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Predicting the Ratio of Nitrification to Immobilization to Reflect the Potential Risk of Nitrogen Loss Worldwide

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Title: Predicting the ratio of nitrification to immobilization to reflect the potential risk of nitrogen loss worldwide

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Please insert "[O]" after Yushu Zhang and Baobao Pan to indicated contributed they equally to this work.

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Abstract

Nitrification and immobilization compete for soil ammonium (NH_4^+); the relative dominance of these two processes has been suggested to reflect the potential risk of nitrogen loss from soils. Here we compiled a database and developed Stochastic Gradient Boosting (SGB) model to predict global potential risk of nitrogen loss based on the ratio of nitrification to immobilization (N/I). We then conducted a meta-analysis to evaluate the effects of common management practices on the N/I ratio. The results showed that soil N/I ratio varied with climate zones and land use. Soil total carbon, total nitrogen, pH, fertilizer nitrogen application rate, mean annual temperature and mean annual precipitation are important factors of soil N/I ratio. Meta-analysis indicated that biochar, straw and nitrification inhibitor application reduced soil N/I ratio by 67%, 64% and 78%, respectively. Returning plantation to forest and cropland to grassland decreased soil N/I ratio by 88% and 45%, respectively. However, fertilizer nitrogen application increased soil N/I ratio by 92%. Our study showed that soil N/I ratio and its associated risk level of nitrogen loss were highly related to long-term soil and environmental properties with high spatial heterogeneity.

Keywords Nitrate loss; Nitrification; Immobilization; Land use types; Climatic regions

INTRODUCTION

Nitrogen in soil is an important plant nutrient, but its loss to the environment is ecologically and economically undesirable. Nitrate (NO_3^-) is readily lost via leaching or transformed to gaseous nitrogen during nitrification and denitrification, which leads to eutrophication and water contamination.[1] Excessive NO_3^- concentrations in drinking water are toxic to humans especially infants.[2-4] The production and consumption of NO_3^- via nitrification and denitrification, respectively, result in nitrogen loss as nitrous oxide (N_2O), which is a powerful greenhouse gas causing global warming and stratospheric ozone depletion.[5, 6] A range of empirical models have been developed to predict soil nitrogen loss risk using the parameters of agricultural management, percolation, soil properties,[7] soil erosion index,[8, 9] environmental indicators,[10] or stable nitrogen isotopes.[4, 11] However, some of these models have been validated only in specific locations or their input parameters are often difficult to obtain, which could limit the model prediction capacity. A more representative indicator is needed to estimate overall nitrogen loss.

Nitrate loss is dependent on soil NO_3^- availability, which is an intrinsic factor regulated by immobilization and nitrification in the soil. Immobilization and nitrification are two important microbial processes that compete for NH_4^+. Immobilization is vital for conserving soil nitrogen, which converts NH_4^+ to organic nitrogen, and reduces availability of substrates for ammonia volatilization.[12] On the contrary, nitrification may lead to nitrogen loss via N_2O during nitrification[13], leaching or runoff[14], and as dinitrogen and N_2O via subsequent denitrification.[15] Thus, the ratio of nitrification to immobilization (N/I ratio) could reflect the competition between heterotrophic and autotrophic microbes for NH_4^+.[16] Soils with a high N/I ratio have a

61 greater potential of nitrogen loss through leaching, runoff or denitrification than those with a
62 low N/I ratio.[16, 17] Thus, the N/I ratio has been used to evaluate the risk of nitrogen loss.[16, 18]
63 Only a handful of studies reported nitrification rates at a global scale;[19] a comprehensive global-
64 scale assessment of N/I ratio is lacking.[20-22] To estimate the potential risk of nitrogen loss
65 worldwide, it is therefore important to map the variability of the N/I ratio based on the spatial
66 heterogeneity of edaphic and climatic factors. We also adopted stochastic gradient boosting
67 (SGB) model, a machine-learning based model, to explore the driving factor of nitrification and
68 immobilization.[23, 24] Because many studies focused on the driving factors of nitrification and/or
69 immobilization individually in a particular location, but excluded the interactions among the
70 factors affecting the two processes.
71 Management practices have been widely studied and adopted to reduce nitrogen loss via N_2O
72 emission and nitrate leaching[25-27] through for example, reducing fertilizer nitrogen application
73 rate, applying nitrification inhibitors[26, 28] and organic amendments e.g. biochar.[25, 29] However, a
74 quantitative synthesis is lacking on the effects of mitigation strategies on the N/I ratio and
75 subsequent N_2O and NO_3^- loss simultaneously.
76 Using the database compiled from global literatures, we first established SGB models to
77 investigate the interactions of factors driving immobilization and nitrification, and then
78 calculated the N/I ratio. Secondly, the global distribution of soil nitrification and immobilization
79 and the N/I ratio were mapped by SGB models using global soil and environmental databases.
80 Finally, we conducted a meta‐analysis to assess the effects of different management practices
81 on the potential risk of nitrogen loss. This study aimed to (a) reveal the global pattern of soil
82 N/I ratio as an indicator of the potential risk of soil nitrogen loss worldwide; (b) test the

relationships between soil N/I ratio and climatic factors and soil properties; (c) evaluate the effect of management practices on the potential risk of nitrogen loss.

MATERIALS AND METHODS

Database compilation

Table 1 Summary statistics of gross rates of nitrification and immobilization and environmental factors

Properties	n	Median	Min	Max	SD
N rate (mg N kg^{-1}soil d^{-1})	811	1.4	0.0020	35	4.4
I rate (mg N kg^{-1}soil d^{-1})	811	2.0	0.0005	155	11
N/I ratio	811	0.62	0.0003	2062	100
MAP (mm)	811	907	141	7000	732
MAT (°C)	789	8.7	-4.7	27	6.1
Clay content (%)	245	20	0.45	70	16
Soil pH	789	5.5	2.7	9.6	1.4
Soil TC (g kg^{-1}soil)	786	30	1.1	850	96.2
Soil total nitrogen (g kg^{-1}soil)	808	2.1	0.17	24	4.1
Soil carbon / nitrogen ratio	786	13	3.9	124	7.4
Bulk Density (g cm^{-3})	216	1.1	0.08	8.1	0.89
NH_4^+ (mg kg^{-1}soil)	310	4.7	0.0293	93	13
NO_3^- (mg kg^{-1}soil)	309	9.3	0.0000	1157	85.7
Soil WFPS (%)	624	49	12	100	13
Soil temperature (°C)	759	24	1.7	45	6.5
Nitrogen input (mg kg^{-1}soil)	762	20	0.11	399	48

N: nitrification, I: NH_4^+ immobilization, MAP: mean annual precipitation, MAT: mean annual temperature, TC: total carbon, WFPS: water-filled pore space, SD: standard deviation.

Extensive keyword searches from Web of Science (ISI), SCOPUS, CAB Abstracts (ISI), Academic Search Complete (EBSCO) and Google Scholar, and the reference list of cited

93 references were conducted. The keywords used in the search were: ammonium/NH_4^+
94 immobilization; ammonium/NH_4^+ nitrification; N/nitrogen immobilization; nitrification and
95 their combinations. Studies were included if they met the following criteria: a) gross
96 nitrification and immobilization rates were reported simultaneously; b) details on experimental
97 design and conditions were given to enable cross-checking for duplicate publication. We
98 compiled a database of 1105 observations from 191 papers published prior to 2019 that satisfied
99 these selection criteria. Data from tables and text were directly extracted, whereas data
100 presented in figures was extracted by WebPlotDigitizer Version 4.4
101 (https://automeris.io/WebPlotDigitizer).[30] We extracted the geographic coordinates (latitude
102 and longitude) of the location where soil samples were collected, environmental conditions
103 (mean annual temperature [MAT] and mean annual precipitation [MAP]), soil physicochemical
104 properties (soil texture, clay content, soil pH, soil total nitrogen and carbon (TC) content, soil
105 carbon/ nitrogen ratio, etc.) and management practice e.g. nitrogen application rate and land
106 use type (Table 1). To improve the normality, data were log transformed when necessary for
107 further analysis. This database was used for training the machine learning based stochastic
108 gradient boosting (SGB) models and for performing the meta-analysis.

109 **Stochastic gradient boosting model development for global prediction**

110 A SGB model is a decision tree-based model combined with boosting techniques to improve
111 the performance of prediction while simultaneously reducing errors and overfitting.[23, 31] A SGB
112 model can be used as a variable selection process to eliminate unimportant variables to achieve
113 better generalization of the dependent variable.[32] This model can handle both numerical and
114 categorical variables as features.[23, 31]

We constructed SGB models for nitrification (SGB_N) and immobilization (SGB_I), and then we calculated the N/I ratio (gross nitrification rate divided by gross immobilization rate). In both models, four parameters were calibrated: learn rate (LC), subsample fraction (SF), number of trees (NT), and minimum terminal node (MINCHILD). Learn rate controls the contribution size of each tree to the final model. Subsample fractions (SF) avoid model overfitting. The number of trees depends on the learn rate. Minimum terminal nodes (MINCHILDs) are controlled by the size of dataset. Different combinations of these four parameters were tested and the optimal configurations of LC, SF, NT and MINCHILD were 0.1, 0.5, 1000 and 3, and 0.1, 0.9, 1000 and 10, respectively, for SGB_N and SGB_I.[33, 34]

We then attempted to predict nitrification and immobilization rates worldwide by SGB technique using our database. Long-term soil properties (soil total nitrogen, pH, etc.) and climatic conditions (MAT and MAP) are the potential key drivers of the nitrification and immobilization processes because they can affect soil microbial abundance and composition.[18, 19, 35, 36] We therefore used long-term edaphic and environmental conditions as input variables to predict nitrification and immobilization. We conducted a series of stepwise variable selection (Tables S1 & S2) procedures, widely used in machine learning variable selection,[37] to optimize the number of variables in SGB models without compromising prediction capacities. We included all variables to build the first model, then we removed the less important input variables and used the remaining variables to build the next model until the model could not convergent.

Global database of soil and climate properties

Potential driving factors of soil and climate data were obtained from different sources and

integrated into a spatial GIS database to project SGB_N and SGB_I at a global scale. The soil property database with a spatial resolution of 1 km^2 was obtained from the World Inventory of Soil Emission (WISE) database developed by the International Soil Reference and Information Centre (ISRIC) (www.isric.org).[38] The climate data at 0.5° resolution was collected from Climatic Research Unit (CRU TS v4.01) (http://www.cru.uea.ac.uk/data/) from 1911 to 2010.[39] Land use system was sourced from FAO [40] and land use types were categorized into cropland, grassland, plantation, marsh and forest to match the training dataset. Data on synthetic nitrogen fertilizer application rates in cropland, plantation and grassland (at 0.5° resolution) were obtained from Xu et al. (2018)[41] and Lu et al. (2016).[42] The ESRI ArcGIS software (v. 10.4.1 ESRI) was used to plot the global distribution map (Figures1, 2 and S1). In this study, all SGB models were constructed using TreeNet® (Salford Systems).

Model validation

The SGB model prediction performance was evaluated using 10-fold cross-validation[43]. For each running of validation, the whole database was divided into 10 subsamples, nine of which were used as training data and the remaining one as test data. Model performance was estimated by averaging the test results from each subsample.[44] Three widely used validation indices: regression coefficients of determination (R^2), root mean square error (RMSE) and the Nash–Sutcliffe model efficiency (NSE) were used to measure the percentage of variation explained by the model and the model accuracy.

$$R^2 = \frac{\sum_{i=1}^{n}(P_i - O_{avg})^2}{\sum_{i=1}^{n}(O_i - O_{avg})^2}$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(P_i - O_i)^2}$$

$$\mathrm{MSE} = \frac{1}{n}\sum_{i=1}^{n}(P_i - O_i)^2$$

$$\mathrm{NSE} = 1 - \frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}(O_i - O_{avg})^2}$$

Where n is the number of data pairs, O_i is the observed value, P_i is its predicted value. O_{avg} and P_{avg} are the mean observed and predicted values, respectively.

Meta-analysis

The meta-analysis was carried out based on the studies on the effects of mitigation strategies on nitrification, immobilization and the calculated N/I ratio in our database. For nitrogen fertilization, we used zero or lowest nitrogen input as the control and the increment of fertilization relative to the lowest rate as treatments. Organic matter application included manure, biochar and straw as they are widely used in the field. We categorized farmland restoration strategies into cropland to forest, plantation to forest, grassland to forest, and cropland to grassland. Management of soil moisture was divided into increasing moisture under dry (water filled pore space (WFPS) <50%) and sufficient conditions (WFPS ≥50%).[45] Other management practices e.g. tillage and nitrification inhibitor application were also considered in the analysis. A total of 294 observations from 108 studies were included in the meta-analysis.

The response ratio r is the ratio of the mean value of the treatment to the control group; the effect of management practice on the target variables is represented by the natural log of the response ratio [46]:

$$\ln\ r = \ln\left(\frac{\overline{x}^T}{\overline{x}^C}\right)$$

where $\overline{x}^T$ and $\overline{x}^C$ are the mean values of the treatment group and the control group, respectively. Results are reported as the percentage change under treatment effects ((r-1) ×100).

Negative percentage changes mean that the treatment decreased nitrification, immobilization and the N/I ratio when compared to the control whereas positive changes indicate an increase due to the corresponding treatment. Generally, effect sizes are weighted by the inverse of pooled variance,[47] replication[48, 49] or unweighted[33] depending on the availability of standard deviations in the studies included in the meta-analysis. Extreme weights might be generated by variance-based weighting function[50]. Therefore, replication-based weight was adopted in this study:

$$\text{Weight} = (n_c \times n_T)/(n_c + n_T)$$

Where n_c and n_T are the number of replicates of the control and treatment, respectively.

The meta-analysis was conducted by MetaWin version 2.1[51]. A fixed-effect model with 4999 iterations bootstrapping was used to generate the mean effect size and the 95% confidence intervals (CIs).[51] The effects of mitigation strategies were considered significant if the 95% CIs did not overlap with zero.

RESULTS

General description of the literature-based dataset

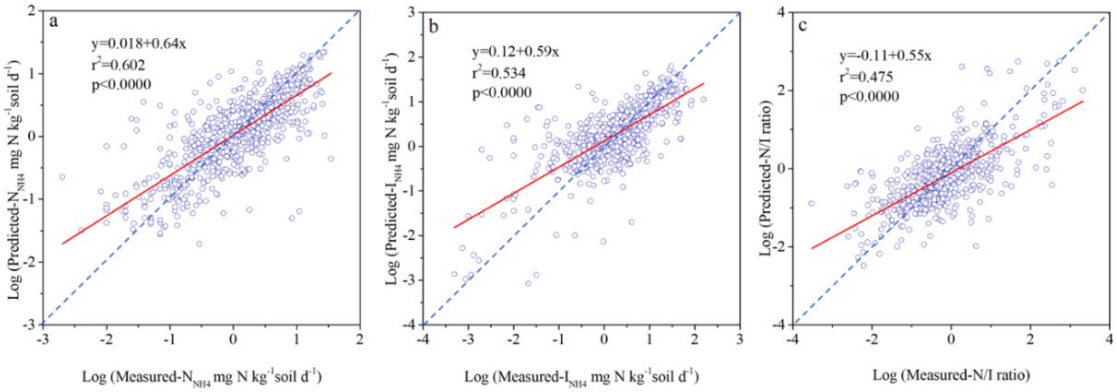
Study sites spanned from 175°E to 122°W and 64°N to 44°S (Table 1). The soil incubation temperature was controlled at around 21°C, with a median soil moisture of 49% WFPS (Table 1). The median nitrification rate in the topsoil (< 30 cm) was 1.4 mg N kg^{-1} soil d^{-1} (range: 0.002 to 35 mg N kg^{-1} soil d^{-1}). The median of immobilization rate was 2.0 mg N kg^{-1} soil d^{-1} (range: 0.0005 to 155 mg N kg^{-1} soil d^{-1}). The N/I ratio ranged from 0.0003 to 2062 with a median of 0.62 (Table 1).

Global predictions of nitrification, immobilization, and the N/I ratio by SGB models

SGB_N was developed to predict soil nitrification rate with R^2 of 0.60 (Figure 1a). Soil pH, TC,

total nitrogen, MAP, MAT, land use types and fertilizer nitrogen application rate were included as input variables according to the stepwise variable selection (Table S3). SGB_I was developed with soil total nitrogen, pH, clay content, MAP, fertilizer nitrogen application rate and land use types (Table S3), and the R^2 was 0.53 (Figure 1b). Based on the predicted results from SGB_N and SGB_I, the N/I ratio was calculated (Figure 1c and Table S3). SGB_N, SGB_I and the N/I ratio demonstrated satisfactory estimation and were used to reflect the spatial variability when upscaling to a global scale.

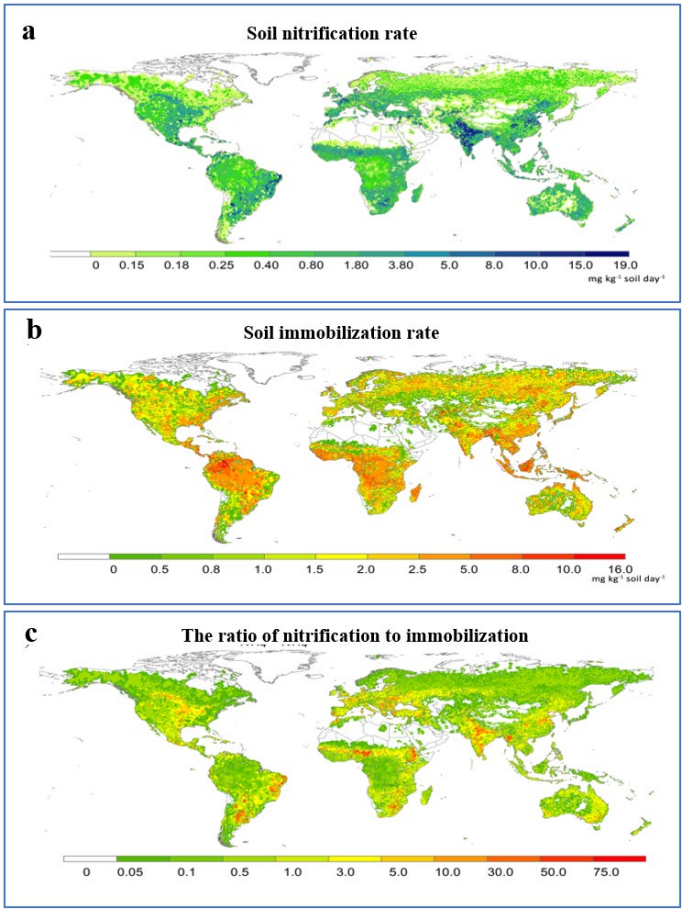
We attempted to predict the global distribution of nitrification and immobilization by SGB_N and SGB_I with input variables from global soil and climate databases (Figure S1), and then calculated the corresponding N/I ratio. We observed high spatial variation in nitrification, immobilization and the N/I ratio. Higher nitrification rates were found in cropland in the tropical and subtropical regions (Figure 2a and Figure S1e). On the contrary, forest areas across different climatic zones mostly had high immobilization rates (Figure 2b). In line with nitrification, higher N/I ratios were found in the tropical and subtropical regions than other climatic regions (Figure 2c). The global mean N/I ratio was 1.46. The mean N/I ratio was higher in cropland (3.29) than in plantation (2.36), followed by grassland (0.91), marsh (0.24) and forest (0.16, Figure 3a). The highest N/I ratio was found in the south subtropical zone (2.86), followed by tropical (1.82), north subtropical (1.42), north temperate (1.11), south temperate (0.44) and north polar area (0.11, Figure 3b).



220

221 Figure 1 Relationship between measured and predicted nitrification (a), immobilization (b)

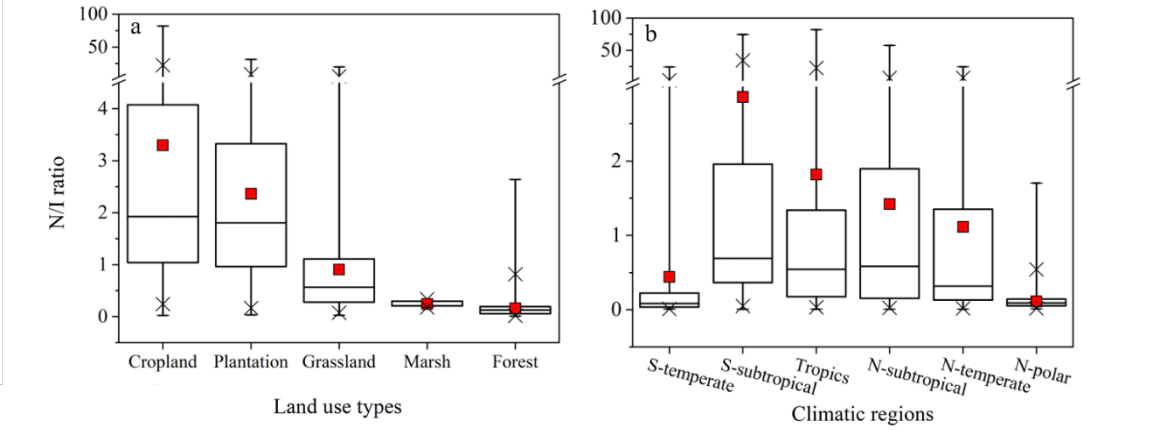
222 and the N/I ratio (c).



223

224 Figure 2 Global distribution of gross rates of nitrification (a), immobilization (b) and N/I ratio

225 (c)



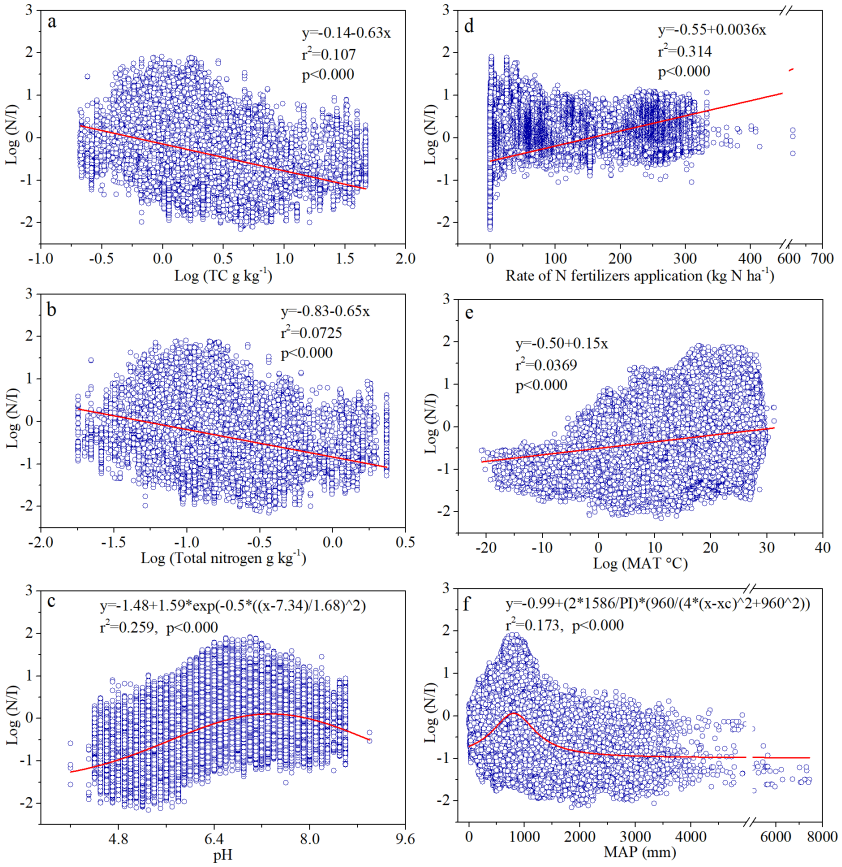
226

227 Figure 3 Predicted N/I ratio of different land use types (a) and climatic regions (b). S = south;

228 N = north; S-temperate= -40° ~ -66.5°; S-subtropical= -23.5° ~ -40.0°; tropics = -23.5° ~

229 23.5°; N-subtropical = 23.5° ~ 40.0°; N-temperate= 40.0° ~ 66.5°; N-polar region= 66.5° ~

230 90.0°.



231

232 Figure 4 Relationships between soil N/I ratio and total carbon (TC, a), total nitrogen (b), pH

(c), fertilizer nitrogen rates (d), mean annual temperature (MAT, e) and mean annual precipitation (MAP, f).

We compared our prediction of the N/I ratio with the predicted nitrogen loss from different pathways in agricultural systems in a study using stable nitrogen isotopes,[11] and found a significant correlation between the longitudinal distribution of the two predictions (Figure S2). Soil N/I ratio significantly decreased with TC and total nitrogen with a slope of 0.63 and 0.65 (Figures 4a and b, $p<0.0001$) but slightly increased with fertilizer nitrogen application rates and MAT with a slope of 0.0036 and 0.15, respectively (Figures 4 d and e, $p<0.0001$). High N/I ratios can be observed under soil pH of 6.0 -7.5 (Figure 4c, $p<0.0001$). Soil N/I ratio was also correlated with MAP, and N/I ratios were high when MAP was 500-1500 mm (Figure 4f, $p<0.0001$).

Management strategies to reduce the N/I ratio

The meta-analysis showed that increased fertilizer nitrogen input did not affect immobilization, except that increasing nitrogen input by 75-150 kg ha^{-1} decreased immobilization (Figure 5a). In contrast, increasing fertilizer nitrogen input increased nitrification rate and the N/I ratio by 61% (Figure 5b) and 92% (Figure 5c), respectively.

Application of organic matter overall significantly increased soil immobilization and nitrification rates by 164% and 45%, respectively (Figures 5 a and b). Soil N/I ratio was reduced by 67% and 64%, respectively, with biochar and straw incorporation, but was unaffected by manure application (Figure 5c). The use of nitrification inhibitor significantly increased immobilization by 27% and reduced nitrification by 71%, subsequently decreasing the N/I ratio by 78% (Figure 5).

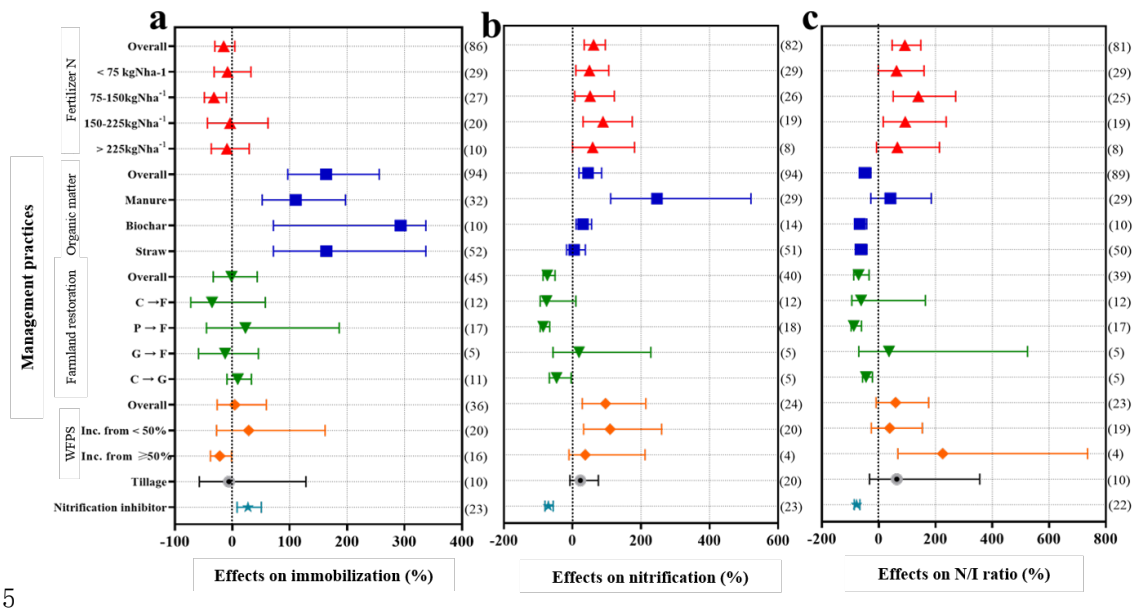


Figure 5 Effects of fertilizer nitrogen rate, organic matter, returning farmland, moisture content, and nitrification inhibitor on NH_4^+ immobilization (a), nitrification (b), and the N/I ratio (c). Means and 95% confidence intervals are depicted. Numbers of experimental observations are in parentheses. Organic matter includes straw, biochar and manure. WFPS: water filled pore space, Inc: increase. Nitrification inhibitor includes N-Serve_24E, 2-ethynyl_pyridine, 4-amino-l,2,4-triazole, nitrapyrin and dicyandiamide. C→F: converting cropland to forest, P→F: converting plantation to forest, G→F: converting grassland to forest, C→G: converting cropland to grassland.

Returning plantation to forest and cropland to grassland significantly reduced nitrification by 86% and 46%, respectively, but did not affect immobilization (Figures 5 a and b), thereby decreasing the N/I ratio by 88% and 45% (Figure 5c). Tillage and increasing water input under dry conditions (WFPS <50%) did not significantly affect the N/I ratio (Figure 5c). However, when the soil moisture was sufficient (WFPS $\geqslant$ 50%), further increase in water input significantly reduced immobilization rate, resulting in 225% increase in the N/I ratio (Figure

5c).

DISCUSSION

The global distribution of soil N/I ratio

The high spatial heterogeneity of the N/I ratio could be attributed to the diverse soil and environmental conditions and their interactions. The mean N/I ratios of different land use types indicated that the potential risk of nitrogen loss followed the order of cropland > plantation > grassland > marsh > forest (Figure 3a). Higher soil nitrogen runoff loss and N_2O emission was observed in agricultural land than grassland and forest, which suggests that farmland is susceptible to nitrogen loss.[52, 53] The application of nitrogen fertilizers in cropland and plantation increases nitrification and potential nitrogen loss (Figure 4d) because the activity of ammonia oxidizing bacteria and archaea are stimulated by nitrogen input.[54] The abundance of *amoA* gene of *comammox Nitrospira* could also be increased by nitrogen application.[55] In addition, the gross rate of immobilization may be decreased by nitrogen input (Figure 5).[56]

Nitrification and immobilization rates are highly related to soil and environmental properties and long-term fertilizer nitrogen application. These input variables are available from global soil and climate databases, which facilitates the extrapolation of the N/I ratio to a global scale. We found that the longitudinal pattern of the predicted N/I ratio was significantly correlated with that of the nitrogen loss from cropland (Figure S2).[11] This suggests that soil N/I ratio could be used to indicate the potential risk of nitrogen loss at a global scale.

The potential risk of nitrogen loss varies with climatic zones (Figure 3b). Nitrification increases with MAT ($p < 0.001$) (Figure 4e) and may outcompete immobilization for soil NH_4^+ [57]. Dan et al. (2019)[58] and Lan et al. (2014)[59] reported that the effect of increasing temperature (5°C -

35°C) on nitrification was greater than that on immobilization. Therefore, the N/I ratio and potential risk of nitrogen loss in tropical and subtropical regions (with high MAT) are higher than other climatic regions. The higher potential risk of nitrogen loss in the south subtropical regions than tropics may be attributed to the difference in MAP between these regions. MAP of 500-1500 mm in the south subtropical regions provides an optimal oxygen and moisture conditions for nitrifiers and the occurrence of nitrification (Figure 4f and S1g).[60]

Soil TC, total nitrogen and pH were important factors affecting the N/I ratio (Figures 4 a, b and c). Both immobilization and nitrification are stimulated by soil TC,[36, 61] but the extent of stimulation was greater on immobilization than nitrification.[61] As a result, the N/I ratio decreased with increasing TC (Figure 4a). Soil total nitrogen affects the N/I ratio via carbon/ nitrogen ratio, which is positively correlated with immobilization but negatively with nitrification.[61, 62] High N/I ratios are observed when soil pH is 6.0 -7.5 (Figure 4c) because slightly acidic to neutral pH is desirable for nitrifying bacteria.[63]

Mitigation of nitrogen loss

Our meta-analysis demonstrates that the use of nitrification inhibitors can effectively reduce N/I ratio (Figure 5c), and subsequently the potential risk of nitrogen loss. Nitrification inhibitors inhibit the first step of nitrification, thereby decreasing NO_3^- leaching, N_2O and dinitrogen emissions.[28, 64] It has been reported that nitrification inhibitors decreased N_2O emissions by 40 to 57% and NO_3^- leaching by 30 to 50%,[27, 28, 65] although the inhibitors may induce NH_3 volatilization.[66] Organic matter application increased immobilization to a greater extent than nitrification (Figures 5 a and b), reducing the N/I ratio (Figure 5c). This observation in line with a meta-analysis conducted by Liu et al. (2019),[29] who reported that biochar could reduce

nitrogen loss via NH_3 volatilization, N_2O emissions and nitrogen leaching. Our previous study also found that immobilization was significantly increased by rice straw incorporation, which decreased soil NH_4^+ availability and gross nitrification rate.[61] Straw application has been suggested as an effective approach to reduce NO_3^- leaching.[67] However, manure application increased both immobilization and nitrification but did not affect the N/I ratio (Figures 5). In fact, the effects of organic matter addition on immobilization and nitrification are dependent on their carbon/nitrogen ratio.[68, 69] The relationship between carbon/nitrogen ratio of organic matter applied and soil N/I ratio warrants further research.

Converting plantation to forest and cropland to grassland significantly reduced nitrification (Figure 5 a) and the N/I ratio (Figure 5c). In general, soil immobilization rate was higher in natural ecosystems than that in agricultural systems because of the higher carbon/ nitrogen ratio of natural soils.[70] It has been reported that grassland soils may be more prone to nitrogen loss through NO_3^- leaching or denitrification than forest soil, which has a lower N/I ratio.[71]

Limitations

First, some studies determined nitrification rate using $^{15}NH_4^+$ labelling. This may underestimate the N/I ratio and potential risk of nitrogen loss because heterotrophic nitrifiers could use both NH_4^+ and organic nitrogen as substrates,[72] but the gross nitrification rate determined via $^{15}NH_4^+$ labelling experiments did not account for heterotrophic nitrification from organic nitrogen. This is not an issue for the gross rate of nitrification determined via $^{15}NO_3^-$ labelling because both heterotrophic and autotrophic nitrification were considered. Second, soil gross immobilization and nitrification rates included in this study were mostly measured under controlled conditions in laboratory experiments. This may lead to potential bias of prediction in the extrapolation to

field conditions.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://**********

Supporting information of the methodology, stepwise selection of variable of SGB_N and SGB_I, stochastic gradient boosting (SGB) model performance. Global distribution of soil total carbon, soil total nitrogen, soil pH, soil clay content, land use type, mean inorganic nitrogen fertilizer application rate, mean annual precipitation, and mean annual temperature. Longitudinal pattern of predicted N/I ratio (this study) and the risk of nitrogen loss risk in cropland predicted by stable nitrogen isotopes.[11]

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[O]Y.Z. and B.P. contributed equally to this work. D.C. and Y.Z. designed the study. Y.Z. and B.P. analyzed the data and interpreted the results. Y.Z., B.P., and S.L. wrote the paper. D.C., S.L., E.B., and P.H. contributed to the discussion and revision of the paper.

Notes

The authors declare no conflict of interests.

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