil retention, and losses, so the amounts of fertilizer-N losses (N_{loss}) could be calculated by the following equation:

$$N_{loss} = \text{N application rate} - N_{uptake} - N_{retention} \tag{1}$$

where N application rate represents the rate of added ^{15}N-labeled fertilizer (kg N ha^{-1}) and N_{uptake} and $N_{retention}$ represent the amounts of ^{15}N-fertilizer recovered in crop and soil, respectively.

The proportion of lost fertilizer-N was calculated by dividing N_{loss} by the N application rate.

Since the European Union and North America are representative developed regions and China is the largest developing country, we divided the experimental sites into the regions or countries of the European Union and North America, China, and other countries. The mean values and the 95% confidence intervals (95% CIs) of SOC content, fertilizer-N application rates, grain yield, and the fates of fertilizer-N within different regions and countries were generated by bootstrapping (4 999 iterations) in a unweighted random-effects meta-analysis using Metawin 2.1 (Rosenberg et al., 2000).

Soil textures were divided into three classifications, i.e., coarse (sand, loamy sand, sandy loam, loam, silt loam, and silt), medium (sandy clay loam, clay loam, and silty clay loam), and fine (sandy clay, silty clay, and clay) (Sha et al., 2020). To ensure sufficient sample sizes, the classifications of medium and fine were merged into one group, i.e., medium + fine. The difference in the proportion of lost fertilizer-N between the resultant two texture groups was determined by the *t* test performed with SPSS 22.0 software (SPSS Inc., Chicago, IL, USA).

Linear regression analysis (generalized linear model) and linear mixed-effects analysis were conducted to evaluate the effects of natural factors and soil parameters (SOC, TN, and pH) on the proportion of lost fertilizer-N. To minimize the interference of anthropogenic N fertilization on the fates of fertilizer-N, we constrained the N application rates to > 200 kg N $\mathrm{ha^{-1}}$ in this analysis, which represented the patterns of fertilizer-N losses in conventional management practices (Chen et al., 2014; Maaz et al., 2021).

We carried out side-by-side comparisons to assess the potential of N application rate optimization in alleviating fertilizer-N losses and maintaining crop yields. The conventional and corresponding optimized N application rates were identified based on the description of the experimental design within each specific study that established multiple N application rates. The natural log of the response ratio (ln*R*) was calculated as the effect size, according to the following equation:

$$\ln R = \ln \frac{X_o}{X_c} \tag{2}$$

where X_o and X_c are the fertilizer-N loss amounts or crop yields for the optimized and conventional N application rates, respectively. The mean values and the 95% CIs of effect sizes were calculated by the same approach used to evaluate the mean fertilizer-N losses in different countries or regions. To facilitate interpretation, the results of this analysis were reported as the percentage change (*PC*) under the optimized and conventional N application by the following equation:

$$PC = (\exp(\ln R - 1)) \times 100\% \tag{3}$$

In addition to the side-by-side comparisons, a linear regression analysis was conducted to show the dynamics of fertilizer-N loss amounts and proportions as affected by increasing N application rates. Since the fertilizer-N losses should be zero when no fertilizer-N was applied, the linear regression model was forced to pass through the origin. Given that SOC has been widely reported to have significant impacts on fertilizer-N retention and the associated loss (e.g., Xia et al., 2018; Quan et al., 2021), the observations of fertilizer-N losses were subgrouped into SOC levels of 0−10, 10−20, and > 20 g $\mathrm{kg^{-1}}$ to assess the potential effect of SOC promotion on the mitigation of fertilizer-N losses. We also established two scenarios, i.e., implementing optimized N application rates in soils with low SOC levels (0−10 g $\mathrm{kg^{-1}}$; Scenario A) and implementing conventional N application rates in soils with high SOC levels (10−20 or > 20 g $\mathrm{kg^{-1}}$; Scenario B), to evaluate the interactive impacts of optimizing N application rates and promoting SOC levels on fertilizer-N losses. The mean conventional and optimized N application rates were obtained from the data sets in the aforementioned side-by-side comparisons. The change in SOC stock between the two scenarios was estimated, and the detailed calculations are presented in the Supplementary calculations.

Linear regression analyses were conducted using GraphPad Prism 7 (GraphPad Software, San Diego, CA, USA). The linear mixed-effect model was estimated using the "*lmertest*" and "*MuMIn*" packages in R (version 4.0.3), with "study" considered as a random effect. The importance of natural factors, soil parameters, and fertilizer-N application that determine the proportion of lost fertilizer-N was evaluated by a random forest model performed using the "*rfPermute*" package in R (version 4.0.3).

3 Results

3.1 Regional patterns of the fates of fertilizer-N

The mean SOC contents in major cereal-cropped soils in the European Union and North America were 31.4%−69.8% higher than those in China and other countries or regions (Table 1). China exhibited the highest conventional fertilizer-N application rates (230−255 kg N $\mathrm{ha^{-1}}$ $\mathrm{season^{-1}}$) but also the leading fertilizer-N loss amounts (75.9−114 kg N $\mathrm{ha^{-1}}$ $\mathrm{season^{-1}}$) among the countries or regions. Correspondingly, the fertilizer-N use efficiency, i.e., the proportion of fertilizer-N utilized by crops, was detected to be lowest in China (31.1%−35.0%) among the collected studies. The proportion of lost fertilizer-N in rice-cropped soils in the European Union and North America was significantly lower than that in China and other countries or regions ($P < 0.05$), but no significant difference in this proportion was detected in wheat- and maize-cropped soils among different countries or regions.

3.2 Effect of natural factors and soil parameters on the proportion of fertilizer-N losses to total applied N

Both linear regression analysis and linear mixed-effects analysis showed that the MAP had significantly positive correlations with the proportion of fertilizer-N losses in maize-cropped soils (Ss. 1b, S2, and S3), but no statistically significant relationship between the two factors was detected in

Table 1 Soil conditions and the fertilizer-nitrogen (N) fates for the cropping seasons of wheat, maize, and rice in China, European Union and North America, and other countries/regions.

Country/ region	Soil organic arbon (g kg^{-1})[a]	Soil total nitrogen (g kg^{-1})	Cropping season	Fertilizer-N application rate (kg N ha^{-1} season^{-1})	Crain yield (mg ha^{-1} season^{-1})	Fate of fertilizer-N (%)			Fertilizer-N loss amount (kg N ha^{-1} season^{-1})
						Crop uptake	Soil retention	Loss	
China	10.6 [a] (9.36−11.87) [b] *31* [c]	1.13 (1.00−1.28) *31*	Wheat	255 (241−271) *30*	6.23 (5.73−6.84) *15*	35.0 (30.9−39.0) *30*	34.0 (29.9−38.8) *30*	30.9 (26.9−34.7) *30*	85.6 (74.4−98.7) *30*
			Maize	230 (221−244) *41*	9.49 (8.14−10.87) *28*	31.3 (27.9−35.2) *41*	35.9 (31.8−39.9) *41*	32.8 (27.8−38.2) *41*	75.9 (63.7−89.7) *41*
			Rice	233 (217−248) *18*	8.54 (8.01−8.89) *11*	31.1 (26.2−35.6) *18*	19.1 (16.0−22.0) *18*	49.8 (44.5−56.2) *18*	114 (103−125) *18*
European Union and North America	18.0 (13.4−22.5) *12*	1.24 (0.94−1.58) *14*	Wheat	147 (110−168) *4*	6.81 *1*	40.8 (33.6−47.3) *4*	26.9 (20.4−33.5) *4*	32.3 (19.3−45.3) *4*	49.3 (22.4−76.1) *4*
			Maize	189 (181−198) *36*	7.87 (6.46−9.37) *13*	44.2 (40.7−48.0) *36*	28.3 (24.4−32.3) *36*	29.3 (24.9−33.6) *36*	55.8 (47.0−63.8) *36*
			Rice	168 *2*	/ [d]	/	/	21.7 (21.6−21.8) *2*	36.5 (36.3−36.6) *2*
Other	13.7 (8.16−20.5) *8*	1.45 (0.84−2.20) *7*	Wheat	150 *2*	/	39.5 (39.0−40.0) *2*	41.0 (39.0−43.0) *2*	19.5 (18.0−21.0) *2*	29.3 (27.0−31.5) *2*
			Maize	201 (179−217) *15*	12.07 (10.65−13.37) *9*	42.1 (36.8−46.6) *15*	21.0 (15.2−26.9) *15*	36.9 (28.3−45.1) *15*	72.3 (57.0−92.8) *15*
			Rice	155 (150−163) *12*	8.00 (6.62−9.17) *12*	45.0 (36.6−52.3) *12*	14.4 (11.1−17.5) *12*	40.6 (33.1−46.9) *12*	63.8 (50.9−77.9) *12*

[a] represents the average value. [b] represents the 95% confidence interval of the average value. [c] represents the number of observations. [d] represents no available data.

wheat- and rice-cropped soils (Fig. 1a, and c). The proportion of lost fertilizer-N tended to decrease with increasing SOC content, but a significant correlation was detected only in rice- and maize-cropped soils (Figs. 1 and S4a, b, c). The relationship between the proportion of lost fertilizer-N and TN content also tended to be negative (Figs. S4d, e, f and S5d, e, f), but significant results were observed only in the maize cropping season. Soil pH exhibited a negative relationship with the proportion of lost fertilizer-N in maize-cropped soils ($P < 0.05$), but an inverse relationship was detected in rice-cropped soils ($P < 0.05$; Figs. 1 and S4g, h, i).

The random forest model revealed that, except for the N application, the proportion of lost fertilizer-N in the rice-cropped soil was mainly driven by the soil pH and SOC content (Fig. 1), while that in the maize-cropped soil was more attributable to the SOC content and MAP. The results regarding wheat-cropped soil showed that MAP and soil pH were the principal natural and soil factors that influenced the percentage of fertilizer-N loss. Neither the correlation analysis, *t* test, nor random forest model revealed a significant effect of MAT or soil texture on the proportion of lost fertilizer-N (Figs. 2, S2d, e, f and S6).

3.3 Relationships between the application rates and losses of fertilizer-N under different SOC levels

The proportion of fertilizer-N losses increased significantly with the fertilizer-N application rates in the wheat- and maize-cropped soils, but no significant relationships between the two variables were detected in the rice season (Figs. 1 and S7). However, the magnitude of fertilizer-N losses was stimulated by the fertilizer-N application rates in all cropping seasons ($P < 0.05$; Fig. 2). Side-by-side comparisons showed that compared with conventional N application rates, implementing optimized N application rates could reduce the amount of fertilizer-N losses by 61.8%, 64.9%, and 49.5% for wheat-, maize-, and rice-cropped soils, respectively ($P < 0.05$), without affecting crop yield (Fig. 2a, b, c).

The amount of fertilizer-N losses increased linearly with the fertilizer-N application rates ($P < 0.05$; Fig. 2d, e, f), and the slope of the fitted line tended to be lower in soils with higher SOC levels. Optimizing N fertilization rates in conjunction with the improvement of SOC levels was found to reduce fertilizer-N losses: conversion from the conventional regimes of N application in soils with low SOC contents (0−10 g kg^{-1}; Scenario A) to the optimized regimes

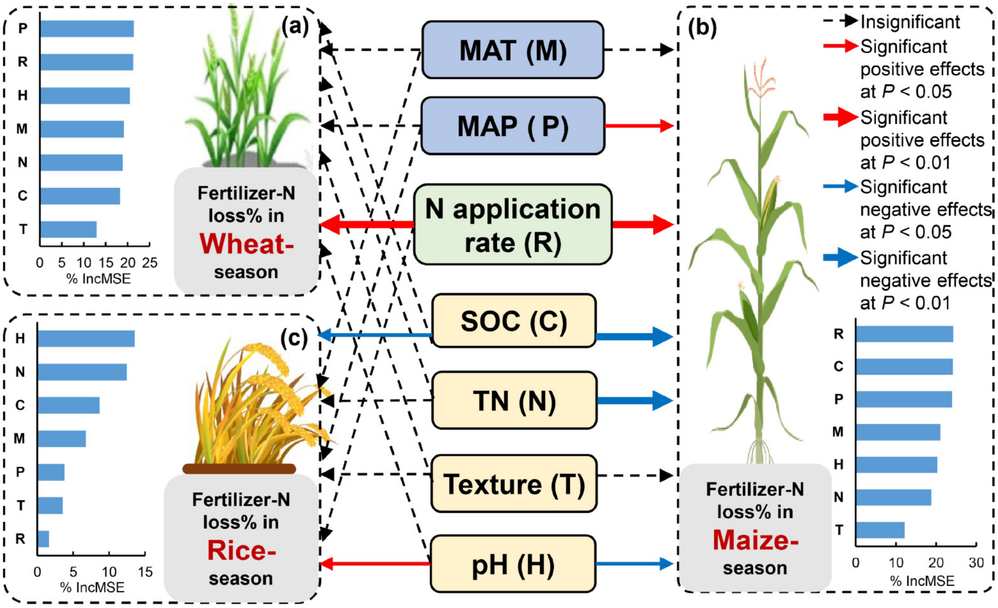

Fig. 1 Diagram illustrating the impact of natural factors, soil parameters, and nitrogen (N) application rate on the proportion of fertilizer-N losses to the applied N in the cropping seasons of (a) wheat, (b) maize, and (c) rice. MAT, MAP, SOC, TN, texture, and pH represent mean annual temperature, mean annual precipitation, soil organic carbon content, soil total N content, soil texture, and soil pH, respectively. Dotted and solid arrows indicate the nonsignificant and significant relationships between the parameters and the proportion of fertilizer-N losses, respectively. The relationships between soil texture and the proportion of fertilizer-N losses were evaluated by the *t* test. The relationships between the other parameters and the proportion of fertilizer-N losses were generated from the linear regression analysis. Detailed information on the relationships between the variables is shown in Figs. S2 − S7. The histograms present the results from the random forest model, which reveal the importance of the parameters in the proportion of fertilizer N losses. Percent increases in the mean squared error (MSE) were used to reveal the importance of the factors, and higher values imply higher importance.

of N application in the context of high SOC contents (10−20 or > 20 g kg^{-1}; Scenario B) could mitigate fertilizer-N losses by 25.6, 35.4, and 64.5 kg N ha^{-1} for wheat-, rice- and maize-cropped soils, respectively.

4 Discussion

4.1 Factors that influence fertilizer-N losses in soils cultivated with different crops

The fates of fertilizer-N are assigned to the pathways of crop uptake, soil retention, and losses (Sebilo et al., 2013; Poffenbarger et al., 2018). However, owing to the limited crop N demand and soil N retention capacity, ample studies have reported that increasing the fertilizer-N application rate would induce a significant augmentation in fertilizer N losses, leading to increased pressure on the environment (Chen et al., 2014; Shelton et al., 2018; Huddell et al., 2020). In line with previous reports, the present analysis indicated that the fertilizer-N application rate had significantly positive correlations with the amounts of fertilizer-N losses, and increasing the fertilizer-N application rate by 1 kg ha^{-1} could increase fertilizer-N losses by 0.31 − 0.45 kg ha^{-1} ($P < 0.05$; Fig. 2d, e, f). To alleviate fertilizer N losses, optimized N application rates were established by many studies to reduce N input while maintaining crop yield (e.g., Ma et al., 2018; Liang et al., 2020). Our pairwise comparisons showed that optimization of fertilizer-N application rates could reduce fertilizer-N losses by 49.5%−64.9% relative to conventional rates without compromising crop yield (Fig. 2a, b, c), which suggested an effective solution for alleviating fertilizer N losses (Wang et al., 2014; Yao et al., 2017). The results were supported by a previous meta-analysis on ^{15}N tracing studies, which documented that reducing fertilizer-N application rates by 50% achieved approximately 42% alleviation of N losses (Quan et al., 2021).

The percentage of fertilizer-N losses in different cereal cropping seasons was influenced by various natural factors and soil parameters (Fig. 1), which suggested the need for crop- and region-specific strategies to reduce N losses (Wang et al., 2014; Yin et al., 2019; Huddell et al., 2020). In the maize season, MAP showed a significant positive linear relationship with the percentage of fertilizer N losses, but this relationship was not significant in the wheat and rice seasons. Higher precipitation in the maize season could increase N losses through leaching and runoff, while the flooding conditions in the rice season might diminish its effects (Fang et al., 2006; Nair et al., 2020). Although MAP did not correlate linearly with the percentage of fertilizer

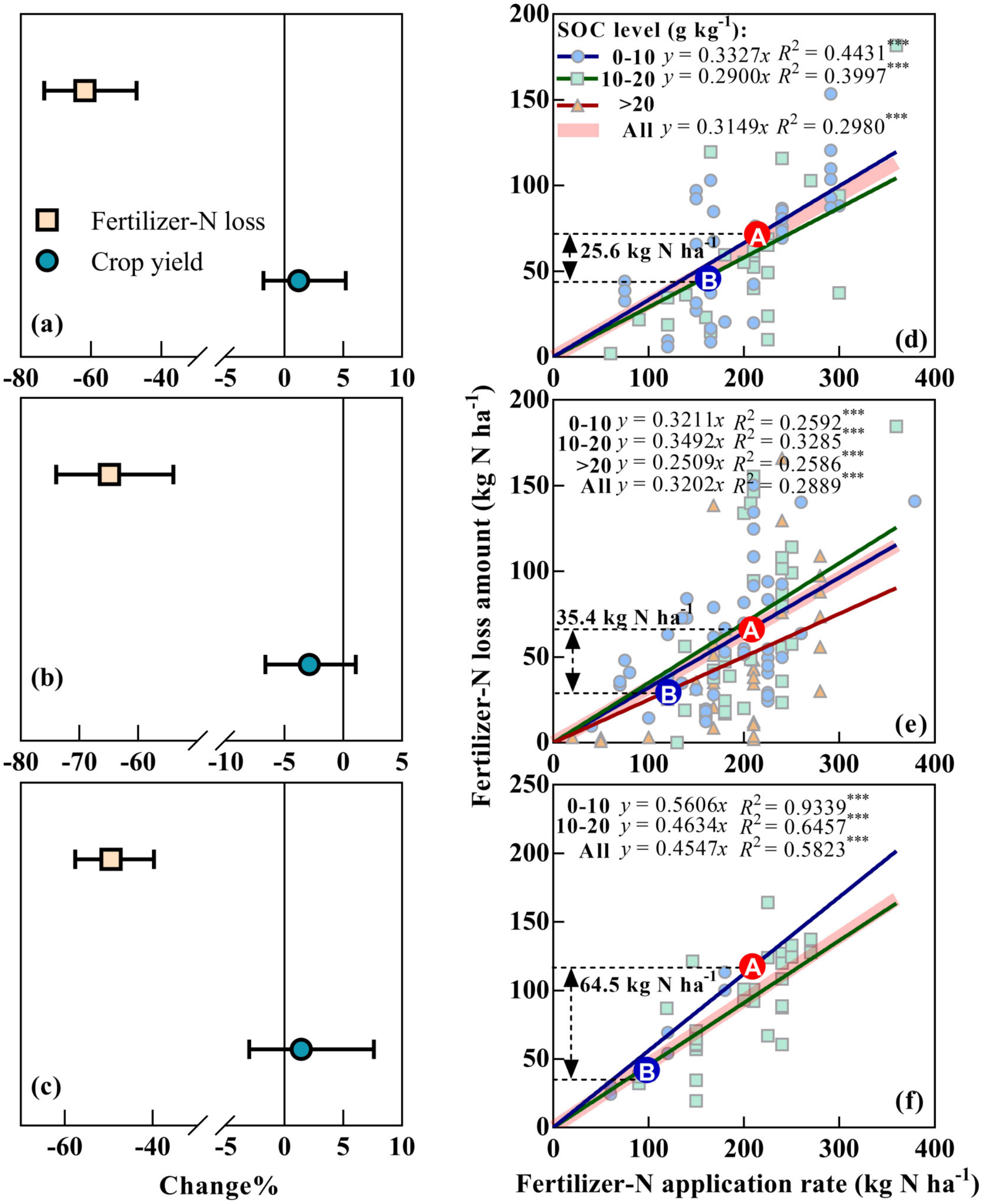

Fig. 2 Percent change in fertilizer-nitrogen (N) loss amounts and crop yield under optimized N application rates relative to conventional N application rates (a−c) and relationships between the amounts of fertilizer-N losses and N application rates under different soil organic carbon (SOC) levels (d−f) in the (a and d) wheat-, (b and e) maize-, and (c and f) rice-cropping seasons. Error bars represent 95% confidence intervals. 0−10, 10−20, and > 20 represent the SOC levels of 0−10, 10−20, and > 20 g kg^{-1}, respectively. *** represents a significance level of 0.001. A and B represent the scenarios of implementing optimized N application rates in soils with low SOC levels (0−10 g kg^{-1}) and implementing conventional N application rates in soils with high SOC levels (10−20 or > 20 g kg^{-1}), respectively. The double-headed arrows and the corresponding values indicate the mitigation of fertilizer N losses under the conversion from scenario A to B.

losses in the wheat season, it was still identified as the main factor affecting the percentage of fertilizer-N losses by the random forest model. This might be because precipitation in the wheat season was usually lower than that in the maize and rice seasons (Xu et al., 2017; Liu et al., 2020a), and wheat yield was more sensitive to MAP than maize and rice yields (Ray et al., 2015). The variation in precipitation in the wheat season could affect fertilizer-N losses by altering the crop uptake of fertilizer-N, which might result in a nonlinear relationship between MAP and fertilizer-N losses.

The percentage of fertilizer-N losses tended to increase with the soil pH in the rice season ($P < 0.05$; Figs. 1c and

S4i). This is likely due to NH_3 volatilization being identified as the major pathway of N losses in rice-cropped paddy soils (Lü et al., 2019; Sun et al., 2019b; Chen et al., 2020), and higher soil pH could facilitate the conversion of NH_4^+ to NH_3, which fosters volatilization losses (Cai et al., 2002; Sun et al., 2019b). However, negative correlations between soil pH and the percentage of fertilizer-N losses were detected in the maize season ($P < 0.05$; Figs. 1b and S4h), in agreement with the trend observed in a previous meta-analysis (Quan et al., 2020). This trend could potentially be ascribed to several factors: 1) The ample rainfall during the maize growing season might have caused NH_4^+ to leach into deeper soil layers, thereby weakening the response of N losses to pH via NH_3 volatilization (Michalczyk et al., 2016; Ti et al., 2019); 2) both previous studies and our own observed the inhibitory effect of acidic soils (particularly those with a pH below 6.0) on maize crop nitrogen utilization (data not shown; Pan et al., 2019; Wang et al., 2021), which might contribute to a decrease in fertilizer-N losses in soils with a higher pH; and 3) the consumption of oxygen induced by ammonia oxidation in the soil matrix of upland soils (Yang et al., 2021) could stimulate dissimilatory nitrate reduction to ammonium (Luvizotto et al., 2019), a process that has been demonstrated to have positive correlations with soil pH and could aid in preventing nitrate losses (Cheng et al., 2022).

The percentage of fertilizer-N losses tended to decline with the SOC content, especially in the maize and rice cropping seasons ($P < 0.01$; Figs. 1b, c and S4b,c). A global meta-analysis conducted by Xia et al. (2018) illustrated a trade-off relationship between SOC sequestration and N losses, which supported our findings. These results indicated that the risk of N losses tended to be higher in soils with low fertility than in soils with high fertility, emphasizing the necessity of implementing precise N management strategies and building SOC stocks in infertile soils to achieve sustainable utilization of fertilizer-N (Foley et al., 2011; Zhang et al., 2021).

4.2 Potentials and opportunities to achieve sustainable fertilizer-N loss alleviation

The fertilizer-N loss amounts in China tended to be higher than those in the European Union and North America, and other countries or regions (Table 1), which agreed with the results of a previous global meta-analysis (Quan et al., 2021). This was partly due to the higher N application rates (Table 1). However, neither our analysis nor previous studies found a significant increase in crop yield in China compared to other countries, despite the high fertilizer-N input and the associated cost of N losses (Table 1; George, 2014; Gomiero, 2016). Therefore, there is considerable potential to improve N-use efficiency for Chinese croplands (Chen et al., 2014; Quan et al., 2020). A quantitative analysis focusing on smallholder farms in China concluded that closing the fertilizer-N use efficiency gap could alleviate N losses by 49.0%−54.0% while simultaneously improving crop yield by 5.40%−6.30% (Lü et al., 2019).

SOC has multiple functions in improving soil chemical, physical, and biological properties (Shao et al., 2021; Huo et al., 2023), which is conducive to retaining soil mineral-N (Poeplau et al., 2018; Oldfield et al., 2019) and improving the crop utilization of applied N (Zhang et al., 2021). However, the SOC levels in China are significantly lower than those in the European Union and North America, and might also be responsible for the abundant fertilizer-N losses (Elrys et al., 2022). The present analysis suggested that at a given N application rate, soils with higher SOC levels tended to have lower fertilizer-N losses. For instance, at conventional N application rates, increasing the SOC level has the potential to reduce fertilizer-N losses by 12.8% −21.9% (Fig. 2d, e, f). This suggested that improvement of SOC levels would presumably decrease the reliance of crops on intensive fertilizer-N application in the widespread infertile soils in developing and underdeveloped countries (Foley et al., 2011), which in turn provides opportunities for reducing N application rates. By implementing optimized N application rates based on SOC promotion (Scenario B), mitigation potential could be multiplied to 34.8%−59.6% compared to conventional practice (Scenario A), while simultaneously reducing N fertilizer consumption by 25.2% −51.2% and maintaining crop yield (Fig. 2). Notably, the mitigation potential in the rice season was approximately twice as high as that in the wheat and maize seasons (Fig. 2), highlighting the need for mitigation strategies to prioritize paddy soils.

Moreover, promoting SOC levels could also help to attain C-neutral agriculture, since SOC sequestration is one of the most effective measures to neutralize greenhouse gas (GHG) emissions (Sihvonen et al., 2021; Xu et al., 2022). We estimated that the SOC stock needs to be elevated by 15.0−37.0 mg ha^{-1} if Scenario A was converted to Scenario B, which implied that 55.0−135 mg carbon dioxide-equivalent (CO_2-eq) ha^{-1} of atmospheric GHG would be removed through this conversion. By 2050, global GHG emissions will reach ~3000 Tg CO_2-eq yr^{-1} (Tilman et al., 2011), and reactive N losses will more than double compared with 2010 levels (Sun et al., 2019a). In this context, improving SOC levels provides a win–win solution to simultaneously achieve the mitigation of fertilizer-N losses and the stabilization of climate change (Poirier et al., 2014; Amelung et al., 2020; Zhang et al., 2020).

Therefore, the results of our analysis highlight that integrated optimization of soil N and C management could be posited as a strategy for sustainable mitigation of fertilizer-N losses. On the one hand, optimizing N application and improving crop varieties could be implemented to promote N use efficiency and consequently lower the potential substrates for fertilizer-N losses; on the other hand, the use of organic amendments could provide opportunities to elevate the SOC level and thereby improve fertilizer-N retention. In addition, regulating soil pH could also assist in alleviating ammonia volatilization in rice-cropped soils (Sun et al., 2020).

4.3 Limitations and implications for future study

This study might be constrained by some limitations. First, the absence of effective data points in the European Union and North America, particularly those regarding rice-cropped soils, may have attenuated the ability of our analysis to draw more integrated conclusions. Additionally, we did not examine the impact of other management practices, such as the N fertilizer application method and irrigation regimes, on fertilizer-N losses, which should be addressed in future research. Nevertheless, this study provides an overview of the driving factors of fertilizer-N losses and their mitigation potential at a global scale, and this information is essential for accurately assessing the environmental risks caused by N fertilization and establishing crop-specific mitigation strategies.

Our analysis underscores the significance of enhancing SOC levels in alleviating fertilizer-N losses. However, achieving expedited SOC sequestration is a challenging task, given that the current mean SOC sequestration rate of cropland soils globally amounts to only 0.56 mg C ha^{-1} yr^{-1} (Zomer et al., 2017). This stresses the need for innovative strategies and efficient organic amendments to effectively achieve SOC sequestration, which merits urgent attention in future studies.

5 Conclusions

The analysis investigated the patterns, driving factors, and mitigation potential of crop-specific N fertilizer losses at the global scale. Fertilizer-N losses in China exceeded those in the European Union, North America, and other countries/regions, primarily due to higher N application rates and lower SOC levels in China. MAP, SOC content, and soil pH are the key natural or soil parameters influencing fertilizer-N loss proportions in wheat-, maize-, and rice-cropped soils, respectively. The fertilizer-N application rate exhibited a significantly positive correlation with the amount of N losses; at a given application rate, soils with higher SOC levels tended to have lower fertilizer-N losses. Implementing optimized N application rates along with SOC improvement measures could potentially mitigate 34.8%−59.6% of fertilizer-N losses compared to conventional practices without compromising crop yield. This study highlights that optimizing fertilizer-N application in conjunction with SOC-promoting practices could be proposed as a potential approach for the sustainable mitigation of fertilizer-N losses. Future research should focus on innovative strategies and efficient organic amendments to achieve SOC sequestration in the short-term.

Conflict of interest

The authors declare that they have no competing interest.

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Electronic supplementary material

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