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

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

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6 this work.

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22

23 **Abstract**

24 Nitrification and immobilization compete for soil ammonium (NH_4^+); the relative dominance
25 of these two processes has been suggested to reflect the potential risk of nitrogen loss from soils.
26 Here we compiled a database and developed Stochastic Gradient Boosting (SGB) model to
27 predict global potential risk of nitrogen loss based on the ratio of nitrification to immobilization
28 (N/I). We then conducted a meta-analysis to evaluate the effects of common management
29 practices on the N/I ratio. The results showed that soil N/I ratio varied with climate zones and
30 land use. Soil total carbon, total nitrogen, pH, fertilizer nitrogen application rate, mean annual
31 temperature and mean annual precipitation are important factors of soil N/I ratio. Meta-analysis
32 indicated that biochar, straw and nitrification inhibitor application reduced soil N/I ratio by 67%,
33 64% and 78%, respectively. Returning plantation to forest and cropland to grassland decreased
34 soil N/I ratio by 88% and 45%, respectively. However, fertilizer nitrogen application increased
35 soil N/I ratio by 92%. Our study showed that soil N/I ratio and its associated risk level of
36 nitrogen loss were highly related to long-term soil and environmental properties with high
37 spatial heterogeneity.

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

39 **INTRODUCTION**

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

53 Nitrate loss is dependent on soil NO_3^- availability, which is an intrinsic factor regulated by
54 immobilization and nitrification in the soil. Immobilization and nitrification are two important
55 microbial processes that compete for NH_4^+ . Immobilization is vital for conserving soil nitrogen,
56 which converts NH_4^+ to organic nitrogen, and reduces availability of substrates for ammonia
57 volatilization.¹² On the contrary, nitrification may lead to nitrogen loss via N_2O during
58 nitrification¹³, leaching or runoff¹⁴, and as dinitrogen and N_2O via subsequent denitrification.¹⁵
59 Thus, the ratio of nitrification to immobilization (N/I ratio) could reflect the competition
60 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 N₂O
72 emission and nitrate leaching²⁵⁻²⁷ 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 N₂O and NO₃⁻ 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

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

85 MATERIALS AND METHODS

86 Database compilation

87 **Table 1** Summary statistics of gross rates of nitrification and immobilization and environmental

88 factors

Properties	n	Median	Min	Max	SD
<i>N</i> rate (mg N kg ⁻¹ soil d ⁻¹)	811	1.4	0.0020	35	4.4
<i>I</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

89 N: nitrification, I: NH₄⁺ immobilization, MAP: mean annual precipitation, MAT: mean annual
 90 temperature, TC: total carbon, WFPS: water-filled pore space, SD: standard deviation.

91 Extensive keyword searches from Web of Science (ISI), SCOPUS, CAB Abstracts (ISI),

92 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}

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

124 We then attempted to predict nitrification and immobilization rates worldwide by SGB
125 technique using our database. Long-term soil properties (soil total nitrogen, pH, etc.) and
126 climatic conditions (MAT and MAP) are the potential key drivers of the nitrification and
127 immobilization processes because they can affect soil microbial abundance and composition.^{18,}
128 ^{19, 35, 36} We therefore used long-term edaphic and environmental conditions as input variables to
129 predict nitrification and immobilization. We conducted a series of stepwise variable selection
130 (Tables S1 & S2) procedures, widely used in machine learning variable selection,³⁷ to optimize
131 the number of variables in SGB models without compromising prediction capacities. We
132 included all variables to build the first model, then we removed the less important input
133 variables and used the remaining variables to build the next model until the model could not
134 convergent.

135 **Global database of soil and climate properties**

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

137 integrated into a spatial GIS database to project SGB_N and SGB_I at a global scale. The soil
 138 property database with a spatial resolution of 1 km² was obtained from the World Inventory of
 139 Soil Emission (WISE) database developed by the International Soil Reference and Information
 140 Centre (ISRIC) (www.isric.org).³⁸ The climate data at 0.5° resolution was collected from
 141 Climatic Research Unit (CRU TS v4.01) (<http://www.cru.uea.ac.uk/data/>) from 1911 to 2010.³⁹
 142 Land use system was sourced from FAO⁴⁰ and land use types were categorized into cropland,
 143 grassland, plantation, marsh and forest to match the training dataset. Data on synthetic nitrogen
 144 fertilizer application rates in cropland, plantation and grassland (at 0.5° resolution) were
 145 obtained from Xu et al. (2018)⁴¹ and Lu et al. (2016).⁴² The ESRI ArcGIS software (v. 10.4.1
 146 ESRI) was used to plot the global distribution map (Figures 1, 2 and S1). In this study, all SGB
 147 models were constructed using TreeNet® (Salford Systems).

148 **Model validation**

149 The SGB model prediction performance was evaluated using 10-fold cross-validation⁴³. For
 150 each running of validation, the whole database was divided into 10 subsamples, nine of which
 151 were used as training data and the remaining one as test data. Model performance was estimated
 152 by averaging the test results from each subsample.⁴⁴ Three widely used validation indices:
 153 regression coefficients of determination (R^2), root mean square error (RMSE) and the Nash–
 154 Sutcliffe model efficiency (NSE) were used to measure the percentage of variation explained
 155 by the model and the model accuracy.

$$156 \quad R^2 = \frac{\sum_{i=1}^n (P_i - O_{avg})^2}{\sum_{i=1}^n (O_i - O_{avg})^2}$$

$$157 \quad RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (P_i - O_i)^2}$$

158
$$\text{MSE} = \frac{1}{n} \sum_{i=1}^n (P_i - O_i)^2$$

159
$$\text{NSE} = 1 - \frac{\sum_{i=1}^n (P_i - O_i)^2}{\sum_{i=1}^n (O_i - O_{avg})^2}$$

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

162 **Meta-analysis**

163 The meta-analysis was carried out based on the studies on the effects of mitigation strategies
 164 on nitrification, immobilization and the calculated N/I ratio in our database. For nitrogen
 165 fertilization, we used zero or lowest nitrogen input as the control and the increment of
 166 fertilization relative to the lowest rate as treatments. Organic matter application included
 167 manure, biochar and straw as they are widely used in the field. We categorized farmland
 168 restoration strategies into cropland to forest, plantation to forest, grassland to forest, and
 169 cropland to grassland. Management of soil moisture was divided into increasing moisture under
 170 dry (water filled pore space (WFPS) <50%) and sufficient conditions (WFPS ≥50%).⁴⁵ Other
 171 management practices e.g. tillage and nitrification inhibitor application were also considered in
 172 the analysis. A total of 294 observations from 108 studies were included in the meta-analysis.
 173 The response ratio r is the ratio of the mean value of the treatment to the control group; the
 174 effect of management practice on the target variables is represented by the natural log of the
 175 response ratio ⁴⁶:

176
$$\ln r = \ln \left(\frac{\bar{x}^T}{\bar{x}^C} \right)$$

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

179 Negative percentage changes mean that the treatment decreased nitrification, immobilization
180 and the N/I ratio when compared to the control whereas positive changes indicate an increase
181 due to the corresponding treatment. Generally, effect sizes are weighted by the inverse of pooled
182 variance,⁴⁷ replication^{48, 49} or unweighted³³ depending on the availability of standard deviations
183 in the studies included in the meta-analysis. Extreme weights might be generated by variance-
184 based weighting function⁵⁰. Therefore, replication-based weight was adopted in this study:

$$185 \quad \text{Weight} = (n_c \times n_T) / (n_c + n_T)$$

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

187 The meta-analysis was conducted by MetaWin version 2.1⁵¹. A fixed-effect model with 4999
188 iterations bootstrapping was used to generate the mean effect size and the 95% confidence
189 intervals (CIs).⁵¹ The effects of mitigation strategies were considered significant if the 95% CIs
190 did not overlap with zero.

191 **RESULTS**

192 **General description of the literature-based dataset**

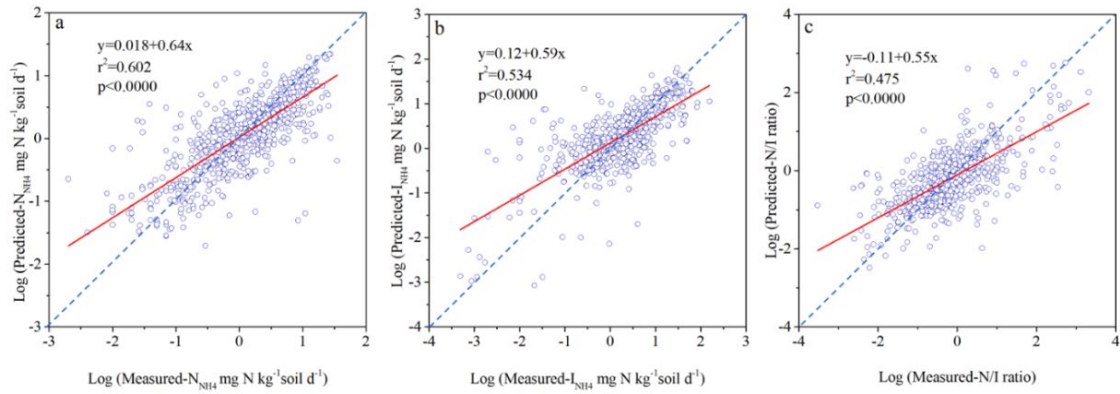
193 Study sites spanned from 175°E to 122°W and 64°N to 44°S (Table 1). The soil incubation
194 temperature was controlled at around 21°C, with a median soil moisture of 49% WFPS (Table
195 1). The median nitrification rate in the topsoil (< 30 cm) was 1.4 mg N kg⁻¹ soil d⁻¹ (range: 0.002
196 to 35 mg N kg⁻¹ soil d⁻¹). The median of immobilization rate was 2.0 mg N kg⁻¹ soil d⁻¹ (range:
197 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
198 0.62 (Table 1).

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

200 SGB_N was developed to predict soil nitrification rate with R² of 0.60 (Figure 1a). Soil pH, TC,

201 total nitrogen, MAP, MAT, land use types and fertilizer nitrogen application rate were included
202 as input variables according to the stepwise variable selection (Table S3). SGB_I was developed
203 with soil total nitrogen, pH, clay content, MAP, fertilizer nitrogen application rate and land use
204 types (Table S3), and the R² was 0.53 (Figure 1b). Based on the predicted results from SGB_N
205 and SGB_I, the N/I ratio was calculated (Figure 1c and Table S3). SGB_N, SGB_I and the N/I ratio
206 demonstrated satisfactory estimation and were used to reflect the spatial variability when
207 upscaling to a global scale.

208 We attempted to predict the global distribution of nitrification and immobilization by SGB_N and
209 SGB_I with input variables from global soil and climate databases (Figure S1), and then
210 calculated the corresponding N/I ratio. We observed high spatial variation in nitrification,
211 immobilization and the N/I ratio. Higher nitrification rates were found in cropland in the
212 tropical and subtropical regions (Figure 2a and Figure S1e). On the contrary, forest areas across
213 different climatic zones mostly had high immobilization rates (Figure 2b). In line with
214 nitrification, higher N/I ratios were found in the tropical and subtropical regions than other
215 climatic regions (Figure 2c). The global mean N/I ratio was 1.46. The mean N/I ratio was higher
216 in cropland (3.29) than in plantation (2.36), followed by grassland (0.91), marsh (0.24) and
217 forest (0.16, Figure 3a). The highest N/I ratio was found in the south subtropical zone (2.86),
218 followed by tropical (1.82), north subtropical (1.42), north temperate (1.11), south temperate
219 (0.44) and north polar area (0.11, Figure 3b).

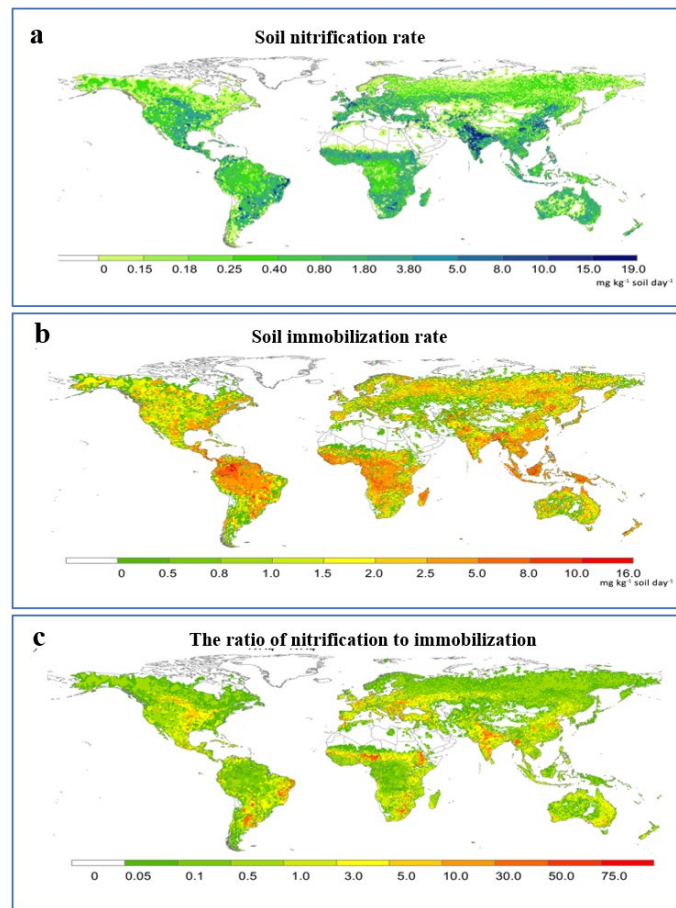


220

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

222

and the N/I ratio (c).

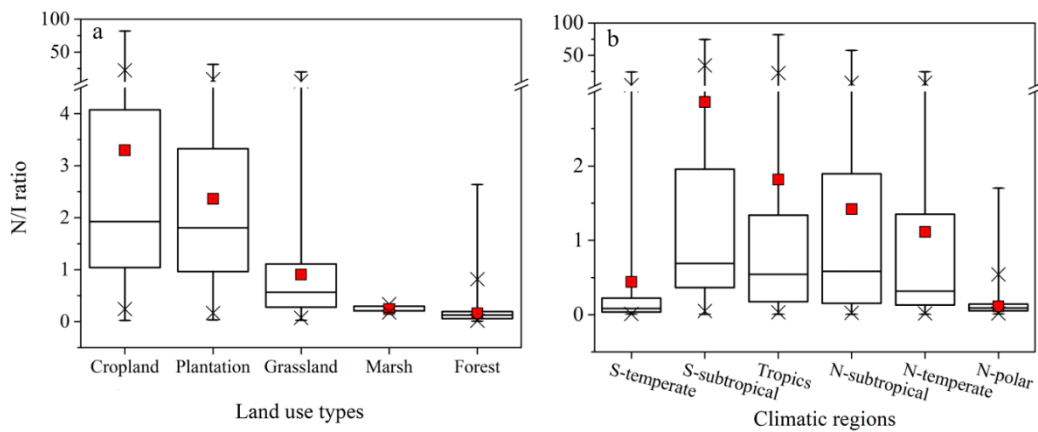


223

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

225

(c)



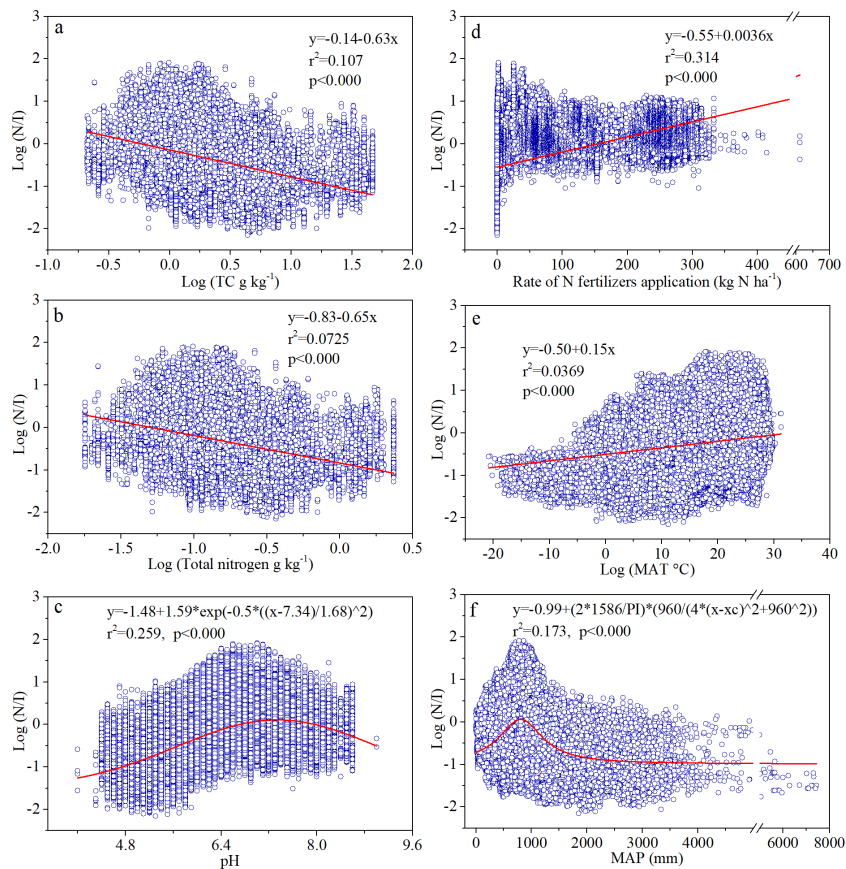
226

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

228 N = north; S-temperate= $-40^{\circ} \sim -66.5^{\circ}$; S-subtropical= $-23.5^{\circ} \sim -40.0^{\circ}$; tropics = $-23.5^{\circ} \sim$

229 23.5° ; N-subtropical = $23.5^{\circ} \sim 40.0^{\circ}$; N-temperate= $40.0^{\circ} \sim 66.5^{\circ}$; N-polar region= $66.5^{\circ} \sim$

230 90.0° .



231

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

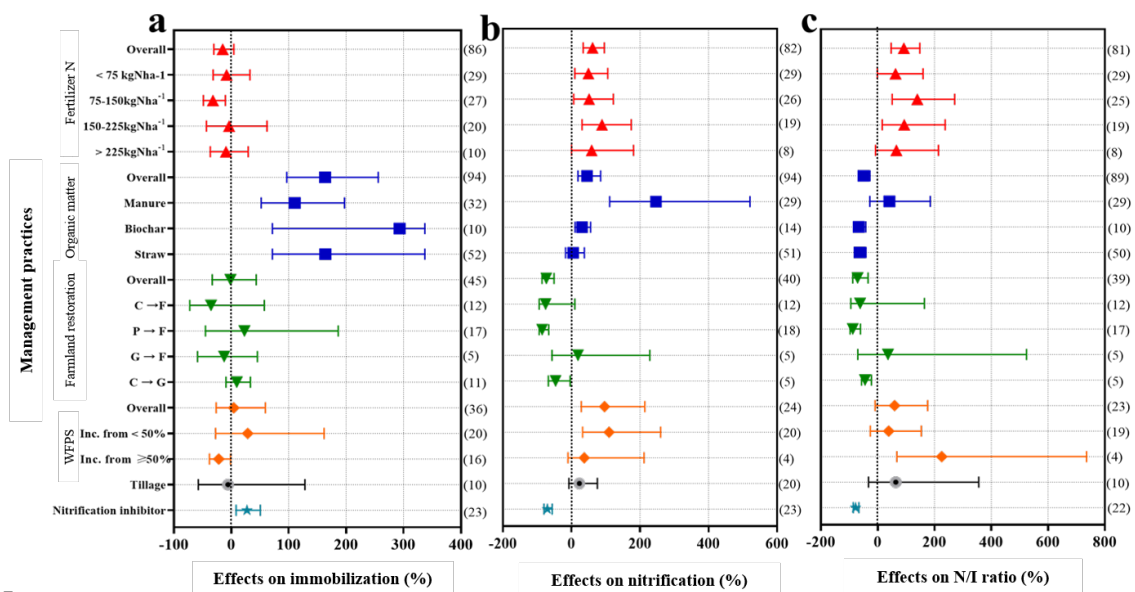
233 (c), fertilizer nitrogen rates (d), mean annual temperature (MAT, e) and mean annual
234 precipitation (MAP, f).

235 We compared our prediction of the N/I ratio with the predicted nitrogen loss from different
236 pathways in agricultural systems in a study using stable nitrogen isotopes,¹¹ and found a
237 significant correlation between the longitudinal distribution of the two predictions (Figure S2).
238 Soil N/I ratio significantly decreased with TC and total nitrogen with a slope of 0.63 and 0.65
239 (Figures 4a and b, $p < 0.0001$) but slightly increased with fertilizer nitrogen application rates and
240 MAT with a slope of 0.0036 and 0.15, respectively (Figures 4 d and e, $p < 0.0001$). High N/I
241 ratios can be observed under soil pH of 6.0 -7.5 (Figure 4c, $p < 0.0001$). Soil N/I ratio was also
242 correlated with MAP, and N/I ratios were high when MAP was 500-1500 mm (Figure 4f,
243 $p < 0.0001$).

244 **Management strategies to reduce the N/I ratio**

245 The meta-analysis showed that increased fertilizer nitrogen input did not affect immobilization,
246 except that increasing nitrogen input by 75-150 kg ha⁻¹ decreased immobilization (Figure 5a).
247 In contrast, increasing fertilizer nitrogen input increased nitrification rate and the N/I ratio by
248 61% (Figure 5b) and 92% (Figure 5c), respectively.

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



255

256 Figure 5 Effects of fertilizer nitrogen rate, organic matter, returning farmland, moisture content,
 257 and nitrification inhibitor on NH₄⁺ immobilization (a), nitrification (b), and the N/I ratio (c).

258 Means and 95% confidence intervals are depicted. Numbers of experimental observations are
 259 in parentheses. Organic matter includes straw, biochar and manure. WFPS: water filled pore

260 space, Inc: increase. Nitrification inhibitor includes N-Serve_24E, 2-ethynyl_pyridine, 4-
 261 amino-1,2,4-triazole, nitrapyrin and dicyandiamide. C→F: converting cropland to forest, P→F:

262 converting plantation to forest, G→F: converting grassland to forest, C→G: converting
 263 cropland to grassland.

264 Returning plantation to forest and cropland to grassland significantly reduced nitrification by
 265 86% and 46%, respectively, but did not affect immobilization (Figures 5 a and b), thereby

266 decreasing the N/I ratio by 88% and 45% (Figure 5c). Tillage and increasing water input under
 267 dry conditions (WFPS <50%) did not significantly affect the N/I ratio (Figure 5c). However,

268 when the soil moisture was sufficient (WFPS ≥ 50%), further increase in water input
 269 significantly reduced immobilization rate, resulting in 225% increase in the N/I ratio (Figure

270 5c).

271 **DISCUSSION**

272 **The global distribution of soil N/I ratio**

273 The high spatial heterogeneity of the N/I ratio could be attributed to the diverse soil and
274 environmental conditions and their interactions. The mean N/I ratios of different land use types
275 indicated that the potential risk of nitrogen loss followed the order of cropland > plantation >
276 grassland > marsh > forest (Figure 3a). Higher soil nitrogen runoff loss and N₂O emission was
277 observed in agricultural land than grassland and forest, which suggests that farmland is
278 susceptible to nitrogen loss.^{52, 53} The application of nitrogen fertilizers in cropland and
279 plantation increases nitrification and potential nitrogen loss (Figure 4d) because the activity of
280 ammonia oxidizing bacteria and archaea are stimulated by nitrogen input.⁵⁴ The abundance of
281 *amoA* gene of *comammox Nitrospira* could also be increased by nitrogen application.⁵⁵ In
282 addition, the gross rate of immobilization may be decreased by nitrogen input (Figure 5).⁵⁶
283 Nitrification and immobilization rates are highly related to soil and environmental properties
284 and long-term fertilizer nitrogen application. These input variables are available from global
285 soil and climate databases, which facilitates the extrapolation of the N/I ratio to a global scale.
286 We found that the longitudinal pattern of the predicted N/I ratio was significantly correlated
287 with that of the nitrogen loss from cropland (Figure S2).¹¹ This suggests that soil N/I ratio could
288 be used to indicate the potential risk of nitrogen loss at a global scale.
289 The potential risk of nitrogen loss varies with climatic zones (Figure 3b). Nitrification increases
290 with MAT ($p < 0.001$) (Figure 4e) and may outcompete immobilization for soil NH₄⁺.⁵⁷ Dan et
291 al. (2019)⁵⁸ and Lan et al. (2014)⁵⁹ reported that the effect of increasing temperature (5°C -

292 35°C) on nitrification was greater than that on immobilization. Therefore, the N/I ratio and
293 potential risk of nitrogen loss in tropical and subtropical regions (with high MAT) are higher
294 than other climatic regions. The higher potential risk of nitrogen loss in the south subtropical
295 regions than tropics may be attributed to the difference in MAP between these regions. MAP of
296 500-1500 mm in the south subtropical regions provides an optimal oxygen and moisture
297 conditions for nitrifiers and the occurrence of nitrification (Figure 4f and S1g).⁶⁰

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

305 **Mitigation of nitrogen loss**

306 Our meta-analysis demonstrates that the use of nitrification inhibitors can effectively reduce
307 N/I ratio (Figure 5c), and subsequently the potential risk of nitrogen loss. Nitrification inhibitors
308 inhibit the first step of nitrification, thereby decreasing NO₃⁻ leaching, N₂O and dinitrogen
309 emissions.^{28, 64} It has been reported that nitrification inhibitors decreased N₂O emissions by 40
310 to 57% and NO₃⁻ leaching by 30 to 50%,^{27, 28, 65} although the inhibitors may induce NH₃
311 volatilization.⁶⁶ Organic matter application increased immobilization to a greater extent than
312 nitrification (Figures 5 a and b), reducing the N/I ratio (Figure 5c). This observation is in line with
313 a meta-analysis conducted by Liu et al. (2019),²⁹ who reported that biochar could reduce

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

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

327 **Limitations**

328 First, some studies determined nitrification rate using $^{15}\text{NH}_4^+$ labelling. This may underestimate
329 the N/I ratio and potential risk of nitrogen loss because heterotrophic nitrifiers could use both
330 NH_4^+ and organic nitrogen as substrates,⁷² but the gross nitrification rate determined via $^{15}\text{NH}_4^+$
331 labelling experiments did not account for heterotrophic nitrification from organic nitrogen. This
332 is not an issue for the gross rate of nitrification determined via $^{15}\text{NO}_3^-$ labelling because both
333 heterotrophic and autotrophic nitrification were considered. Second, soil gross immobilization
334 and nitrification rates included in this study were mostly measured under controlled conditions
335 in laboratory experiments. This may lead to potential bias of prediction in the extrapolation to

336 field conditions.

337 **ASSOCIATED CONTENT**

338 **Supporting Information**

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

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

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370 ^oY.Z. and B.P. contributed equally to this work. D.C. and Y.Z. designed the study. Y.Z. and B.P.
371 analyzed the data and interpreted the results. Y.Z., B.P., and S.L. wrote the paper. D.C., S.L.,
372 E.B., and P.H. contributed to the discussion and revision of the paper.

373 **Notes**

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375 **REFERENCES**

376 (1) Padilla, F. M.; Gallardo, M.; Manzano-Agugliaro, F., Global trends in nitrate leaching
377 research in the 1960–2017 period. *Sci. Total Environ.* **2018**, *643*, 400-413; DOI
378 10.1016/j.scitotenv.2018.06.215.

379 (2) Powlson, D. S.; Addiscott, T. M.; Benjamin, N.; Cassman, K. G.; de Kok, T. M.; van

- 380 Grinsven, H.; L'hirondel, J. L.; Avery, A. A.; Van Kessel, C., When does nitrate become a
381 risk for humans? *J. Environ. Qual.* **2008**, *37*, (2), 291-295; DOI 10.2134/jeq2007.0177.
- 382 (3) Figueroa-Viramontes, U.; Delgado, J. A.; Cueto-Wong, J. A.; Núñez-Hernández, G.; Reta-
383 Sánchez, D. G.; Barbarick, K. A., A new Nitrogen Index to evaluate nitrogen losses in
384 intensive forage systems in Mexico. *Agr. Ecosyst. Environ.* **2011**, *142*, (3-4), 352-364; DOI
385 10.1016/j.agee.2011.06.004.
- 386 (4) Houlton, B. Z.; Marklein, A. R.; Bai, E., Representation of nitrogen in climate change
387 forecasts. *Nat. Clim. Change* **2015**, *5*, (5), 398-401; DOI 10.1038/nclimate2538.
- 388 (5) Zhang, X.; Davidson, E. A.; Mauzerall, D. L.; Searchinger, T. D.; Dumas, P.; Shen, Y.,
389 Managing nitrogen for sustainable development. *Nature* **2015**, *528*, (7580), 51-59; DOI
390 10.1038/nature15743.
- 391 (6) Ravishankara, A.; Daniel, J. S.; Portmann, R. W., Nitrous oxide (N₂O): the dominant
392 ozone-depleting substance emitted in the 21st century. *Science* **2009**, *326*, (5949), 123-125;
393 DOI 10.1126/science.1176985.
- 394 (7) Blicher-Mathiesen, G.; Andersen, H. E.; Carstensen, J.; Børgesen, C. D.; Hasler, B.;
395 Windolf, J., Reprint of "Mapping of nitrogen risk areas". *Agr. Ecosyst. Environ.* **2014**, *198*,
396 83-93; DOI 10.1016/j.agee.2014.06.031.
- 397 (8) Bechmann, M.; Stålnacke, P.; Kværnø, S.; Eggestad, H. O.; Øygarden, L., Integrated tool
398 for risk assessment in agricultural management of soil erosion and losses of phosphorus
399 and nitrogen. *Sci. Total Environ.* **2009**, *407*, (2), 749-759; DOI 10.1016/j.scitotenv.
400 2008.09.016.
- 401 (9) Drewry, J.; Newham, L.; Greene, R., Index models to evaluate the risk of phosphorus and

- 402 nitrogen loss at catchment scales. *J. Environ. Manage.* **2011**, *92*, (3), 639-649; DOI
403 10.1016/j.jenvman.2010.10.001.
- 404 (10) Buczko, U.; Kuchenbuch, R. O., Environmental indicators to assess the risk of diffuse
405 nitrogen losses from agriculture. *Environ. Manage.* **2010**, *45*, (5), 1201-1222; DOI
406 10.1007/s00267-010-9448-8.
- 407 (11) Wang, C.; Houlton, B. Z.; Dai, W.; Bai, E., Growth in the global N₂ sink attributed to N
408 fertilizer inputs over 1860 to 2000. *Sci. Total Environ.* **2017**, *574*, 1044-1053; DOI
409 10.1016/j.scitotenv.2016.09.160.
- 410 (12) He, Z.; Calvert, D.; Alva, A.; Li, Y.; Banks, D., Clinoptilolite zeolite and cellulose
411 amendments to reduce ammonia volatilization in a calcareous sandy soil. *Plant Soil* **2002**,
412 *247*, (2), 253-260; DOI 10.1023/A:1021584300322.
- 413 (13) Zhang, Y.; Ding, H.; Zheng, X.; Ren, X.; Cardenas, L.; Carswell, A.; Misselbrook, T.,
414 Land-use type affects N₂O production pathways in subtropical acidic soils. *Environ. Pollut.*
415 **2018**, *237*, 237-243; DOI 10.1016/j.envpol.2018.02.045.
- 416 (14) Moreno Lucas, F.; Cabrera, F.; Murillo Carpio, J. M.; Fernández Luque, J. E.; Fernández
417 Boy, E.; Cayuela, J. A., Nitrate leaching under irrigated agriculture; Springer Press: Berlin,
418 Germany, 1996.
- 419 (15) Houlton, B. Z.; Bai, E., Imprint of denitrifying bacteria on the global terrestrial biosphere.
420 *PNAS* **2009**, *106*, (51), 21713-21716; DOI 10.1073/pnas.0912111106.
- 421 (16) Stockdale, E.; Hatch, D.; Murphy, D.; Ledgard, S.; Watson, C., Verifying the nitrification
422 to immobilisation ratio (N/I) as a key determinant of potential nitrate loss in grassland and
423 arable soils. *Agronomie* **2002**, *22*, 831-838; DOI 10.1051/agro:2002060.

- 424 (17) Tietema, A.; Wessel, W. W., Gross nitrogen transformations in the organic layer of acid
425 forest ecosystems subjected to increased atmospheric nitrogen input. *Soil Biol. Biochem.*
426 **1992**, *24*, (10), 943-950; DOI 10.1016/0038-0717(92)90021-o.
- 427 (18) Zhang, Y.; Ding, H.; Zheng, X.; Cai, Z.; Misselbrook, T.; Carswell, A.; Müller, C.; Zhang,
428 J., Soil N transformation mechanisms can effectively conserve N in soil under saturated
429 conditions compared to unsaturated conditions in subtropical China. *Biol. Fertil. Soils*
430 **2018**, *54*, (4), 495-507; DOI 10.1007/s00374-018-1276-7.
- 431 (19) Li, Z.; Zeng, Z.; Tian, D.; Wang, J.; Fu, Z.; Zhang, F.; Zhang, R.; Chen, W.; Luo, Y.; Niu,
432 S. J. G. C. B., Global patterns and controlling factors of soil nitrification rate. *Global*
433 *Change Biol.* **2020**, *26*, (7), 4147-4157; DOI 10.1111/gcb.15119.
- 434 (20) Zhang, Y.; Zheng, X.; Ren, X.; Zhang, J.; Misselbrook, T.; Cardenas, L.; Carswell, A.;
435 Müller, C.; Ding, H., Land-use type affects nitrate production and consumption pathways
436 in subtropical acidic soils. *Geoderma* **2019**, *337*, 22-31; DOI 10.1016/j.geoderma.
437 2018.09.012.
- 438 (21) Zhao, Y.; Wang, J.; Cai, Z.; Müller, C.; Zhang, J., Short-term effects of nitrapyrin, rice
439 straw and its biochar application on N transformation in soils of humid subtropical China.
440 *Acta Agr. Scand. B.-S. P.* **2018**, *68*, (5), 448-456; DOI 10.1080/09064710.2018.1424232.
- 441 (22) Wang, J.; Cheng, Y.; Jiang, Y.; Sun, B.; Fan, J.; Zhang, J.; Müller, C.; Cai, Z., Effects of 14
442 years of repeated pig manure application on gross nitrogen transformation in an upland red
443 soil in China. *Plant Soil* **2017**, *415*, (1-2), 161-173; DOI 10.1007-s11104-016-3156-y.
- 444 (23) Friedman, J. H., Greedy function approximation: a gradient boosting machine. *Ann. Stat.*
445 **2001**, *29*, (5), 1189-1232; DOI 10.2307/2699986.

- 446 (24) Friedman, J. H., Stochastic gradient boosting. *Comput. Stat. Data Anal.* **2002**, *38*, (4), 367-
447 378; DOI 10.1016/S0167-9473(01)00065-2.
- 448 (25) Borchard, N.; Schirrmann, M.; Cayuela, M. L.; Kammann, C.; Wrage-Mönnig, N.;
449 Estavillo, J. M.; Fuertes-Mendizábal, T.; Sigua, G.; Spokas, K.; Ippolito, J. A. J. S. o. t. T.
450 E., Biochar, soil and land-use interactions that reduce nitrate leaching and N₂O emissions:
451 a meta-analysis. *Sci. Total Environ.* **2019**, *651*, 2354-2364; DOI 10.1016/j.scitotenv.2018.
452 10.060.
- 453 (26) Eagle, A. J.; Olander, L. P.; Locklier, K. L.; Heffernan, J. B.; Bernhardt, E. S., Fertilizer
454 management and environmental factors drive N₂O and NO₃ losses in corn: A meta -
455 analysis. *Soil Sci. Soc. Am. J.* **2017**, *81*, (5), 1191-1202; DOI 10.2136/sssaj2016.09.0281.
- 456 (27) Xia, L.; Lam, S. K.; Chen, D.; Wang, J.; Tang, Q.; Yan, X., Can knowledge - based N
457 management produce more staple grain with lower greenhouse gas emission and reactive
458 nitrogen pollution? A meta - analysis. *Global Change Biol.* **2017**, *23*, (5), 1917-1925; DOI
459 10.1111/gcb.13455.
- 460 (28) Di, H. J.; Cameron, K. C., Inhibition of nitrification to mitigate nitrate leaching and nitrous
461 oxide emissions in grazed grassland: a review. *J. Soils Sediments* **2016**, *16*, (5), 1401-1420;
462 DOI 10.1007/s11368-016-1403-8.
- 463 (29) Liu, Q.; Liu, B.; Zhang, Y.; Hu, T.; Lin, Z.; Liu, G.; Wang, X.; Ma, J.; Wang, H.; Jin, H.,
464 Biochar application as a tool to decrease soil nitrogen losses (NH₃ volatilization, N₂O
465 emissions, and N leaching) from croplands: Options and mitigation strength in a global
466 perspective. *Global Change Biol.* **2019**, *25*, (6), 2077-2093; DOI 10.1111/gcb.14613.
- 467 (30) Rohatgi, A., WebPlotDigitizer Version: 4.1. Website;

468 <https://automeris.io/WebPlotDigitizer>.

469 (31) Friedman, J. H., Stochastic gradient boosting. *Comput. Stat. Data An.* **2002**; DOI
470 10.1016/S0167-9473(01)00065-2.

471 (32) Xu, Z.; Huang, G.; Weinberger, K. Q.; Zheng, A. X. In *Gradient boosted feature selection*,
472 Proceedings of the 20th ACM SIGKDD international conference on Knowledge discovery
473 and data mining, 2014; 2014; pp 522-531; DOI 10.1145/2623330.2623635.

474 (33) Wang, S.; Zhuang, Q.; Wang, Q.; Jin, X.; Han, C., Mapping stocks of soil organic carbon
475 and soil total nitrogen in Liaoning Province of China. *Geoderma* **2017**, *305*, 250-263; DOI
476 10.1016/j.geoderma.2017.05.048.

477 (34) Yang, R. M.; Zhang, G. L.; Liu, F.; Lu, Y. Y.; Yang, F.; Yang, F.; Yang, M.; Zhao, Y. G.; Li,
478 D. C., Comparison of boosted regression tree and random forest models for mapping
479 topsoil organic carbon concentration in an alpine ecosystem. *Ecol. Indic.* **2016**, *60*, 870-
480 878; DOI 10.1016/j.ecolind.2015.08.036.

481 (35) Hu, H.W.; Macdonald, C. A.; Trivedi, P.; Anderson, I. C.; Zheng, Y.; Holmes, B.; Bodrossy,
482 L.; Wang, J.T.; He, J.Z.; Singh, B. K., Effects of climate warming and elevated CO₂ on
483 autotrophic nitrification and nitrifiers in dryland ecosystems. *Soil Biol. Biochem.* **2016**, *92*,
484 1-15; DOI 10.1016/j.soilbio.2015.09.008.

485 (36) Xie, Y.; Yang, C.; Ma, E.; Tan, H.; Zhu, T.; Müller, C., Biochar stimulates NH₄⁺ turnover
486 while decreasing NO₃⁻ production and N₂O emissions in soils under long-term vegetable
487 cultivation. *Sci. Total Environ.* **2020**, *737*, 140266. DOI 10.1016/j.scitotenv.2020.140266.

488 (37) Rakotomamonjy, A., Variable selection using SVM-based criteria. *J. Mach. Learn. Res.*
489 **2003**, (3), 1357-1370; DOI 10.1162/153244303322753706.

- 490 (38) Batjes, N. H. *World soil property estimates for broad-scale modelling (WISE30sec)*;
491 ISRIC-World Soil Information: 2015.
- 492 (39) Harris, I.; Jones, P. D.; Osborn, T. J.; Lister, D. H., Updated high - resolution grids of
493 monthly climatic observations - the CRU TS3. 10 Dataset. *Int. J. Climatol.* **2014**, *34*, (3),
494 623-642; DOI 10.1002/joc.3711.
- 495 (40) Nachtergaele, F.; Petri, M., Land Degradation Assessment in Drylands: Mapping Land Use
496 Systems at Global and Regional Scales for Land Degradation Assessment Analysis. *Food
497 and Agriculture Organization of the United Nations Press:Rome, Italy* 2011.
- 498 (41) Xu, R.; Tian, H.; Pan, S.; Dangal, R. S. S.; Chen, J.; Chang, J.; Lu, Y.; Skiba, U. M.;
499 Tubiello, F. N.; Zhang, B., Half-degree gridded manure and fertilizer nitrogen inputs in
500 global grassland systems during 1860-2016. Supplement to: Xu, Rongting; Tian, Hanqin;
501 Pan, Shufen; Dangal, R S Shree; Chen, Jian; Chang, Jinfeng; Lu, Yonglong; Skiba, Ute
502 Maria; Zhang, Bowen (2019): Increased nitrogen enrichment and shifted patterns in the
503 world's grassland: 1860-2014. *Earth System Science Data*, 11(1), 175-187,
504 <https://doi.org/10.5194/essd-11-175-2019>. PANGAEA. 2018.
- 505 (42) Lu, C.; Tian, H., Half-degree gridded nitrogen and phosphorus fertilizer use for global
506 agriculture production during 1900-2013. Supplement to: Lu, C; Tian, H (2017): Global
507 nitrogen and phosphorus fertilizer use for agriculture production in the past half century:
508 shifted hot spots and nutrient imbalance. *Earth Syst. Sci. Data* **2016**, *9*, (3), 181-192; DOI
509 10.5194/essd-9-181-2017.
- 510 (43) Kohavi, R. In *A study of cross-validation and bootstrap for accuracy estimation and model
511 selection*, Ijcai, 1995; Montreal, Canada: 1995; pp 1137-1145.

- 512 (44) James, G.; Witten, D.; Hastie, T.; Tibshirani, R. An introduction to statistical learning.
513 Springer Press: New York, 2013.
- 514 (45) Franzluebbers, A., Microbial activity in response to water-filled pore space of variably
515 eroded southern Piedmont soils. *Appl. Soil Ecol.* **1999**, *11*, (1), 91-101; DOI
516 10.1016/S0929-1393(98)00128-0.
- 517 (46) Hedges, L. V.; Gurevitch, J.; Curtis, P. S., The meta - analysis of response ratios in
518 experimental ecology. *Ecology* **1999**, *80*, (4), 1150-1156; DOI 10.1890/0012-
519 9658(1999)080[1150:TMAORR]2.0.CO;2.
- 520 (47) Liu, S.; Lin, F.; Wu, S.; Ji, C.; Sun, Y.; Jin, Y.; Li, S.; Li, Z.; Zou, J., A meta - analysis of
521 fertilizer - induced soil NO and combined NO+ N₂O emissions. *Global Change Biol.* **2017**,
522 *23*, (6), 2520-2532; DOI 10.1111/gcb.13485.
- 523 (48) Lam, S. K.; Chen, D.; Norton, R.; Armstrong, R.; Mosier, A. R., Nitrogen dynamics in
524 grain crop and legume pasture systems under elevated atmospheric carbon dioxide
525 concentration: A meta - analysis. *Global Change Biol.* **2012**, *18*, (9), 2853-2859; DOI
526 10.1111/j.1365-2486.2012.02758.x.
- 527 (49) Pan, B.; Lam, S. K.; Mosier, A.; Luo, Y.; Chen, D., Ammonia volatilization from synthetic
528 fertilizers and its mitigation strategies: a global synthesis. *Agr. Ecosyst. Environ.* **2016**, *232*,
529 283-289; DOI 10.1016/j.agee.2016.08.019.
- 530 (50) Van Groenigen, K. J.; Osenberg, C. W.; Hungate, B. A., Increased soil emissions of potent
531 greenhouse gases under increased atmospheric CO₂. *Nature* **2011**, *475*, (7355), 214-216;
532 DOI 10.1038/nature10176.
- 533 (51) Rosenberg, M. S.; Adams, D. C.; Gurevitch, J. M., Statistical software for meta-analysis.

534 Version. 2000.

535 (52) Macheferf, S.; Dise, N.; Goulding, K.; Whitehead, P., Nitrous oxide emission from a range
536 of land uses across Europe. *Hydrol. Earth Syst. Sc.* **2002**, *6*, (3), 325-337; DOI
537 10.5194/hess-6-325-2002.

538 (53) Fu, B.; Meng, Q.; Qiu, Y.; Zhao, W.; Zhang, Q.; Davidson, D., Effects of land use on soil
539 erosion and nitrogen loss in the hilly area of the Loess Plateau, China. *Land Degrad. Dev.*
540 **2004**, *15*, (1), 87-96; DOI 10.1002/ldr.572.

541 (54) Zhang, Y.; Zhang, J.; Zhu, T.; Müller, C.; Cai, Z., Effect of orchard age on soil nitrogen
542 transformation in subtropical China and implications. *J. Environ. Sci.* **2015**, *34*, 10-19;
543 DOI 10.1016/j.jes.2015.03.005.

544 (55) Li, C.; Hu, H.W.; Chen, Q.L.; Chen, D.; He, J.Z., Comammox Nitrospira play an active
545 role in nitrification of agricultural soils amended with nitrogen fertilizers. *Soil Biol.*
546 *Biochem.* **2019**, *138*, 107609; DOI 10.1016/j.soilbio.2019.107609.

547 (56) Gao, W.; Kou, L.; Zhang, J.; Müller, C.; Wang, H.; Yang, H.; Li, S., Enhanced deposition
548 of nitrate alters microbial cycling of N in a subtropical forest soil. *Biol. Fertil. Soils* **2016**,
549 *52*, (7), 977-986; DOI 10.1007/s00374-016-1134-4.

550 (57) Hoyle, F.; Murphy, D.; Fillery, I., Temperature and stubble management influence
551 microbial CO₂-C evolution and gross N transformation rates. *Soil Biol. Biochem.* **2006**,
552 *38*, (1), 71-80; DOI 10.1016/j.soilbio.2005.04.020.

553 (58) Dan, X.; Chen, Z.; Dai, S.; He, X.; Cai, Z.; Zhang, J.; Müller, C., Effects of Changing
554 Temperature on Gross N Transformation Rates in Acidic Subtropical Forest Soils. *Forests*
555 **2019**, *10*, (10), 894; DOI 10.3390/f10100894.

- 556 (59) Lan, T.; Han, Y.; Roelcke, M.; Nieder, R.; Cai, Z., Temperature dependence of gross N
557 transformation rates in two Chinese paddy soils under aerobic condition. *Biol. Fertil. Soils*
558 **2014**, *50*, (6), 949-959; DOI 10.1007/s00374-014-0917-8.
- 559 (60) Yu, T.; Zhuang, Q., Quantifying global N₂O emissions from natural ecosystem soils using
560 trait-based biogeochemistry models. *Biogeosci. Discuss.* **2019**, *16*, (2), 207-222; DOI
561 10.5194/bg-16-207-2019.
- 562 (61) Zhang, Y.; Zheng, X.; Guo, B.; Yu, J.; Carswell, A.; Misselbrook, T.; Zhang, J.; Müller, C.;
563 Chen, D.; Ding, H., Mechanisms behind the inhibition of autotrophic nitrification
564 following rice-straw incorporation in a subtropical acid soil. *Soil Till. Res.* **2019**, *196*,
565 104436; DOI 10.1016/j.still.2019.104436.
- 566 (62) Bengtsson, G.; Bengtson, P.; Månsson, K. F., Gross nitrogen mineralization-,
567 immobilization-, and nitrification rates as a function of soil C/N ratio and microbial activity.
568 *Soil Biol. Biochem.* **2003**, *35*, (1), 143-154; DOI 10.1016/S0038-0717(02)00248-1.
- 569 (63) Nicol, G. W.; Leininger, S.; Schleper, C.; Prosser, J. I., The influence of soil pH on the
570 diversity, abundance and transcriptional activity of ammonia oxidizing archaea and
571 bacteria. *Environ. Microbiol.* **2008**, *10*, (11), 2966-2978; DOI 10.1111/j.1462-
572 2920.2008.01701.x.
- 573 (64) Friedl, J.; Scheer, C.; Rowlings, D. W.; Mumford, M. T.; Grace, P. R., The nitrification
574 inhibitor DMPP (3, 4-dimethylpyrazole phosphate) reduces N₂ emissions from intensively
575 managed pastures in subtropical Australia. *Soil Biol. Biochem.* **2017**, *108*, 55-64; DOI
576 10.1016/j.soilbio.2017.01.016.
- 577 (65) Qiao, C.; Liu, L.; Hu, S.; Jana E. Compton Tara L. Greaver; Li, Q. How inhibiting

578 nitrification affects nitrogen cycle and reduces environmental impacts of anthropogenic
579 nitrogen input. *Global Change Biol.* **2015**, *21*, 1249-1257, DOI 10.1111/gcb.12802.

580 (66) Lam, S.K.; Suter, H.; Mosier, A.R.; Chen, D. Using nitrification inhibitors to mitigate
581 agricultural N₂O emission: a double-edged sword? *Global Change Biol.* **2017**, *23*, (2):485-
582 489, DOI 10.1111/gcb.13338.

583 (67) Yang, S.; Wang, Y.; Liu, R.; Xing, L.; Yang, Z., Improved crop yield and reduced nitrate
584 nitrogen leaching with straw return in a rice-wheat rotation of Ningxia irrigation district.
585 *Sci. Rep.* **2018**, *8*, (1), 1-8; DOI 10.1038/s41598-018-27776-5.

586 (68) Griffin, T.; He, Z.; Honeycutt, C., Manure composition affects net transformation of
587 nitrogen from dairy manures. *Plant Soil* **2005**, *273*, (1-2), 29-38; DOI 10.1007/s11104-
588 004-6473-5.

589 (69) Graham, R. F.; Wortman, S. E.; Pittelkow, C. M., Comparison of organic and integrated
590 nutrient management strategies for reducing soil N₂O emissions. *Sustainability* **2017**, *9*,
591 (4), 510; DOI 10.3390/su9040510.

592 (70) Booth, M. S.; Stark, J. M.; Rastetter, E., Controls on nitrogen cycling in terrestrial
593 ecosystems: a synthetic analysis of literature data. *Ecol. Monogr.* **2005**, *75*, (2), 139-157;
594 DOI 10.1890/04-0988.

595 (71) Lang, M.; Cai, Z.C.; Mary, B.; Hao, X.; Chang, S. X., Land-use type and temperature affect
596 gross nitrogen transformation rates in Chinese and Canadian soils. *Plant Soil* **2010**, *334*,
597 (1-2), 377-389; DOI 10.1007/s11104-010-0389-z.

598 (72) Zhang, J.; Sun, W.; Zhong, W.; Cai, Z., The substrate is an important factor in controlling
599 the significance of heterotrophic nitrification in acidic forest soils. *Soil Biol. Biochem.*

