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Nitrogen (N) losses from croplands substantially contribute to global N pollution. Assessing the reduction in N losses through improved N management practices is complex due to varying site conditions, such as land use, climate, soil properties and local farming methods. In this Article, we conducted a meta-analysis to evaluate the effects of improved practices on N loss reduction, analysing data from 1,065 studies with 6,753 pairs of observations comparing standard and optimized practices. Without considering site-specific conditions, optimized management practices can reduce N₂O emissions by 3–39%, NH₃ emissions by 15–68%, N run-off by 21–37% and N leaching by 19–52%. After considering local conditions and current practices, average reductions on a global scale were 31% for N₂O, 23% for NH₃, 18% for N run-off and 17% for N leaching. The effectiveness of N loss reduction was mainly influenced by optimized management practices and, to a lesser extent, site conditions. The results of this study underscore the importance of implementing optimized, site-specific management to effectively reduce N losses from global croplands.

Although nitrogen (N) is an essential nutrient for plant growth and agricultural productivity¹, increased N inputs lead to elevated N losses, resulting in detrimental environmental consequences². These losses mainly comprise the emission of nitrous oxide (N₂O) and ammonia (NH₃) to the atmosphere and the leaching and run-off of nitrate into water bodies. These N losses give rise to a range of environmental issues, including climate warming, increased concentration of fine particulate matter in air, ozone depletion, water eutrophication, soil acidification and biodiversity loss^{2,3}. Addressing these issues is crucial to mitigate climate change and promote environmental sustainability⁴.

Addressing the challenges associated with elevated N inputs requires the adoption of sustainable nutrient, crop and soil management practices in agricultural systems. This involves optimizing fertilizer types, application rates, timing and placement to align N supply

with crop N demand, which is known as the 4R nutrient stewardship principle⁵. In addition, promoting crop practices such as straw incorporation, cover cropping and crop diversification can enhance N use efficiency, improve soil health and reduce environmental impacts^{6–8}. Conservation tillage practices, including reduced or zero tillage, can also contribute to the preservation of soil structure and organic matter, further improving nutrient retention and minimizing erosion risks⁹. Also, the addition of biochar has been demonstrated to reduce N losses in soils with low soil fertility, attributed to its ability to enhance soil nutrient retention, increase microbial activity, modify soil pH and facilitate the formation of stable organic N compounds, thereby reducing N losses to air and water^{10,11}. Adopting an integrated approach that combines sustainable nutrient, crop and soil management practices can contribute to the reduction of N losses.

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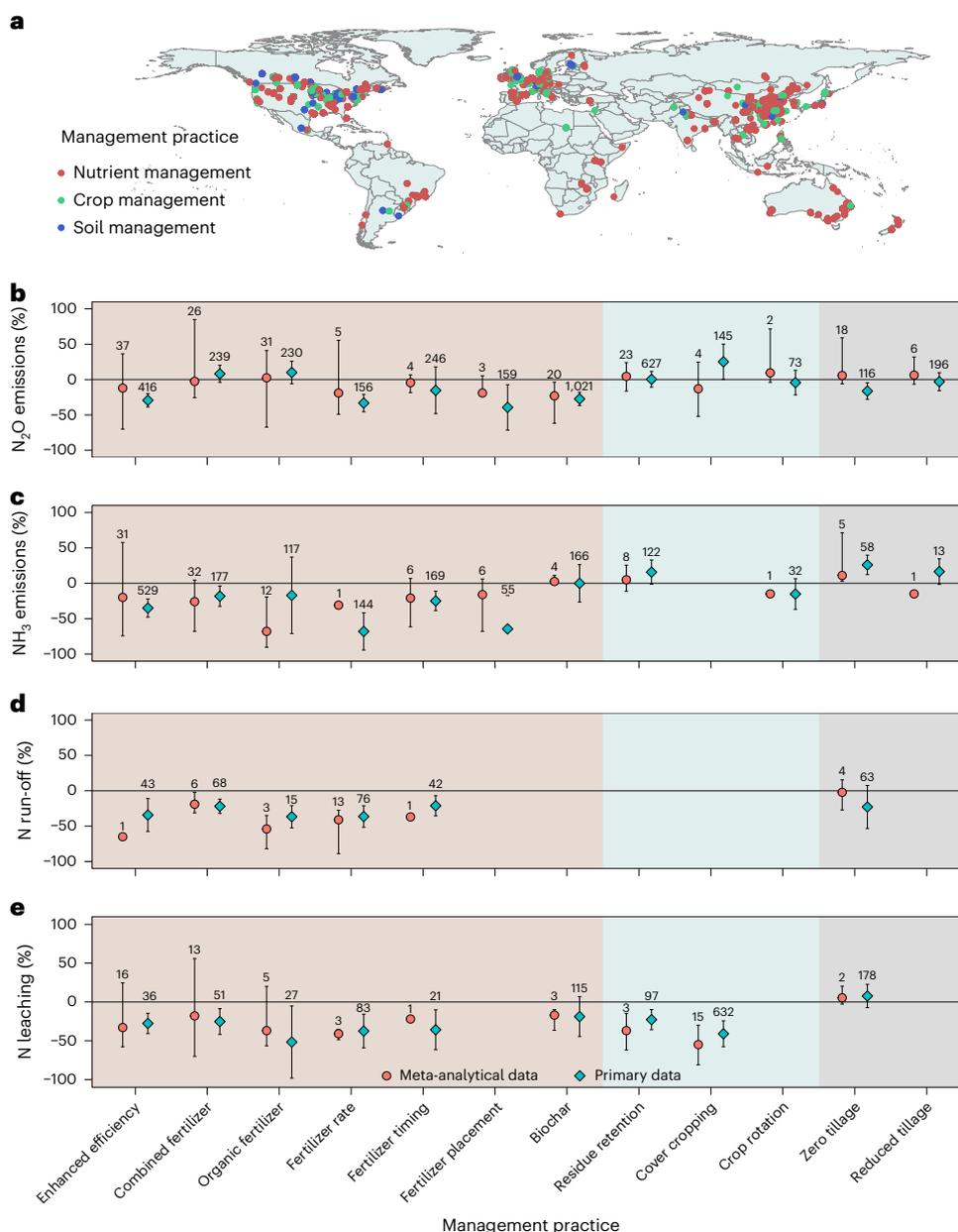


Fig. 1 | Global analysis of management practices on nitrogen losses.

a, Geographical distribution of sample sites of the primary studies included in the global meta-analysis. **b–e**, The effects of management practices on N_2O emissions (**b**), NH_3 emissions (**c**), N run-off (**d**) and N leaching (**e**) based on the meta-analytical data and primary data of the meta-analyses. The data are

presented as mean values (dots); the error bars represent the 95% confidence intervals. The values above the data points indicate the number of observations. The light pink, light green, and light grey shading represent nutrient, crop, and soil management practices, respectively.

Research on the impacts of agricultural management has until now primarily focused on assessing the impacts of individual practices on N uptake and losses^{6–9,12}. For example, in a recent study, Guo et al.¹² explored the effects of fertilizer strategies, including fertilizer sources, application rates and methods, on mitigating global-scale N losses. Some recent comprehensive studies assessed the effects of combined management practices on N uptake¹³ by plants and N losses¹⁴ to air and water at a global scale. However, these studies either did not account for the actual site conditions controlling N uptake and/or losses when aggregating the management-induced impacts on a global scale^{12,14} or did not account for the current adoption of improved management practices when evaluating their potential to increase N uptake¹³ or reduce N losses^{12,14}. Site conditions, including climatic conditions and soil characteristics, are essential for modulating the effectiveness of

management strategies to reduce N losses¹⁵. These conditions can affect soil nutrient availability, soil retention capacity and transport pathways, ultimately influencing the fate of applied N in agricultural systems. Therefore, quantifying the effects of site-specific conditions on the impacts of management practices on N losses is essential for developing efficient strategies to minimize N losses. In addition, it is crucial to account for the current adoption of improved management practices when evaluating their potential to reduce N losses, as illustrated for the impacts of agricultural management practices on NH_3 emissions¹⁶ and soil carbon sequestration¹⁷. This can be done by assessing the spatial variation in current practices, including the areas where improved practices are already applied. However, this integrated approach that accounts for both site conditions and the current adoption of best practices has never been applied in studies

assessing the spatial variation in various N losses simultaneously from global croplands.

In this Article, we used literature-based statistical models to assess and predict the impacts of management practices on N losses to air (NH₃ and N₂O) and water (run-off and leaching) as a function of site conditions and used the results to make site-specific predictions at the global scale. We developed a model that integrates impact estimates from published meta-analyses to predict the change in N losses in response to agronomic practices, denoted hereafter as meta-model. We also developed meta-regression models from field observations to predict N losses based on the original research data used in the published meta-analyses collected. We compared the outcomes of these two approaches to explore the similarities and differences between them. Finally, we assessed the impacts of optimized management practices and site conditions, that is, land use, climate and soil properties, on the spatial variation in N losses at the global scale using this developed meta-regression models. In upscaling the results, we assessed the potential areas where the practices can be applied, correcting for the areas where they are already practiced.

Results

Overall impacts of management practices on N losses

Separate evaluations of the aggregated data from meta-analyses and of the underlying primary data from those studies revealed a consistent trend in their respective outcomes. However, the results derived from the primary data showed a markedly greater level of statistical significance for the management impacts on N leaching, N run-off, and NH₃ and N₂O emissions (Fig. 1b–e) compared with those derived from the published meta-analyses. The analysis based on the primary data indicates a significant reduction in N₂O emissions in response to the use of enhanced efficiency fertilizer (–29%), applying the right fertilizer rate (–33%), right fertilizer placement (–39%), biochar application (–27%) and zero tillage (–16%; Fig. 1b). However, the effect of right fertilizer timing (–15%), crop rotation (–4%), reduced tillage (–3%), combined fertilizer (8%), organic fertilizer (10%), residue retention (0.4%) and cover cropping (25%) on N₂O emissions was not significant ($P > 0.05$). The NH₃ emissions were reduced by enhanced efficiency fertilizer (–35%), combined fertilizer (–18%), and right fertilizer rate (–68%), timing (–25%) and placement (–65%, $P < 0.05$; Fig. 1c). Conversely, zero tillage (26%) increased NH₃ emissions, while residue retention (16%) and reduced tillage (16%) had a positive, but not a significant effect on NH₃ emissions ($P > 0.05$). In addition, organic fertilizer (–17%) and crop rotation (–15%) had no obvious impact on NH₃ emissions ($P > 0.05$). Significant reductions in N run-off resulted from enhanced efficiency fertilizer (–34%), combined fertilizer (–22%), organic fertilizer (–37%), and right fertilizer rate (–36%) and timing (–21%; Fig. 1d). Zero tillage (–23%) had no significant impact on N run-off ($P > 0.05$). In the context of N leaching, nutrient management (enhanced efficiency fertilizer, combined fertilizer, organic fertilizer, right fertilizer rate and timing, and biochar) and crop management (residue retention and cover cropping) consistently reduced the N leaching by between 19% and 52% (Fig. 1e).

Site conditions impact the effectiveness of management practices

The meta-regression analysis of the primary study data showed that the effects of nutrient, crop and soil management practices on N losses were strongly controlled by site conditions (Fig. 2 and Supplementary Table 7). An increase in N application rate led to higher N losses, where the N losses were strongly dependent on crop type, with high N losses particularly occurring for non-cereal crops such as vegetables. Overall, nutrient management was more effective in reducing N losses than crop and soil management. The impact of site conditions on the effect of management on all N losses varied across management practices. For N₂O emissions, this is indicated by the interaction between enhanced

efficiency fertilizer and soil pH, between right fertilizer rate and N application rate, between right fertilizer rate and crop type, between right fertilizer placement and crop type, and between zero tillage and crop type (Fig. 2a). Crop type, soil clay content and mean annual temperature reduced N₂O emissions, while soil pH, soil organic carbon and mean annual precipitation increased N₂O emissions. For NH₃ emissions, the interaction of site conditions and management effects is evidenced by the interaction between combined fertilizer and N application rate, and between residue retention and soil clay content (Fig. 2b). Mean annual precipitation reduced NH₃ emissions, while crop type (rice and wheat), soil pH, soil clay content, soil organic carbon and mean annual temperature increased NH₃ emissions. For N run-off, the interaction of site conditions and management impacts is indicated by the interaction between enhanced efficiency fertilizer and crop type (rice and wheat; Fig. 2c). Also, crop type (rice and wheat), soil clay content and mean annual precipitation reduced N run-off, while soil pH, soil organic carbon and mean annual temperature increased N run-off. Finally, for N leaching, the interacting impact of site conditions and management practices is shown by the interaction between combined fertilizer and soil pH, between combined fertilizer and mean annual precipitation, between right fertilizer rate and N application rate, between right fertilizer rate and soil clay content, between right fertilizer rate and crop type, and between residue retention and crop type (Fig. 2d). Crop type (rice), soil pH and soil organic carbon reduced N leaching, while crop type (wheat), soil clay content, mean annual precipitation and mean annual temperature increased N leaching.

Global potential to decrease N losses

Using the meta-regression model (Fig. 2), we estimated the potential mean effects of optimized management practices on global N losses from cropland (Fig. 3). In addition, we analysed the effect of each practice separately (Supplementary Figs. 2–5). Due to differences in data availability, the evaluated practices varied from twelve for N₂O emissions (Supplementary Fig. 2), nine for NH₃ emissions (Supplementary Fig. 3), six for N run-off (Supplementary Fig. 4) and nine for N leaching (Supplementary Fig. 5).

For N₂O emissions, applying enhanced efficiency fertilizer and combined fertilizer resulted in mean reductions of 4.4% and 0.3%, respectively, compared with mineral fertilizer (Supplementary Fig. 2a,b). Optimal fertilizer rate, timing and placement decreased mean N₂O emissions by 3.7%, 5.5% and 0.1%, respectively (Supplementary Fig. 2d–f). Biochar addition and reduced tillage decreased N₂O emissions by 8.7% and 12.9%, respectively (Supplementary Fig. 2g,i). Combining these seven management practices caused a global mean reduction in N₂O emissions of 31% (Fig. 3a). For NH₃ emissions, enhanced efficiency fertilizer and organic fertilizer resulted in mean reductions of 8% and 0.5%, respectively, but combined fertilizer had no effect (Supplementary Fig. 3a–c). Optimal fertilizer rate, timing and placement resulted in mean reductions of 2.1%, 3.3% and 13.9%, respectively (Supplementary Fig. 3d–f). Crop rotation resulted in a mean reduction in NH₃ emissions of 8.3% (Supplementary Fig. 3h). Combining these seven management practices reduced NH₃ emissions on average by 23% (Fig. 3b). For N run-off, the use of enhanced efficiency fertilizer, combined fertilizer and organic fertilizer led to mean reductions of 3%, 1.1% and 1.7%, respectively (Supplementary Fig. 4a–c). Optimal fertilizer rate and timing led to mean reductions of 0.6% and 3.3%, respectively (Supplementary Fig. 4d,e). Zero tillage led to a mean reduction in N run-off of 14.2% (Supplementary Fig. 4f). The integration of these six management practices reduced global mean N run-off by 18% (Fig. 3c). For N leaching, enhanced efficiency fertilizer, combined fertilizer and organic fertilizer reduced the mean values by 4.6%, 1% and 1.3%, respectively (Supplementary Fig. 5a–c). Optimal fertilizer rate, timing and placement reduced the mean values by 2.1%, 5.1% and 0.2%, respectively (Supplementary Fig. 5d–f). Residue retention and cover cropping reduced the mean values by

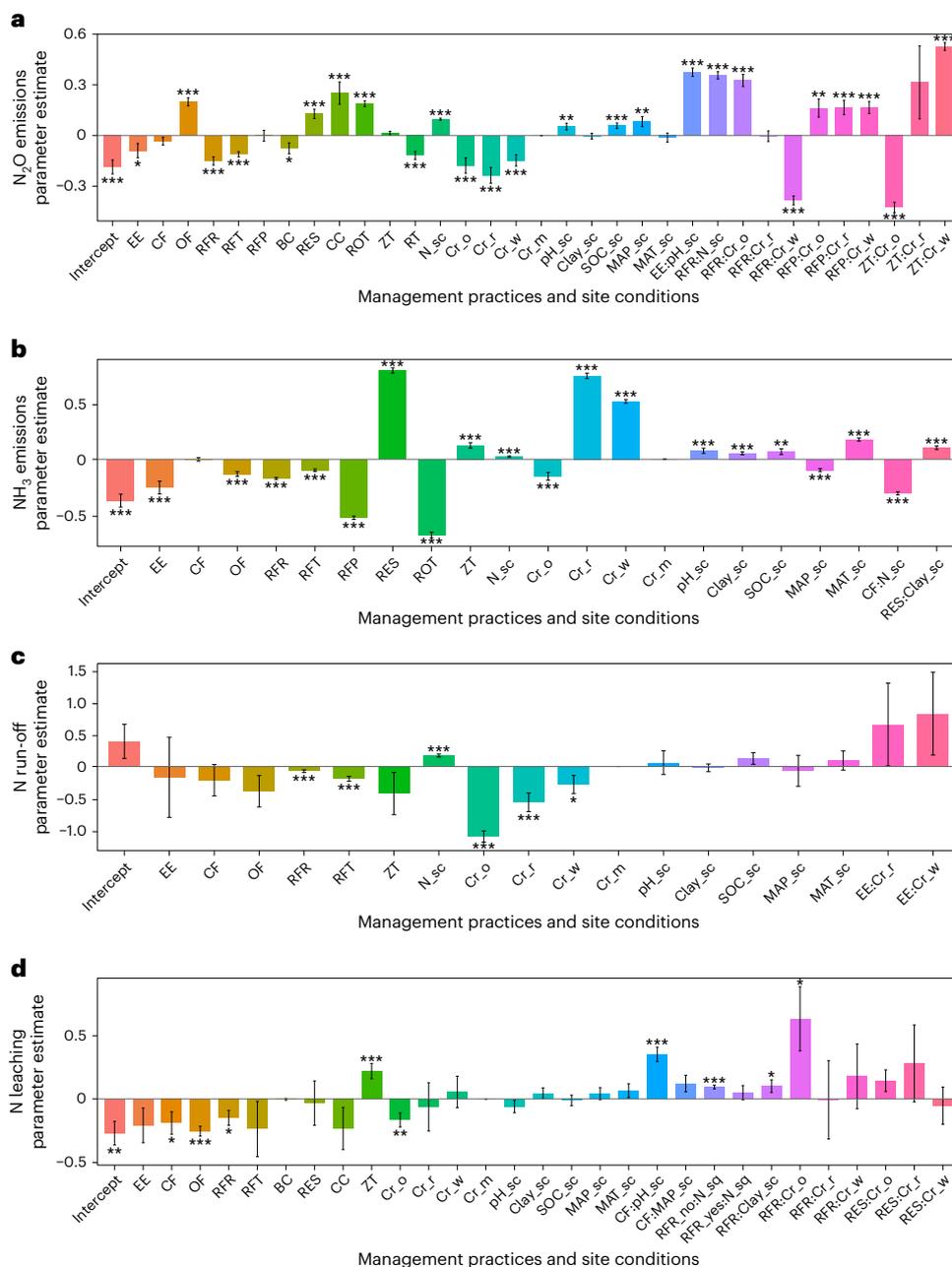


Fig. 2 | Contributions of management practices and site conditions to nitrogen losses. a–d, Parameter estimates for the contribution of management practices and site conditions to the variation in N₂O emissions (a), NH₃ emissions (b), N run-off (c) and N leaching (d). ‘Intercept’ applies to all model terms. The color indicates interactions between variables. All data are presented as mean values (bars); the error bars represent the standard error of the mean. Asterisks represent statistically significant differences ($*P < 0.05$; $**P < 0.01$; $***P < 0.001$). Moderators were tested through analysis of variance (ANOVA) with linear contrasts of model coefficients using the metafor R package⁵⁸. Exact *P* values are

available in Source Data Fig. 2. Nutrient management: EE, enhanced efficiency fertilizer; CF, combined fertilizer; OF, organic fertilizer; RFR, right fertilizer rate; RFT, right fertilizer timing; RFP, right fertilizer placement; BC, Biochar. Crop management: RES, residue retention; CC, cover cropping; ROT, crop rotation. Soil management: ZT, zero tillage; RT, reduced tillage. Site conditions: Cr_o, crop type other; Cr_r, crop type rice; Cr_w, crop type wheat; Cr_m, crop type maize; N_sc, N application rate scaled; Clay_sc, soil clay content scaled; pH_sc, soil pH scaled; MAP_sc, mean annual precipitation scaled; MAT_sc, mean annual temperature scaled. ‘Scaled’ indicates that the numerical variables are scaled to a unit variance.

0.7% and 6.7%, respectively (Supplementary Fig. 5h). On average, the integration of these eight management practices reduced N leaching by 17% (Fig. 3d).

Discussion

Management practices vary in their effects on N losses

Through conducting a meta-analysis of 6,753 paired field observations, we identified 12 key management practices that can be used to mitigate

N losses from global croplands. According to our meta-analysis, nutrient management causes larger reductions in N losses than crop and soil management. In particular, the use of enhanced efficiency fertilizers can have a substantial impact on all N losses (N₂O emissions, NH₃ emissions, N run-off and N leaching) with an average reduction of 28–35%. Compared with urea, one of the N fertilizers most commonly applied, these enhanced efficiency fertilizers can reduce N losses by lowering the rate of soil N conversion^{18–20}.

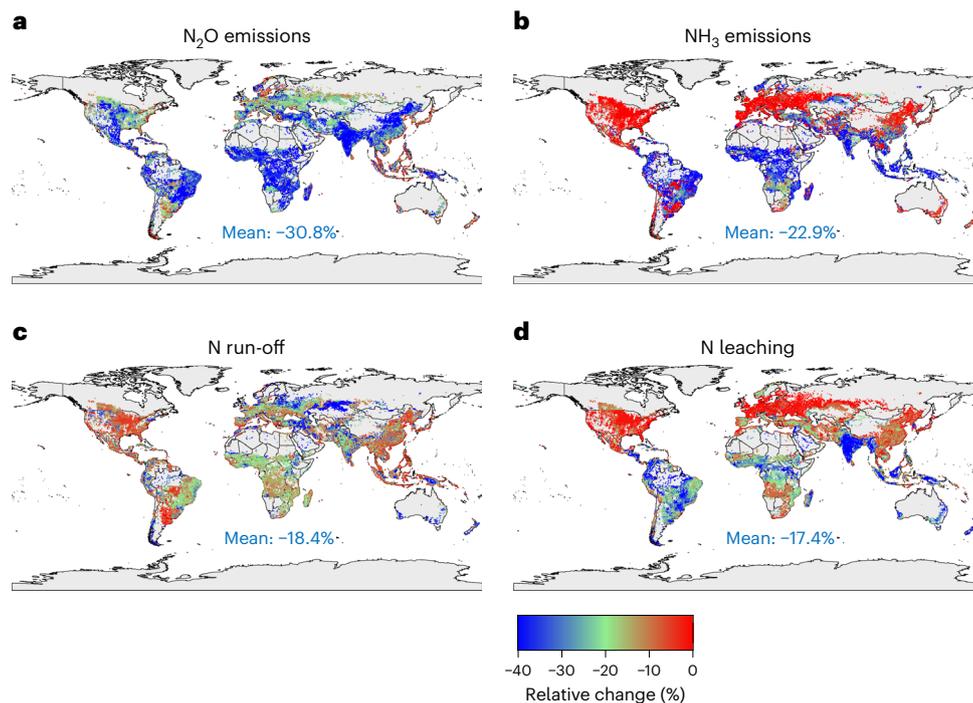


Fig. 3 | Predicted impacts of optimal management practices on nitrogen losses in global croplands. a–d, Predicted spatial variation in the impacts of combined optimal management practices on the relative average changes in N_2O emissions (a), NH_3 emissions (b), N run-off (c) and N leaching (d) in global croplands.

In recent years, the effect of replacing mineral fertilizer with organic fertilizer on N losses has been widely studied. Compared with normal urea, the application of organic fertilizer has been shown to effectively decrease NH_3 emissions, N run-off and N leaching but increase N_2O emissions^{21–24}, which is consistent with the results of this study. Liu et al.²⁵ indicated that a portion of the organic N in organic fertilizer is retained in the soil, leading to lower soil ammonium and nitrate concentrations compared with similar amounts of N applied in synthetic fertilizers. This reduces the risk of N leaching²⁶ and N_2O emissions, which are generated through nitrification and, in the case of N_2O , also by denitrification²⁷. However, the application of organic fertilizer can also stimulate soil microbial activity, including nitrifying and denitrifying bacteria²⁸, thereby promoting denitrification processes and thus the emission of N_2O (refs. 29,30). Note that the beneficial impacts of manure also depend on the adoption of appropriate application technologies according to the 4R principles.

Optimizing fertilizer strategies, including right fertilizer rate, type (for example, urea versus other fertilizer types), timing (for example, split applications) and placement (for example, deep placement), can lead to a 15–68% reduction in N losses according to previous studies^{31–34}. For example, in regions with excessive fertilizer application, reducing the amount of applied fertilizer has led to decreases of 30–35% in N losses³¹. When urea is applied to the soil surface, up to 50% of N is volatilized as NH_3 (ref. 35), whereas the amount of N volatilized is less than 5% when using, for example, calcium ammonium nitrate. During the crop growing season, increased splitting frequency of N fertilizer application, such as timing fertilizer application according to the different growth periods of crops, can effectively reduce N leaching³⁶. Deep placement of fertilizer is more effective in reducing NH_3 emissions than surface application³⁷ because the upward movement of NH_3 is impaired by the soil³⁸. In recent years, accumulating evidence has supported our finding that biochar can reduce N_2O emissions from soil^{18,39–41}. Biochar reduces N_2O emissions via different mechanisms controlled by its properties, such as its capacity to transport electrons^{42,43}, increase soil pH (ref. 44), adsorb denitrification substrates⁴⁵ and alter soil structure⁴¹.

Our research indicates that cover crops can effectively reduce N leaching by N uptake outside the main cropping season while concurrently improving soil fertility by adding carbon into the soil reservoir^{46,47}. The incorporation of carbon leads to a rise in the stock of soil organic carbon in agricultural soils, subsequently enhancing soil water retention capacity and aggregate stability^{47–49}. However, crop management can also lead to an increase in N_2O and NH_3 emissions due to enhanced N release through the decomposition of crop residues on the surface, requiring additional mitigation measures such as their incorporation into soil to minimize these emissions. Also, soil management practice (zero or reduced tillage) increases NH_3 emissions due to the limited use of injection or incorporation techniques that reduce emissions. The results of relevant earlier studies^{35,50,51} are consistent with our findings, specifically, the cumulative NH_3 emissions in zero tillage is three times that of standard tillage after the application of urea–ammonium nitrate solution.

Spatial variation in the effects of management practices on N losses

Significant variation exists in the impacts of management practices on N losses across regions, primarily affected by differences in local site conditions and the occurrence of traditional farming practices and their potential for change. Including both aspects is unique in this Article and has not been considered in any previous study that extended results to a global scale¹⁴. In tropical or subtropical regions, where standard practices are often applied with high losses of NH_3 and N_2O (refs. 14,52,53), the effectiveness of optimized agricultural management is relatively more pronounced. However, the use of N in many of those areas (for example, central Africa) is low and thus the absolute effect is limited. It is noteworthy that some management practices are effective for a certain type of N loss (for example, crop management for N leaching) but counter effective for other N losses (for example, N_2O emissions) and the optimal combination of measures considering those trade-offs may thus lead to lower emission reductions.

When applied on a global scale, the adoption of optimized management practices across global cropland leads to average reductions

of 31% for N_2O , 23% for NH_3 , 18% for N run-off and 17% for N leaching. Recently, Xu et al.¹⁶ estimated a global potential reduction of 38% for NH_3 emissions based on a dataset of 2,775 pairs of field observations of unfertilized and fertilized plots varying in fertilizer type, placement and application time as well as tillage practice, which is higher than our estimate. This might be due to the method used to assess the spatial variation in current practices, highlighting the relevance of adequate upscaling procedures. In addition, the uncertainty in the estimated reduction percentages is large when considering the standard deviation in the effect sizes of the measures (>50% for all N compounds), implying that the maps for the impact of best management practices only give an indication of where the highest impacts might occur. Further research is needed to better unravel the impacts of site conditions on these N losses to allow for a more robust upscaling of the spatial variation in their potential reductions.

Some countries, such as China and India, suffer severe issues as a result of excessive N application⁵⁴. Addressing this situation by optimizing fertilizer application rates in relation to crop demand and unavoidable losses depending on climatic conditions, increasing the frequency of fertilizer application and incorporating enhanced efficiency fertilizers can, therefore, significantly enhance the reduction of N losses^{18,31,34}. These management practices are crucial in regions with excessive N application to contribute to the balance of N inputs and outputs⁴. Therefore, N management needs to consider regional variations and adopt context-specific, sustainable management strategies to balance the demands of agricultural production with environmental conservation to achieve more effective and sustainable use of N resources on a global scale.

Methods

The approach used for data collection and data analysis was similar to that used in our recent comprehensive study on the effects of combined management practices on N use efficiency¹³.

Data collection

Selection of meta-analyses. Following the steps of the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) protocol, we searched for relevant meta-analysis studies published in peer-reviewed journals, estimating the effect of management practices on N losses up to December 2022 using Web of Science (<https://www.webofscience.com>) and Scopus (<https://www.scopus.com>). The search terms included nutrient management (primarily referring to the addition of external materials to farmland, including enhanced efficiency fertilizer, combined fertilizer, organic fertilizer, fertilizer placement, fertilizer rate, fertilizer timing and biochar), crop management (mainly referring to direct interventions in crops, including residue retention, cover cropping and crop rotation), soil management (primarily referring to artificial disturbances to the soil, including zero and reduced tillage), N losses (N_2O emissions, NH_3 emissions, N run-off and leaching) and meta-analysis. The search terms are reported in detail in Supplementary Text 1. We distinguished between N run-off and N leaching as these losses have distinct flow paths leading to the aquatic environment. Run-off is the flow of water over the land surface, carrying soil and pollutants into surface waters. Leaching is the movement of water through the soil, transporting dissolved substances into the groundwater.

We selected 84 reported meta-analyses (Supplementary Table 1) using the following criteria: (1) at least one management practice affects N losses and at least one of the N losses is reported (the management practice should be the only difference between control and treatment, see Supplementary Table 2 for details), (2) limited to field experiments measured at plot scale⁵⁵ (thus excluding laboratory and pot experiments and watershed modelling studies), (3) limited to arable land (crop type must be reported), excluding grasslands and forests, (4) the measurement period covers the whole cropping

season, (5) limited to standard methods of N loss quantification (Supplementary Table 3) and (6) effect sizes were reported as the relative ratio of treatment effect to control. When results of the same plots were reported for several studies, only data from the most recent study were included. For the data presented graphically, the digital software GetData Graph Digitizer 2.25 (<http://getdata-graph-digitizer.com>) was used. The screening process used for the 84 meta-analyses is presented in Supplementary Fig. 1 and the collected data are presented in Supplementary Data 1.

Collection of the primary data from the meta-analyses. From the 1,065 primary studies (duplicates were removed) involved in the 84 meta-analyses, we obtained 6,753 paired observations and extracted the following variables: (1) serial number of reference, (2) geographical distribution of the sample sites, (3) site conditions (climatic conditions and soil properties), (4) crop type, (5) experimental duration, (6) nutrient, crop and soil management practices applied, (7) mean N losses from experimental and control treatments, (8) standard deviation (SD) of practices and (9) number of replicates (estimated to be three when the number of replicates was not given in the report). When studies did not provide the SD or standard errors, we estimated the SD based on the coefficient of variation (CV) being 1.25 times the average CV of other studies in the database to avoid bias in the modelled impacts, a common practice in meta-analyses⁵⁶. When primary studies did not report site conditions that might influence the effect of management practices on N losses, we obtained them from public datasets on climatic conditions and/or soil properties (see the Data availability section for details) based on a given latitude and longitude. The 1,065 primary studies were located in all major agricultural regions, but were unevenly distributed (Fig. 1a). Study sites were mainly located in Asia (48%), North America (27%) and Europe (17%), with fewer sites in Oceania (4%), South America (2%) and Africa (2%; Supplementary Data 2). In total, we extracted 3,624 paired observations for N_2O , 1,582 for NH_3 , 307 for N run-off and 1,240 for N leaching, including both control plots and treatments. The number of management practices being evaluated decreased as follows: biochar application (19%), enhanced efficiency fertilizer (15%), crop residue incorporation (13%), cover cropping (11%), combined fertilizer (8%), fertilizer rate (7%), fertilizer timing (7%), organic fertilizer (6%), zero tillage (6%), fertilizer placement (3%), reduced tillage (3%) and crop rotation (2%).

Data analysis

Definition of meta-model versus meta-regression. We began this study by combining the estimated impacts of previously published meta-analyses, retrieving the predicted impacts of a single measure via the model coefficients of the described models in these studies. When using the term meta-model, we refer to our method for deriving a weighted average of these model estimates from published meta-analyses to obtain a single impact estimate for a specific measure. In addition, we used all original observations collected by the selected meta-analyses to develop a single meta-regression model per N loss pathway, allowing us to use the field observations to disentangle the impacts of measures on N losses while accounting for the site properties controlling these impacts. More details on both approaches are given below.

Estimation of effect sizes of measures. *N losses derived from model estimates in meta-analyses.* We first developed a meta-model based on the presented modelled impact estimates reported in the 84 meta-analyses without using the underlying data. When multiple meta-studies reported the impact of the same management practices on N losses, the weight of the individual effect size was assumed to be inversely proportional to the variance reported and the overall mean change in N losses was calculated as follows⁵⁷:

$$\bar{x} = \frac{\sum (x_i/\sigma_i^2)}{\sum (1/\sigma_i^2)} \quad (1)$$

and

$$\sigma_{\bar{x}} = \frac{1}{\sqrt{\sum 1/\sigma_i^2}} \quad (2)$$

where \bar{x} is the weighted mean of N losses, $\sigma_{\bar{x}}$ is the standard error of the weighted mean, x_i is the individual mean of the reported effect size and σ_i^2 is the individual variance of the reported effect size.

N losses derived from primary data via meta-regression. Using the means, the number of replicates and the SDs of N losses recorded from 1,065 primary studies, we calculated the natural log-transformed response ratio (lnRR, also called the effect size) and its corresponding variance (V_{\lnRR}). The natural log-transformed response ratio helps to mitigate the impact of non-uniform units and enables standardized comparisons across studies or experimental conditions:

$$\lnRR = \ln\left(\frac{X_t}{X_c}\right) \quad (3)$$

$$V_{\lnRR} = \frac{s_t^2}{n_t X_t^2} + \frac{s_c^2}{n_c X_c^2} \quad (4)$$

where X_t and X_c are the means of the treatment and control groups for N losses, respectively, n_t and n_c are the number of replicates of the treatment and control groups, respectively, and s_t and s_c are the SDs of the treatment and control groups, respectively. The relative change in N losses (%) are presented as $(RR - 1) \times 100$. The meta-analysis was performed in R (version 4.3.0) using the metafor package⁵⁸.

Meta-regression model development. We developed a meta-regression model to evaluate soil N losses based on experimental observations used in the collected meta-analytic studies, which we compared with the results of a meta-model that integrates the estimates from these meta-analyses to explore their similarities and differences. This critical examination allowed us to discern the strengths and limitations of each approach, providing insights into the reliability, generalizability and applicability of the findings derived from these distinct data sources. The meta-regression model for N losses was developed in two stages. First, a main factor analysis was performed to assess the main impacts of management practices and site conditions on N losses, excluding the presence of interactions. Then, an optimal meta-regression model selection was performed in which the interactions were also evaluated. Variables were checked for homogeneity, log-transformed where needed and scaled to unit variance before performing the regression.

Main factor analysis using meta-regression. To assess the effect of management practices and site conditions on N losses, we conducted a main factor analysis for all categorical and numerical moderating variables possibly controlling the effect of management on N losses. All nutrient, crop and soil management practices and site conditions were sequentially included in a random effects model to quantify their individual contribution to explaining the variation in N losses. The ANOVA function in R (version 4.3.0) was used to assess the contribution⁵⁸ of each factor as well as the Akaike information criterion (AIC) values for the corresponding factors (Supplementary Tables 5 and 6).

Assessing the integrative impact of management and site properties using meta-regression. As management practices and site conditions might interact, we also evaluated all main and two-way interactions

between variables that significantly influence changes in N losses through a mixed-effects model with interaction terms according to:

$$y_i = \beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + \beta_3 x_{i1} x_{i2} + \dots + u_i + e_i \quad (5)$$

where y_i is the observed effect size (the N loss change due to a management practice) for the i th study, x_{i1} and x_{i2} are the values of the first and second moderator variables for the i th study, respectively, β_0 is a regression coefficient representing the intercept, β_1 and β_2 are the regression coefficients indicating how the average true effect size changes for one unit increase in x_{i1} and x_{i2} , respectively, u_i is the variance of the true effect (residual heterogeneity) of study i , e_i is the sampling error of study i and $x_{i1} x_{i2}$ is the interaction term with coefficient β_3 . The following moderator variables (site conditions) were included: crop type, N amount (as a linear and quadratic term), soil pH, soil clay content, soil organic carbon, mean annual precipitation and mean annual transpiration. Uncertainties in predicted N loss changes were derived by calculating the 95% confidence interval around the predicted mean change using equation (5).

The forward selection method was used for model fitting, which means that management practices and site conditions were added one by one to the meta-regression model⁵⁹. AIC and likelihood ratio tests were used to compare the goodness of fit of the meta-regression models. The lower the AIC value and the higher the log-likelihood ratio, the better the fit of the model⁵⁹. In addition, we also checked the amount of residual heterogeneity based on Q_e (ref. 56), which represents the heterogeneity that cannot be explained by the meta-regression model and is included in the default output of the `rma.mv` function. Thus, the smaller the Q_e , the more explanatory variability and the better the performance of the model. In evaluating the fit of the meta-regression models, we followed the concept of parsimony (that is, a well-fitted model with less variables is preferred over a model with more variables)⁵⁹ to achieve a balance between complexity and performance

Assessing the global potential to decrease N losses. The analysed impacts of the various management practices were extended to global reduction potentials (% of the current practice) for the emissions of N_2O and NH_3 into the atmosphere and the leaching and run-off of nitrate into bodies of water by multiplying them by the potential area where the practice could be applied, corrected for the areas where it is already practiced. This was done by applying the meta-regression model to each of the 0.5° grid cells using global datasets for climate conditions, soil properties and local farming practices (see the Data availability section). As the impacts strongly depend on the actual management practices being applied, we first derived global maps of current practices following the procedures outlined by Lessmann et al.¹⁷. In summary, we combined spatially explicit data from the Koeppen–Geiger classification map⁶⁰, the Spatial Production Allocation Model (SPAM) for land use⁶¹, maps of N fertilizer application rates⁶², N manure production and application rates on cropland and grassland^{63,64}, the global tillage system dataset⁶⁵, and the Food and Agricultural Organization (FAO) of the United Nations databases on cropping systems⁶⁶, crop residue retention⁶⁷ and crop residue burning⁶⁸. These analyses resulted in a spatial dataset that allows assessment of the potential areas for application of the agronomic measures evaluated here: enhanced efficiency fertilizer, combined fertilizer, organic fertilizer, fertilizer placement, fertilizer rate, fertilizer timing and biochar (all nutrient management), residue retention, cover cropping and crop rotation (all crop management), and zero and reduced tillage (all soil management) as summarized below.

Applicability of nutrient management practices. To assess the impacts of using combined fertilizer or organic fertilizer, we only applied these measures in areas where part of the manure was not yet applied, calculated as the difference between produced (excreted) manure

minus the manure that is left on pasture used for grazing minus the N manure already applied on cropland and grassland according to Lessman et al.¹⁷. This implies that the benefits of manure only occur in those areas where currently part of the manure is not yet recycled and thus wasted.

The current and potential applications of enhanced efficiency fertilizer and improved fertilizer placement and timing were based on the agricultural technology level, as given by the SPAM dataset. SPAM includes a global map of cropland that is categorized according to the technology level, including the categories low technology, high technology, irrigated or rainfed. We classified grid cells as having a low technology level when the cropland area with this technology level was more than 50% of the total cropland area. In those areas, we assumed that there is full potential for the application of efficiency fertilizers (including synthetic inhibitor or coated fertilizer) and for optimizing the timing and placement of fertilizers to reduce N losses to air and water. Inversely, we assumed that these three measures are fully practiced, and thus are not effective, in the areas with a high technology level given the higher incomes and higher pressures on and regulations for environmental targets in agriculture.

The measure of fertilizer application rate is particularly relevant for areas where the current N use efficiency (NUE), estimated as the fraction of the effective N input via fertilizer, manure, deposition and fixation used by the crop, is low. Using the global NUE map of IMAGE (0.5° grid cells for cropland⁶⁹), we assumed that measures optimizing the fertilizer amount are only applicable in areas where NUE is less than 0.5. For biochar, we assumed hypothetically that it can be applied everywhere, although its availability might be limited due to the absence of sufficient biomass and high energy costs.

Applicability of crop management practices. From the FAO databases, Lessmann et al.¹⁷ retrieved estimates of the total carbon lost via the burning of crop residues as well as the total carbon entering the soil via above-ground crop residues. They then estimated the area of land where the burning of crop residues is the common practice (category BURN) and where sufficient straw is available to be incorporated (assumed from the total harvestable area with cereals per country). The remaining cropland area was classified as the area where crop residues are incorporated into the soil or left on the surface (category INC). For the current upscaling of N losses, we assumed that all grid cells where more than 25% of the total cropland area does not yet incorporate residues (category BURN) are areas where the measure of residue retention is applicable.

Lessmann et al.¹⁷ estimated per country and climate zone the potential area of cropland where catch crops can be applied. As in that study, we assumed that for all grid cells where less than 25% of the total cropland area per country-climate zone was used for catch crops, the measure of cover cropping was applicable to reduce N losses to air and water.

Using the crop intensity maps generated by Liu et al.⁷⁰, we estimated where biodiversification through crop rotation can be applied as a measure. The original dataset describes the distribution of cropping intensity using satellite data from the period 2001–2019 at 250 m resolution. This dataset was rescaled to a resolution of 0.5°, calculating the mean cropping intensity per grid cell. All grid cells where the cropping intensity is less than 1 are considered as potential areas where crop rotation (more variation in crops over time) can be applied as a measure to reduce N losses.

Applicability of soil management practices. Insights into the current application of tillage and the potentially suitable area to apply zero tillage (conservation agriculture) were derived from a global tillage system dataset⁶⁵. Areas identified with high- and intermediate-intensity tillage have the potential to be converted to zero or reduced tillage. We considered all grid cells where the area with conservation agriculture

(no tillage) was less than 50% of the total cropland area as being relevant for the application of the zero or reduced tillage measure. For all cropland areas where data were missing (in <1% of the total cropland area), we assumed that none of the above nutrient, crop or soil practices has been applied.

Assessment of the combined impacts of best management practices. In our integrative meta-regression models, we assessed the impact of improved management practices compared with a standard practice, accounting for all other accompanying practices implemented, which vary per study or even sometimes observation. This implies that the estimated impact of a measure also includes the variation in other management measures, thereby implicitly accounting for interactions between measures. We thus added site-specific effects of different nutrient, crop and soil management measures. We note that accompanying practices applied in the field trials from which the observations were retrieved are generally standard practice, implying that the estimated combination of measures might be overestimated, but no simple method exists to correct for that. In addition, we did not account for possible trade-offs or co-benefits of measures among the different nitrogen compounds as the selected meta-analyses did not include such trade-offs or co-benefits, and this also holds for the underlying data. Our study thus focused on evaluating the impacts of measures and the combined impacts of best management practices for specific N compounds. The impacts of different measures on other N compounds were thus not included in the upscaling, which may cause higher or lower effects if the combination of measures was optimized for all N compounds together.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The site condition data (climate conditions, soil properties and local farming practices) used in this Article were obtained from openly accessible data sources, including (1) climate data (including mean annual temperature and mean annual precipitation) obtained from the Climatic Research Unit of East Anglia University (<https://crudata.uea.ac.uk/cru/data/hrg>), (2) soil properties (comprising soil clay content, soil organic carbon and soil pH) extracted from the soil grids provided by ISRIC (<http://www.isric.org/explore/soilgrids>), (3) N inputs from fertilizers and manure from PANGAEA (<https://doi.org/10.1594/PANGAEA.871980>)⁷¹, (4) global nitrogen use efficiency on cropland as calculated with the IMAGE model⁶⁹, (5) land-use data from the Spatial Production Allocation Model (<https://www.mapspam.info/data>) and (6) FAO databases for agricultural production, crop residues and burning of crop residues, retrieved from FAOSTAT^{66–68} (www.fao.org/faostat). The data that we collected from the literature are available from GitHub at https://github.com/gerardhros/phd_luncheng/tree/main/articles/paper3. Source data are provided with this paper.

Code availability

Data were structured and coded using Microsoft Excel 2019. Data were analysed using custom code written in R (version 4.3.0). We made use of R packages metafor, metagear, data.table, terra and ggplot2. The code used in this Article can be downloaded from GitHub at https://github.com/gerardhros/phd_luncheng/tree/main/articles/paper3.

References

1. Gojon, A. Nitrogen nutrition in plants: rapid progress and new challenges. *J. Exp. Bot.* **68**, 2457–2462 (2017).
2. Erisman, J. W. et al. Consequences of human modification of the global nitrogen cycle. *Philos. Trans. R. Soc. Lond. B* **368**, 20130116 (2013).

3. Steffen, W. et al. Planetary boundaries: guiding human development on a changing planet. *Science* **347**, 1259855 (2015).
4. Zhang, X. et al. Managing nitrogen for sustainable development. *Nature* **528**, 51–59 (2015).
5. Snyder, C. S. Enhanced nitrogen fertiliser technologies support the '4R' concept to optimise crop production and minimise environmental losses. *Soil Res.* **55**, 463–472 (2017).
6. Hansen, E. M., Munkholm, L. J., Melander, B. & Olesen, J. E. Can non-inversion tillage and straw retention reduce N leaching in cereal-based crop rotations? *Soil Tillage Res.* **109**, 1–8 (2010).
7. Liu, S. et al. Fifteen years of crop rotation combined with straw management alters the nitrogen supply capacity of upland-paddy soil. *Soil Tillage Res.* **215**, 105219 (2022).
8. Qi, J., Jensen, J. L., Christensen, B. T. & Munkholm, L. J. Soil structural stability following decades of straw incorporation and use of ryegrass cover crops. *Geoderma* **406**, 115463 (2022).
9. Busari, M. A., Kukul, S. S., Kaur, A., Bhatt, R. & Dulazi, A. A. Conservation tillage impacts on soil, crop and the environment. *Int. Soil Water Conserv. Res.* **3**, 119–129 (2015).
10. Xia, L. et al. Integrated biochar solutions can achieve carbon-neutral staple crop production. *Nat. Food* **4**, 236–246 (2023).
11. Xu, W. et al. Global meta-analysis reveals positive effects of biochar on soil microbial diversity. *Geoderma* **436**, 116528 (2023).
12. Guo, C., Liu, X. & He, X. A global meta-analysis of crop yield and agricultural greenhouse gas emissions under nitrogen fertilizer application. *Sci. Total Environ.* **831**, 154982 (2022).
13. You, L. et al. Global mean nitrogen recovery efficiency in croplands can be enhanced by optimal nutrient, crop and soil management practices. *Nat. Commun.* **14**, 5747 (2023).
14. Gu, B. et al. Cost-effective mitigation of nitrogen pollution from global croplands. *Nature* **613**, 77–84 (2023).
15. Licker, R. et al. Mind the gap: how do climate and agricultural management explain the 'yield gap' of croplands around the world? *Glob. Ecol. Biogeogr.* **19**, 769–782 (2010).
16. Xu, P. et al. Fertilizer management for global ammonia emission reduction. *Nature* **626**, 792–798 (2024).
17. Lessmann, M., Ros, G. H., Young, M. D. & de Vries, W. Global variation in soil carbon sequestration potential through improved cropland management. *Glob. Change Biol.* **28**, 1162–1177 (2021).
18. Akiyama, H., Yan, X. & Yagi, K. Evaluation of effectiveness of enhanced-efficiency fertilizers as mitigation options for N₂O and NO emissions from agricultural soils: meta-analysis. *Glob. Change Biol.* **16**, 1837–1846 (2010).
19. Lam, S. K. et al. Decreasing ammonia loss from an Australian pasture with the use of enhanced efficiency fertilizers. *Agric. Ecosyst. Environ.* **283**, 106553 (2019).
20. Suman, J. et al. Enhanced efficiency N fertilizers: an effective strategy to improve use efficiency and ecological sustainability. *J. Soil Sci. Plant Nutr.* **23**, 1472–1488 (2023).
21. Liu, M. et al. Organic fertilizer substitutions maintain maize yield and mitigate ammonia emissions but increase nitrous oxide emissions. *Environ. Sci. Pollut. Res.* **30**, 53115–53127 (2023).
22. Shakoor, A. et al. Nitrous oxide emission from agricultural soils: application of animal manure or biochar? A global meta-analysis. *J. Environ. Manage.* **285**, 112170 (2021).
23. Wei, Z., Hoffland, E., Zhuang, M., Hellegers, P. & Cui, Z. Organic inputs to reduce nitrogen export via leaching and runoff: a global meta-analysis. *Environ. Pollut.* **291**, 118176 (2021).
24. Zhang, T. et al. Long-term manure application increased greenhouse gas emissions but had no effect on ammonia volatilization in a Northern China upland field. *Sci. Total Environ.* **633**, 230–239 (2018).
25. Liu, B., Wang, X., Ma, L., Chadwick, D. & Chen, X. Combined applications of organic and synthetic nitrogen fertilizers for improving crop yield and reducing reactive nitrogen losses from China's vegetable systems: a meta-analysis. *Environ. Pollut.* **269**, 116143 (2021).
26. Cui, Z., Yue, S., Wang, G., Zhang, F. & Chen, X. In-season root-zone N management for mitigating greenhouse gas emission and reactive N losses in intensive wheat production. *Environ. Sci. Technol.* **47**, 6015–6022 (2013).
27. You, L. et al. Global meta-analysis of terrestrial nitrous oxide emissions and associated functional genes under nitrogen addition. *Soil Biol. Biochem.* **165**, 108523 (2022).
28. Zhang, X. et al. Benefits and trade-offs of replacing synthetic fertilizers by animal manures in crop production in China: a meta-analysis. *Glob. Change Biol.* **26**, 888–900 (2019).
29. Severin, M., Fuß, R., Well, R., Garlipp, F. & Van den Weghe, H. Soil, slurry and application effects on greenhouse gas emissions. *Plant Soil Environ.* **61**, 344–351 (2015).
30. Velthof, G. L. & Mosquera, J. The impact of slurry application technique on nitrous oxide emission from agricultural soils. *Agric. Ecosyst. Environ.* **140**, 298–308 (2011).
31. Xia, L. et al. Can knowledge-based N management produce more staple grain with lower greenhouse gas emission and reactive nitrogen pollution? A meta-analysis. *Glob. Change Biol.* **23**, 1917–1925 (2016).
32. Huang, S. et al. Effects of fertilizer management practices on yield-scaled ammonia emissions from croplands in China: a meta-analysis. *Field Crops Res.* **192**, 118–125 (2016).
33. Sha, Z. et al. Improved soil-crop system management aids in NH₃ emission mitigation in China. *Environ. Pollut.* **289**, 117844 (2021).
34. Ju, X. et al. Reducing environmental risk by improving N management in intensive Chinese agricultural systems. *Proc. Natl Acad. Sci. USA* **106**, 3041–3046 (2009).
35. Sommer, S. G., Schjoerring, J. K. & Denmead, O. Ammonia emission from mineral fertilizers and fertilized crops. *Adv. Agron.* **82**, 82008–82004 (2004).
36. Kabir, T., De Laporte, A., Nasielski, J. & Weersink, A. Adjusting nitrogen rates with split applications: modelled effects on N losses and profits across weather scenarios. *Eur. J. Agron.* **129**, 126328 (2021).
37. Wu, P. et al. Suitable fertilizer application depth can increase nitrogen use efficiency and maize yield by reducing gaseous nitrogen losses. *Sci. Total Environ.* **781**, 146787 (2021).
38. Yao, Y. et al. Urea deep placement for minimizing NH₃ loss in an intensive rice cropping system. *Field Crops Res.* **218**, 254–266 (2018).
39. Case, S. D. C., McNamara, N. P., Reay, D. S. & Whitaker, J. The effect of biochar addition on N₂O and CO₂ emissions from a sandy loam soil—the role of soil aeration. *Soil Biol. Biochem.* **51**, 125–134 (2012).
40. Chintala, R. et al. Denitrification kinetics in biomass- and biochar-amended soils of different landscape positions. *Environ. Sci. Pollut. Res. Int.* **22**, 5152–5163 (2015).
41. Yanai, Y., Toyota, K. & Okazaki, M. Effects of charcoal addition on N₂O emissions from soil resulting from rewetting air-dried soil in short-term laboratory experiments. *Soil Sci. Plant. Nutr.* **53**, 181–188 (2007).
42. Cayuela, M. L. et al. Biochar and denitrification in soils: when, how much and why does biochar reduce N₂O emissions? *Sci. Rep.* **3**, 1732 (2013).
43. Kappler, A. et al. Biochar as an electron shuttle between bacteria and Fe(III) minerals. *Environ. Sci. Technol. Lett.* **1**, 339–344 (2014).
44. Van Zwieten, L. et al. in *Biochar for Environmental Management* (eds Lehmann, J. & Joseph, S.) Ch. 13 (Routledge, 2012).

45. LeCroy, C., Masiello, C. A., Rudgers, J. A., Hockaday, W. C. & Silberg, J. J. Nitrogen, biochar, and mycorrhizae: alteration of the symbiosis and oxidation of the char surface. *Soil Biol. Biochem.* **58**, 248–254 (2013).
46. Hillel, D., Hatfield, J. & Sauer, T. *Soil Management: Building a Stable Base for Agriculture* (Wiley Online Library, 2011).
47. Abdalla, M. et al. A critical review of the impacts of cover crops on nitrogen leaching, net greenhouse gas balance and crop productivity. *Glob. Change Biol.* **25**, 2530–2543 (2019).
48. Drinkwater, L. E. & Snapp, S. Nutrients in agroecosystems: rethinking the management paradigm. *Adv. Agron.* **92**, 163–186 (2007).
49. Haruna, S. I. & Nkongolo, N. V. Cover crop management effects on soil physical and biological properties. *Procedia Environ. Sci.* **29**, 13–14 (2015).
50. Al-Kanani, T. & MacKenzie, A. Effect of tillage practices and hay straw on ammonia volatilization from nitrogen fertilizer solutions. *Can. J. Soil Sci.* **72**, 145–157 (1992).
51. Rochette, P. et al. Ammonia volatilization following surface application of urea to tilled and no-till soils: a laboratory comparison. *Soil Tillage Res.* **103**, 310–315 (2009).
52. Galloway, J. N. et al. Nitrogen cycles: past, present, and future. *Biogeochemistry* **70**, 153–226 (2004).
53. Gruber, N. & Galloway, J. N. An Earth-system perspective of the global nitrogen cycle. *Nature* **451**, 293–296 (2008).
54. Heffer, P., Gruère, A. & Roberts, T. *Assessment of Fertilizer Use by Crop at the Global Level* (International Fertilizer Industry Association, 2013).
55. Zhang, X. et al. Quantifying nutrient budgets for sustainable nutrient management. *Glob. Biogeochem. Cycles* **34**, e2018GB006060 (2020).
56. Ros, G. H., van Rotterdam, A. M. D., Bussink, D. W. & Bindraban, P. S. Selenium fertilization strategies for bio-fortification of food: an agro-ecosystem approach. *Plant Soil* **404**, 99–112 (2016).
57. Young, M. D., Ros, G. H. & de Vries, W. A decision support framework assessing management impacts on crop yield, soil carbon changes and nitrogen losses to the environment. *Eur. J. Soil Sci.* **72**, 1590–1606 (2020).
58. Viechtbauer, W. Conducting meta-analyses in R with the metafor package. *J. Stat. Softw.* **36**, 1–48 (2010).
59. Harrer, M., Cuijpers, P., Furukawa, T. & Ebert, D. D. *Doing Meta-Analysis with R: A Hands-On Guide* (Chapman and Hall/CRC, 2021).
60. Peel, M. C., Finlayson, B. L. & McMahon, T. A. Updated world map of the Köppen-Geiger climate classification. *Hydrol. Earth Syst. Sci.* **11**, 1633–1644 (2007).
61. Wood-Sichra, U., Joglekar, A. B. & You, L. *Spatial Production Allocation Model (SPAM) 2005: Technical Documentation Harvest Choice Working Paper* (IFPRI, 2016).
62. Lu, C. Q. & Tian, H. Q. Global nitrogen and phosphorus fertilizer use for agriculture production in the past half century: shifted hot spots and nutrient imbalance. *Earth Syst. Sci. Data* **9**, 181–192 (2017).
63. Xu, R. T. et al. Increased nitrogen enrichment and shifted patterns in the world's grassland: 1860–2016. *Earth Syst. Sci. Data* **11**, 175–187 (2019).
64. Zhang, B. et al. Global manure nitrogen production and application in cropland during 1860–2014: a 5 arcmin gridded global dataset for Earth system modeling. *Earth Syst. Sci. Data* **9**, 667–678 (2017).
65. Porwollik, V., Rolinski, S., Heinke, J. & Müller, C. Generating a rule-based global gridded tillage dataset. *Earth Syst. Sci. Data* **11**, 823–843 (2019).
66. FAO/STAT *Agricultural Production, Crops Primary* (FAO, 2020); <http://www.fao.org/faostat/en/#data/QC/visualize>
67. FAO/STAT *Emissions Database, Agriculture—Crop Residues* (FAO, 2020); <http://www.fao.org/faostat/en/#data/GA>
68. FAO/STAT *Emissions Database, Agriculture, Burning—Crop Residues* (FAO, 2020); <http://www.fao.org/faostat/en/#data/GB>
69. Schulte-Uebbing, L. F., Beusen, A. H. W., Bouwman, A. F. & de Vries, W. From planetary to regional boundaries for agricultural nitrogen pollution. *Nature* **610**, 507–512 (2022).
70. Liu, X. et al. Annual dynamic dataset of global cropping intensity from 2001 to 2019. *Sci. Data* **8**, 283 (2021).
71. Zhang, B. et al. Manure nitrogen production and application in cropland and rangeland during 1860–2014: a 5-minute gridded global data set for Earth system modeling. *PANGAEA* <https://doi.org/10.1594/PANGAEA.871980> (2017).

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Author contributions

L.Y., G.H.R., Y.C. and W.d.V. conceived and designed the study. Data collection fieldwork was led and supervised by G.H.R. and W.d.V. The data were collected by L.Y. The analysis was conducted by L.Y. and G.H.R. Figures were produced by L.Y. with the help of G.H.R. The results were critically assessed and interpreted by L.Y., G.H.R., Y.C., F.Z. and W.d.V. The draft paper was written by L.Y., G.H.R., Y.C. and W.d.V. All authors edited and approved the paper.

Competing interests

The authors declare no competing interests.

Additional information

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Data collection Literature survey was conducted in Web of Science (<https://www.webofscience.com>). For the data presented graphically, the digital software GetData Graph Digitizer 2.25 (<http://getdata-graph-digitizer.com>) was used. Data were structured and coded using Microsoft Excel 2019.

Data analysis Data were analysed using custom code written in R version 4.3.0. We made use of R packages metafor, metagear, data.table, terra, and ggplot2. Code is available on GitHub at https://github.com/gerardhros/phd_luncheng/tree/main/articles/paper3.

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Data regarding site factors (climate conditions, soil properties, and local traditional farming practices) used in this study were obtained from openly accessible data sources, including: (1) climate data, including mean annual temperature (MAT) and mean annual precipitation (MAP), obtained from CRU (<https://>

crudata.uea.ac.uk/cru/data/hrg/), (2) soil properties, comprising soil clay content, soil organic carbon, and soil pH, extracted from the soil grids provided by ISRIC (<http://www.isric.org/explore/soilgrids>), (3) N inputs from fertilizers and manure (<https://doi.pangaea.de/10.1594/PANGAEA.871980>), (4) the global nitrogen use efficiency on cropland as being calculated by the IMAGE model, (5) land use data from the Spatial Production Allocation Model (<https://www.mapspam.info/data>), and (6) FAO databases for agricultural production, crop residues and burning of crop residues are retrieved from FAOSTAT available at www.fao.org/faostat. Collected data for the meta-analysis are available within the paper or the supplementary information. All source data (incl. data from the literature review and upscaling) are provided with this paper and are available from GitHub at https://github.com/gerardhros/phd_luncheng/tree/main/articles/paper3.

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Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	In this study, we used meta-analytical and meta-regression models, to evaluate and predict the impacts of management practices on N losses as a function of site factors. We first developed a meta-model by combining existing meta-analytical regression models (n = 84) to predict the change in N losses in response to agronomic practices and its dependency on site factors. We compared these outcomes to the results of a single meta-regression model based on 6,753 paired observations from 1,065 primary studies. We finally evaluated the impact of management and site factors controlling N losses, and applied this model to predict the spatial variation of the potential impact of agronomic management practices on N losses as a function of site factors at a global scale.
Research sample	For meta-analytical data, we performed a literature search for meta-analytical studies on the effect sizes for N losses in response to changes in nutrient, crop and soil management. Searches were performed using Web of Science (https://www.webofscience.com) with search terms (detail see Supplementary Text 1). This search and selection resulted in the inclusion of 84 studies. For primary data, the relevant crop, soil and nutrient management data and site-specific factors were retrieved from the 1,065 primary studies based on the above 84 meta-analytical studies. This resulted in 6,753 paired observations. We estimated the global potential for N losses changes on a 0.5 x 0.5 degree resolution using existing global data sets: (1) climate data, including mean annual temperature (MAT) and mean annual precipitation (MAP), obtained from CRU (http://www.cru.uea.ac.uk/data), (2) soil properties, comprising soil clay content, soil organic carbon, and soil pH, extracted from the soil grids provided by ISRIC (http://www.isric.org/explore/soilgrids), (3) N inputs from fertilizers and manure (https://doi.pangaea.de/10.1594/PANGAEA.871980), (4) the global nitrogen use efficiency on cropland as being calculated by the IMAGE model, and (5) land use data from the Spatial Production Allocation Model (https://www.mapspam.info/data).
Sampling strategy	The 84 meta-analytical studies included four criteria: (1) linked to at least one management practice to the impact of N losses; (2) limited to management of croplands, excluding grasslands and forests; (3) providing estimates based on field studies, thus excluding laboratory or incubation studies; and (4) when meta-analytical studies presented a summary of previous analyses, only the most recent study was selected. For the 1,065 primary studies, the following variables were extracted: (1) serial number of reference; (2) geographical distribution of the sample sites; (3) site conditions (climatic conditions and soil properties); (4) crop type; (5) experimental duration; (6) nutrient, crop and soil management practices applied; (7) mean N losses in experimental and control treatments; (8) standard deviation (SD) of practices; and (9) number of replicates (estimated to be three when the number of replicates was not given in the report).
Data collection	Luncheng You conducted the literature search, screened all literature, extracted all the effect sizes, and coded the information from the studies.
Timing and spatial scale	We collected the meta-analytical data from publications before December 2022. Following peer-review process, we updated our search string in Supplementary Text 1. The included studies were published between 2004 and 2022.
Data exclusions	Limited to management of croplands, excluding grasslands and forests. Providing estimates based on field studies, thus excluding laboratory or incubation studies.

Reproducibility	Our study is an integrated study mainly based on meta-model and published reference data. Our results can be reproduced when following the described methods and data.
Randomization	This is not relevant to our study because our work is not an "Experimental" study but an integrated data analysis. We used global datasets and published reference data to do the integrated analysis.
Blinding	Blinding is not possible in our study. Because we have no choice to collect the global datasets or published reference data (just according to key words) considering the blinding principle.

Did the study involve field work? Yes No

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involvement in the study
<input checked="" type="checkbox"/>	<input type="checkbox"/> Antibodies
<input checked="" type="checkbox"/>	<input type="checkbox"/> Eukaryotic cell lines
<input checked="" type="checkbox"/>	<input type="checkbox"/> Palaeontology and archaeology
<input checked="" type="checkbox"/>	<input type="checkbox"/> Animals and other organisms
<input checked="" type="checkbox"/>	<input type="checkbox"/> Clinical data
<input checked="" type="checkbox"/>	<input type="checkbox"/> Dual use research of concern

Methods

n/a	Involvement in the study
<input checked="" type="checkbox"/>	<input type="checkbox"/> ChIP-seq
<input checked="" type="checkbox"/>	<input type="checkbox"/> Flow cytometry
<input checked="" type="checkbox"/>	<input type="checkbox"/> MRI-based neuroimaging