Supplementary materials for

Global patterns of nitrogen saturation in forests

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Supplementary Texts

Text S1. Indicators of nitrogen saturation status

In the 1980s, European researchers firstly came up with the concept of "nitrogen saturation" [1,2]. It refers to a status when forest ecosystems cannot retain more nitrogen (N), so that additional N input are almost entirely lost via leaching or gaseous emission. Since then, researchers identified different variables to indicate N limitation or saturation status of forests (Fig. S10).

Atmospheric N deposition is a driving force of change from N-limited to N-saturated status. Therefore, forests under higher **N deposition** are more likely to become N-saturated [3]. After N enters forest soils, the relative enrichment of N tend to lower the **soil C:N ratio** [4]. Also, the different effects of N deposition on acid anion and base cation contents may lower **soil pH** [5], leading to soil acidification. Lowered soil pH will, on one hand, decrease the dissolved organic carbon content in soil. On the other hand, input N stimulates the mineralization of soil organic carbon (SOC) by microbes and decreases SOC content. Both of the processes result in lowered **SOC content** in soils [6]. Meanwhile, soil properties influence the retainment of N and the preferential pathway of environmental N loss, i.e., either hydrological or gaseous. For example, soils with higher **clay content** are less permeable. Because less N would be leached out, such soils are more likely to become N-saturated and show higher rates of gaseous N losses. Some researchers also proposed that multiple soil properties could be integrated to form a new indicator, which may better reveal forests in N limitation or N saturation status [7]. The relationship between such an integrative indicator and forest N saturation status, however, comes from observations used to derive the indicator, rather than from underlying mechanisms. Therefore, the parameters used to derive the indicator and their weights may change when different observational data were used.

By definition, N loss from forests can indicate forests reaching N saturation. From the 1990s to the 2000s, **leaching loss of N** was a widely used indicator of forests shifting from N-limited to N-saturated status [8,9]. Progressively, the interpretation of the indicator changes from "the occurrence of N leaching indicates N saturation" to "high N leaching rate indicates N saturation", and then to "high N leaching relative to N input indicates N saturation" [10]. The different interpretation of the indicator leads to different sampling approaches applied. In some studies, samples were taken from nearby water bodies, whereas in some other studies, deep soil solutions were sampled. The former has an advantage of reducing the random errors when sampling spatially heterogenous soils, whereas the latter is more advantageous in connecting N leaching with N input occurring in the same place. However, the differences in sampling approaches prohibit the site-level N leaching data from being combined to reveal N saturation status of forests on regional scale.

Besides, the structure and function of plants can also indicate N saturation status in forests. For instance, the presence or absence of some **signal species** (which are sensitive to changes in soil nutrients) can reflect the change in forest N saturation status to some extent [11]. When forests become N-saturated, the growth of plants become limited by other resources than N. Additional N input can no longer enhance **plant productivity**, which may even suppress plat growth and decrease productivity by changing soil properties. Also, the **resorption rate of N** may decrease relative to that of other nutrients, because plants in N-saturated forests need other nutrients more than N [12]. However, due to the difficulty in investigating plant functional traits, there is a lack of regional dataset derived from a universal sampling method. Therefore, plant functional traits could barely be used to indicate N saturation status on regional scale.

N isotope ratio ($\delta^{15}N$) measured from terrestrial samples (foliar, tree ring, sediment) has been a good, integrated indicator of N cycling processes, because of the isotope fractionation effect (heavier isotope gradually accumulate and enrich in organisms and soils, in the processes of N transformation and transport). In ecosystems where N availability is low, organisms tend to use N more conservatively, bypassing or suppressing N transformation processes where N could potentially be lost; whereas in ecosystems with high N availability, more N transformation processes could be involved, therefore the fractionation effect would be more prominent in high-N than in low-N-availability ecosystems. This is the reason why researchers could use N isotope ratio to indicate the temporal trend of N availability in terrestrial ecosystems over a large scale [13,14].

But restrictions may apply when using N isotope ratio to indicate the spatial variation in N availability (N limitation/saturation status in our study). Because N sources differ among forests – some rely on local N, while some use deposited exogenous N as the major source. In the latter case, measured foliar and soil N isotope ratio may be influenced by the N isotope signature of the deposited N [15], not necessarily reflective of the N transformation processes and availability of N in the local ecosystem. Forests, especially those close to human settlements, are heavily influenced by N deposition. It is therefore problematic to rely on N isotope ratio to indicate the spatially varying N availability in forests, where the different N sources may be confounding [16,17].

Text S2. Estimating the change point of the relationship between N input and soil N_2O emission, so that threshold between low and high N input levels was determined

Soil N_2O emission rate (R_{N2O}) responds almost linearly to low N input (including N deposition and low N addition). High N input, however, may change the ecosystem properties and induce a non-linear response [18]. To estimate the point at which the relationship between N input rate and R_{N2O} changes, we conducted a segmented regression analysis with compiled data from N addition experiments (N_2O_exp dataset; Data S1).

Only a few observations have N input rates above 400 kgN ha^{-1} yr^{-1}, the R_{N2O} values of which show a high variation. Referring to previous research [19-23](Table S3), the change point of the relationship between N input rate and R_{N2O} is unlikely to exceed 400 kgN ha^{-1} yr^{-1}. Therefore, we filtered out observations with N input rates above 400 kgN ha^{-1} yr^{-1}, and conducted a segmented regression (model: R_{N2O} ~ N input rate) in R [24] using the "segmented" package [25]. The algorithm can detect a change point (or change points), and apply different linear models to the data below or above the change point(s). We firstly assumed there was one change point, which was estimated to be 174.70 ± 19.73 kgN ha^{-1} yr^{-1} (n = 532, $R^2 = 0.20$, $p < 0.001$).

Considering the possibility of having multiple change points, we also constructed segmented regression models when assuming 2–4 change points exist. Then we calculated Bayes factors (BF) based on Akaike's An Information Criterion (BIC) of each model, so we can evaluate which model is better [26]. The BFs indicate that there are >95% probabilities that the model with one change point is better than models with multiple change points (Table S4).

To sum up, our data showed that there is one change point in the linear relationship between N input rate and R_{N2O}, which is 174.70 ± 19.73 kgN ha^{-1} yr^{-1} (Fig. S11). We also referred to the change points used or estimated in previous research (Table S3), and conservatively determined the N addition rates below 150 kgN ha^{-1} yr^{-1} to be "low" N input in this study.

Text S3. Calculating the sensitivity of soil N_2O emission to N deposition (s_N) using N cycle parameters

Using data from N addition experiments (Table S1), we built a generalized linear model to simulate the sensitivity (s_N) of soil N_2O emission (R_{N2O}) to N deposition (N_{depo}) of global forests. Due to the limited N addition experiment data available, we could not reserve part of the data for model validation. Instead, we calculated s_N from other N cycle parameters to validate the model-estimated s_N.

In a determined ecosystem, we define c_1 to be the sensitivity of total N loss (N leaching and gaseous N emission combined) to N deposition ($c_1 = \frac{\Delta N_{loss}}{\Delta N_{depo}}$; unit: kgN kgN^{-1}), c_2 to be sensitivity of N leaching to N deposition ($c_2 = \frac{\Delta N_{leach}}{\Delta N_{depo}}$; unit: kgN kgN^{-1}), c_3 to be the nitrification and denitrification end-product ratio ($c_3 = \frac{R_{N2O}}{N_{gas}} = \frac{R_{N2O}}{R_{N2}+R_{NO}+R_{N2O}}$; unit: kgN_2O-N kgN^{-1}).

First of all, gaseous N loss can be calculated as the nitrogen lost in other pathways than leaching.

$$N_{gas} = N_{loss} - \Delta N_{leach}$$

Thus, the change in soil N_2O emission rate caused by N deposition change can be calculated from the change in N loss rate and N leaching loss rate.

$$\Delta R_{N2O} = c_3 \times \Delta N_{gas} = c_3 \times (\Delta N_{loss} - \Delta N_{leach}) = c_3 \times (c_1 - c_2) \times \Delta N_{depo}$$

By definition, s_N is the change in soil N_2O emission rate per unit of N deposition change. It can be inferred that

$$s_N = \frac{\Delta R_{N2O}}{\Delta N_{depo}} = c_3 \times (c_1 - c_2) \qquad \text{(Eq. T1)}$$

To quantify c_1 and c_2, we collected data on the total N loss rate (N_{loss}) and N leaching rate (N_{leach}) data measured in N addition experiments (Data S3; Fig. S12). For literature where the change rate of N pool was provided instead of N_{loss}, c_1 was calculated using Eq. T2.

$$c_1 = \frac{\Delta N_{loss}}{\Delta N_{depo}} = \frac{\Delta N_{depo} - \Delta(\Delta N_{pool})}{\Delta N_{depo}} = 1 - \frac{\Delta N_{pool-N1} - \Delta N_{pool-CK}}{(N_{depo}+N_1) - N_{depo}} \qquad \text{(Eq. T2)}$$

where N_1 is the rate of artificial N addition in the experiment (kgN ha^{-1} yr^{-1}) ; N_{depo} is the background N deposition rate at the site (kgN ha^{-1} yr^{-1}); $\Delta N_{pool\text{-}N1}$ is the change rate of N pool in the N addition plot (kgN ha^{-1} yr^{-1}; $\Delta N_{pool\text{-}CK}$ is the change rate of N pool in the control plot (kgN ha^{-1} yr^{-1}). For N addition experiments with multiple N addition levels, we built linear models (model: $\Delta N_{pool} \sim$ N input rate) to infer the change of ΔN_{pool} per unit of N input (i.e., $1 - c_1$).

Based on the calculated c_1 and c_2, together with the c_3 from previous research [27], we calculated the biome-mean s_N using Eq. T1. Comparing the model-estimated s_N and the calculated s_N (Table S5), we found their correlation coefficient (Pearson's r) to be 0.998.

Text S4. Sensitivity of soil N_2O emission to N deposition (s_N) in deciduous broadleaf and needleleaf forests

Previous research found that the gaseous N product ratio (N_2O:NO) was higher in beech forest than in spruce forests [28], which implies that forest type may have a significant effect on the sensitivity of soil N_2O emission to N deposition (s_N).

To test the hypothesis, we compared the s_N of deciduous broadleaf and needleleaf forests worldwide. s_N values of global forests were from our constructed model. Forest type information was from a global product [29]. Specifically, for each spatial grid which has a s_N value, forest type was determined based on the coordinates of the grid. For grids having multiple types of forests (evergreen broadleaf / deciduous broadleaf / needleleaf / mixed), only grids where deciduous broadleaf / needleleaf forests make up more than 50% the grid area was considered to be a deciduous broadleaf / needleleaf forest grid, whereas the other forest girds were considered to be “mixed”. Mixed forest grids were not considered in the following analysis.

On global scale, we found s_N of deciduous broadleaf forests to be significantly higher than that of needleleaf forests ($p < 0.001$; Fig. S13). On biome scale, however, s_N of broadleaf forests was significantly higher than that of needleleaf forests in temperate biome only ($p < 0.001$). This is probably because forest type indirectly influences s_N through the different capabilities of broadleaf and needleleaf forests to retain and utilize deposited N. In temperate biome where atmospheric N deposition rate is particularly high in broadleaf forests, differences in N deposition caused significantly higher s_N in broadleaf forest than in needleleaf forests.

Text S5. Using two datasets separately to detect thresholds for the classification of N limitation and saturation status

We have two independent datasets on the field-observed N-limited or N-saturated status of global forests, which were indicated by N leaching rate (Nleach dataset) and plant growth response to N input (NuLi dataset), respectively. Because the two indicators may point to different stages of N saturation [30], we firstly used the two datasets separately in the detection of threshold for determining forest N saturation status.

To begin with, we checked whether s_N could distinguish between the N-limited and N-saturated forests. For the forests in Nleach dataset, the mean s_N of N-saturated forests were significantly higher than that of N-limited forests, both on global and biome scales (Fig. S14; p <0.001). Also, the mean s_N of N-saturated forests were significantly higher than that of N-limited forests in NuLi dataset (Fig. S14; p <0.001).

Then, the two datasets were used separately to detect the optimal cutoff value of s_N between N-limited and N-saturated forests. For forest sites in Nleach dataset, we randomly sampled (with replacement) 10 N-limited forests and 10 N-saturated forests. The 20 sites constitute a sample dataset where N-limited and N-saturated sites were equally represented. For each possible cutoff value of s_N (within the range of the s_N values of all samples), forests having higher s_N than the cutoff value were classified as N-saturated forests, and those having s_N no higher than the cutoff value were classified as N-limited forests. The classified N limitation or saturation status were compared with the observed status of the sampled forests, and the proportion of successfully classified forests (i.e., to the same category as observed) was the accuracy of the classification. All possible cutoff values of s_N were tried out (at a precision of 0.0001 kgN_2O-N kgN^{-1}), and the corresponding accuracies of classification were recorded. The cutoff value(s) that shows the highest accuracy of classification is the optimal cutoff value for the sampled forests. The resampling and detection-of-optimal-cutoff-value processes were repeated for 5000 times. Subsequently, we switched to NuLi dataset and repeated the abovementioned processes for another 5000 times.

By comparing the statistical distribution of the detected optimal cutoff values for the two datasets, we observed a considerable overlap (Fig. S15). That means, the two datasets may point to a similar threshold of s_N for the classification of N-limited and N-saturated forests. Therefore, we combined the two datasets to enlarge the sample size and detect a universal threshold for classification.

Supplementary Figures

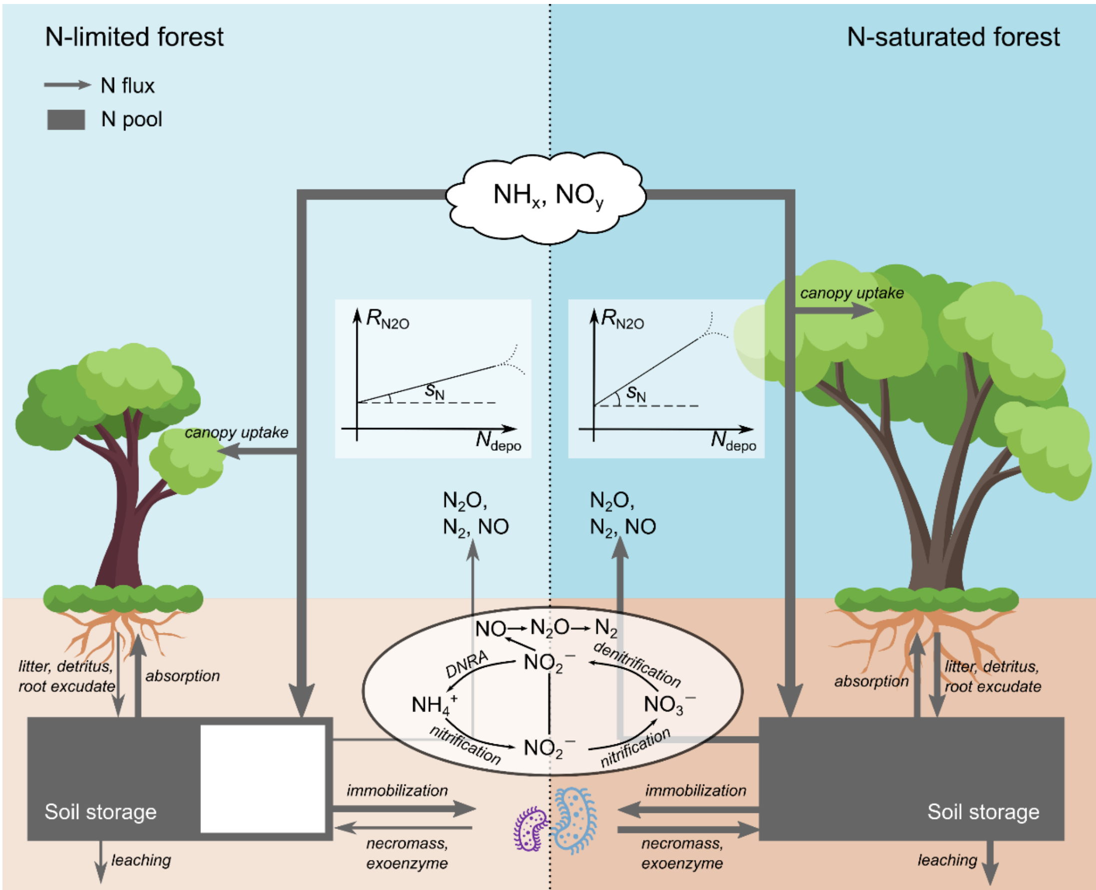


Fig. S1. A simplified illustration of the differences in nitrogen (N) flow in N-limited and N-saturated forests. NH_x: reduced nitrogen; NO_y: oxidized nitrogen; R_{N2O}: soil N_2O emission rate; N_{depo}: atmospheric N deposition rate; s_N: sensitivity of soil N_2O emission to N deposition; DNRA: dissimilatory nitrate reduction to ammonium.

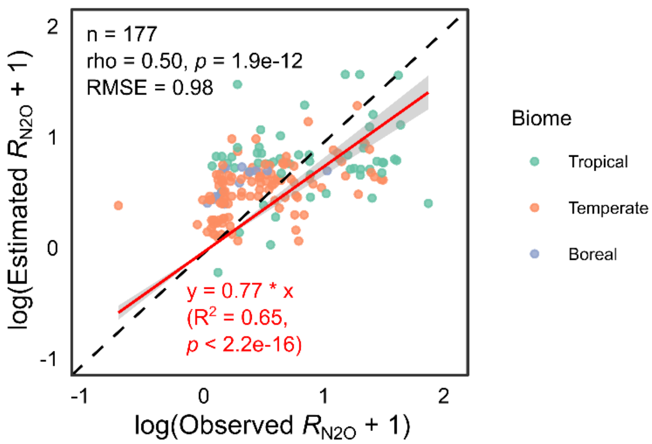


Fig. S2. Comparing estimated and observed soil N_2O emission rates (R_{N2O}). Observations were aggregated to 0.5°×0.5° grids to match with the spatial resolution of the environmental factors. Each point represents a grid-year. Points of different colors represent grid-years in different biomes. Because observed and estimated R_{N2O} do not follow normal distribution, Spearman's rho was used as the coefficient of correlation between them. For the same reason, observed and estimated R_{N2O} were log-transformed before fitting a linear model. The red line and fonts show the fitted linear regression model. Gray shading denotes the standard error. Dashed black line is the 1:1 line.

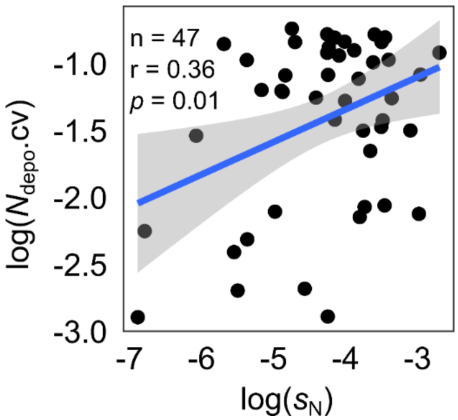
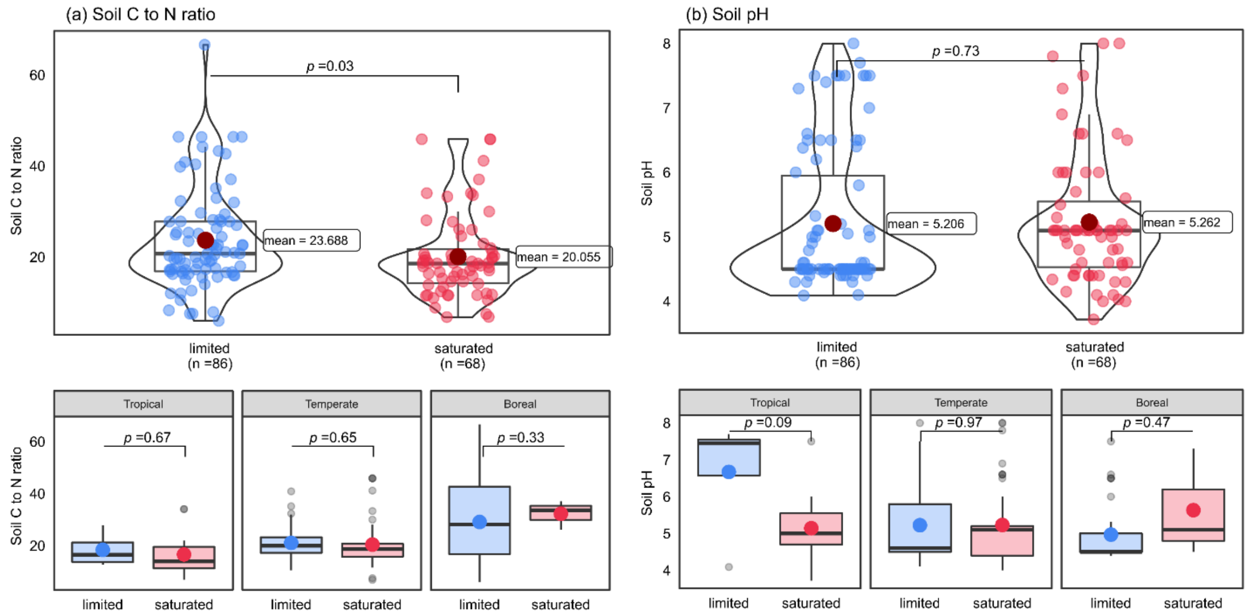
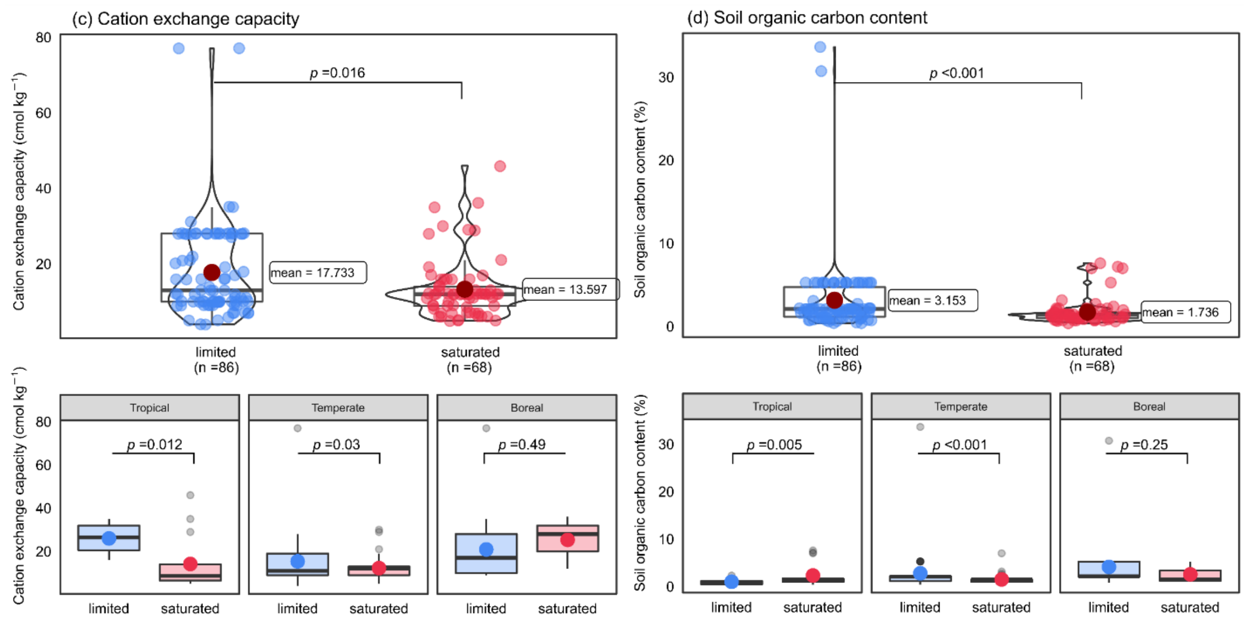


Fig. S3. Correlation test between sensitivity of soil N_2O emission to N deposition (s_N; log-transformed) and annual variation of N deposition (N_{depo}.cv; log-transformed). s_N values were calculated using low N input data from global forest experiment sites (Table S1). Temporal data of N deposition were from a published dataset by Ackerman et al.[31].


(a) Soil C to N ratio
Soil C to N ratio
p =0.03
mean = 23.688
mean = 20.055
limited
(n =86)
saturated
(n =68)
Tropical
Temperate
Boreal
p =0.67
p =0.65
p =0.33
(b) Soil pH
Soil pH
p =0.73
mean = 5.206
mean = 5.262
p =0.09
p =0.97
p =0.47


(c) Cation exchange capacity
Cation exchange capacity (cmol kg⁻¹)
p =0.016
mean = 17.733
mean = 13.597
limited
(n =86)
saturated
(n =68)
Tropical
Temperate
Boreal
p =0.012
p =0.03
p =0.49
(d) Soil organic carbon content
Soil organic carbon content (%)
p <0.001
mean = 3.153
mean = 1.736
p =0.005
p <0.001
p =0.25

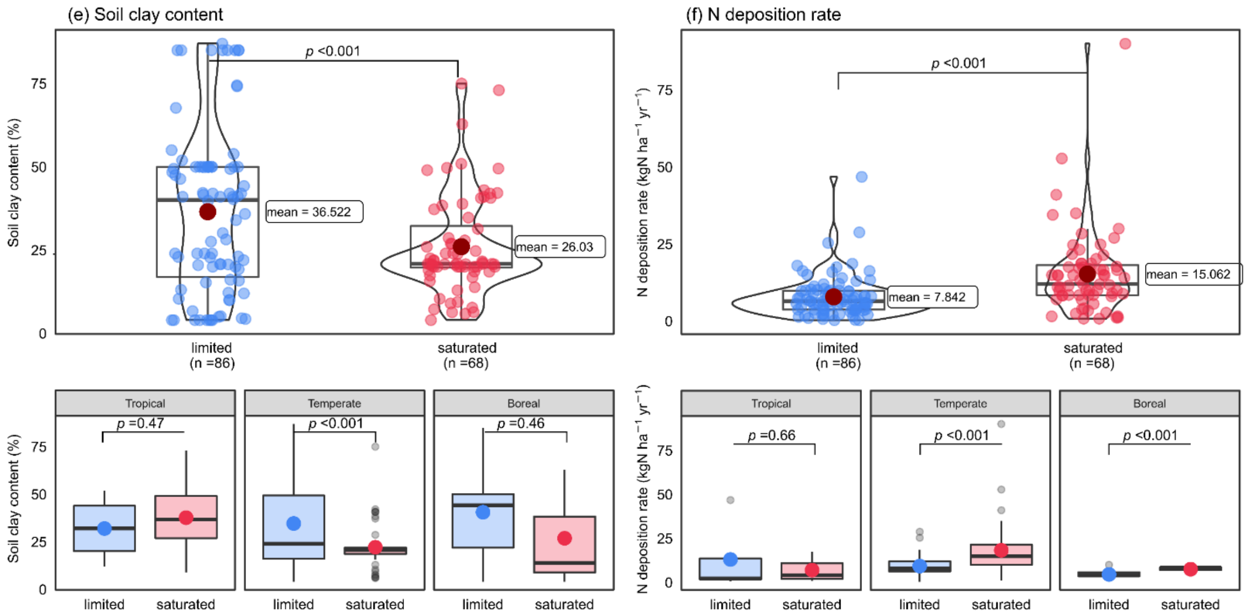


Fig. S4. Comparing the performance of different indicators in distinguishing between N-limited and N-saturated forests. Most of the indicators showed reliable performance (significant difference between groups) on global scale, but none of the indicators could have successfully and consistently distinguished between forests in N-limited or N-saturated status across biomes. It is to be noted that these indicators were selected based on the availability of data (from literature or spatial datasets).

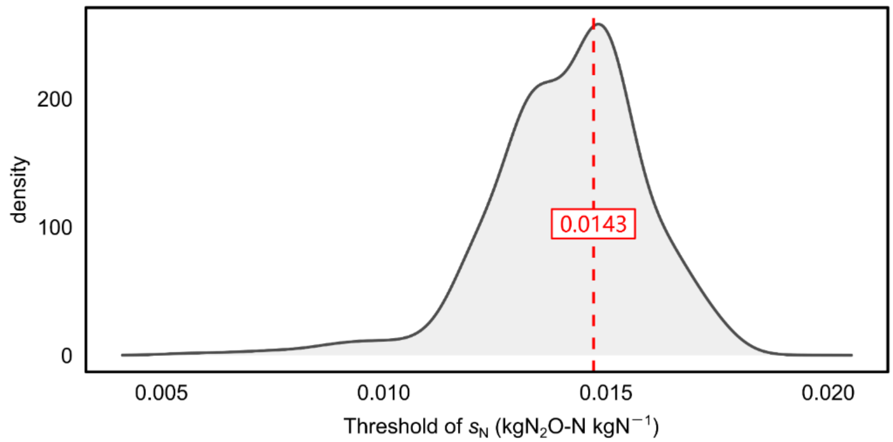


Fig. S5. Density curve showing the statistical distribution of optimal cutoff values of s_N, which were calculated using bootstrap method for 5000 times. The most frequently detected optimal cutoff value (0.0143 kgN_2O-N kg^{-1}), as indicated by the peak of the curve, was used as the optimal threshold.

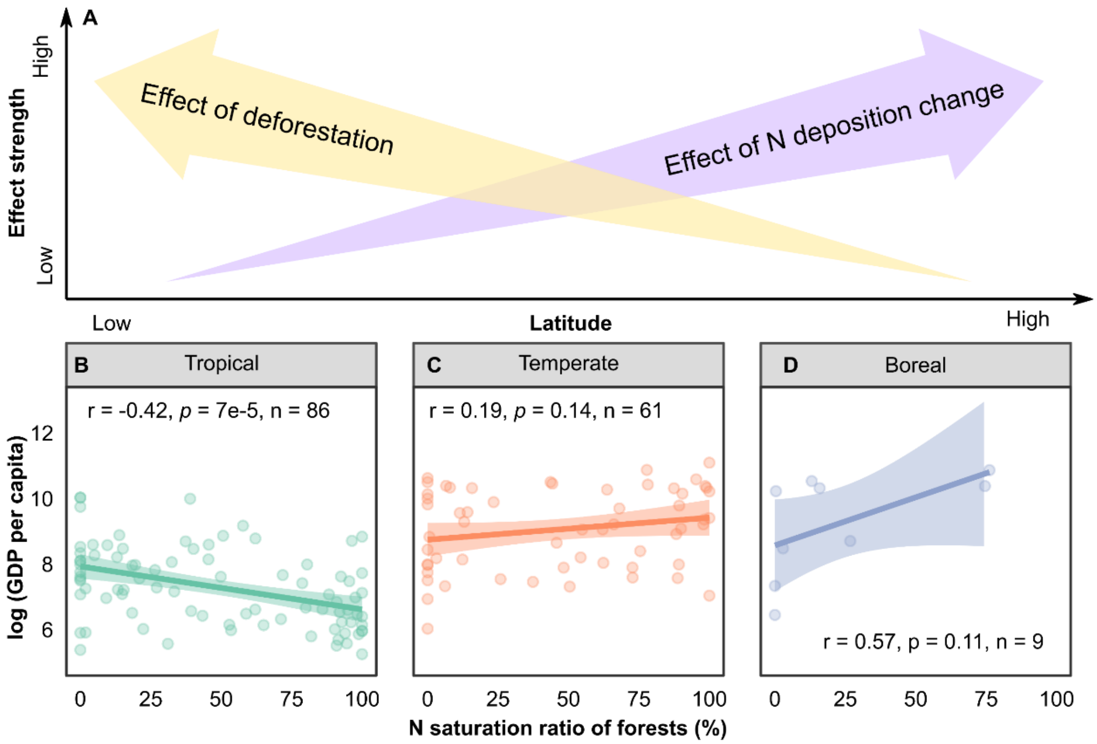


Fig. S6. Varying relationships between forest N saturation status and economic development of different countries. (A) Schematic illustration of the stronger negative effect of deforestation (i.e., replacement of mature forests by young forests during economic development) on the N saturation ratio at lower latitudes and the stronger positive effect of N deposition change on the N saturation ratio at higher latitudes. (B-D) Correlations between log-transformed GDP per capita (unit: USD) and N saturation ratio of forests (%) in different countries. Each point represents a country. Solid lines show the fitted linear models, and shadings represent the standard errors of the fitted models.

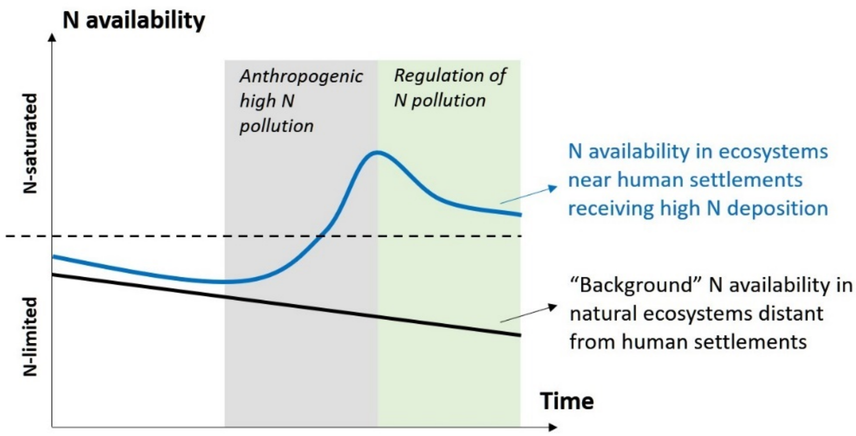


Fig. S7. A framework for explaining the observed declining N availability in natural ecosystems (due to increased CO_2 level and extended growing season) and also high N saturation ratios in forests near human settlements (which are receiving high N deposition).

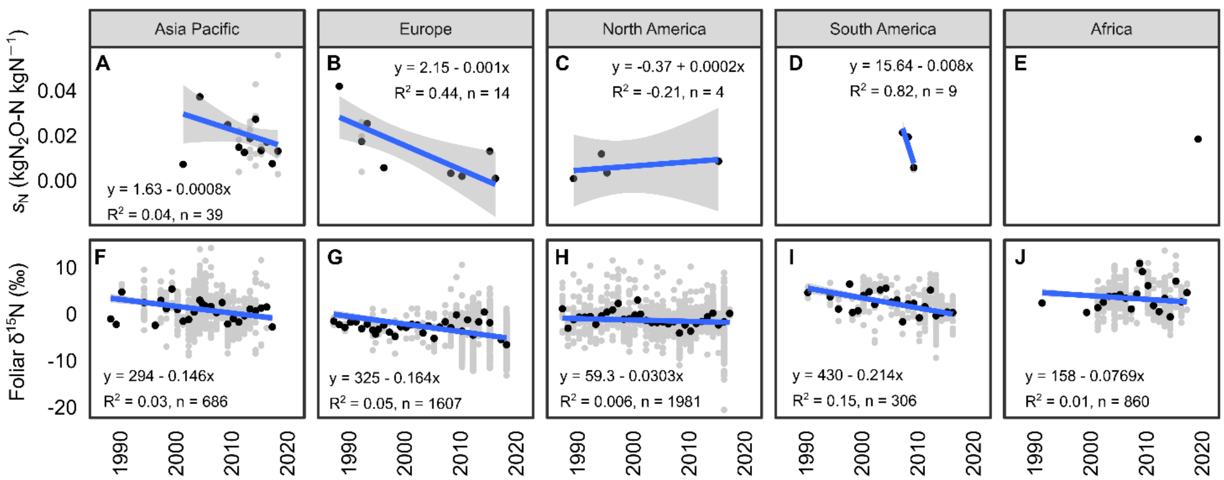


Fig. S8. Temporal change of N availability in different geographic regions, indicated by sensitivity of soil N_2O emission to N deposition (s_N) and foliar N isotope ratio ($\delta^{15}N$). Panels (A-E) Temporal change of s_N. s_N was calculated using global N addition experiment data (Data S1). Each gray point represents a grid-year where N addition experiment data were available and s_N could be calculated. Black points are the annual mean values of s_N. Panels (F-J) Temporal change of foliar $\delta^{15}N$. Foliar $\delta^{15}N$ data were from a published global dataset by Craine et al. [13](https://doi.org/10.5061/dryad.v2k2607). Only data after 1985 were used, so as to match the time frame of s_N data. Blue lines were fitted linear models, and gray shadings represent the standard errors.

The two datasets used different geographic region classifications, so we reclassified data from several regions to facilitate comparison of the two metrics. In s_N dataset: data from "East Asia" and "Southeast Asia and Pacific" were reclassified to "Asia Pacific" region; data from "Western Europe" were reclassified to "Europe" region; data from "Sub-Saharan Africa" were reclassified to "Africa" region; data from "Latin America and Caribbean" were reclassified to "South America" region; no data were available for other regions. In foliar $\delta^{15}N$ dataset: data from "Asia" and "Australia" were reclassified to "Asia Pacific" region. Data and code used for producing this figure (and all other figures) could be found in supplementary materials.

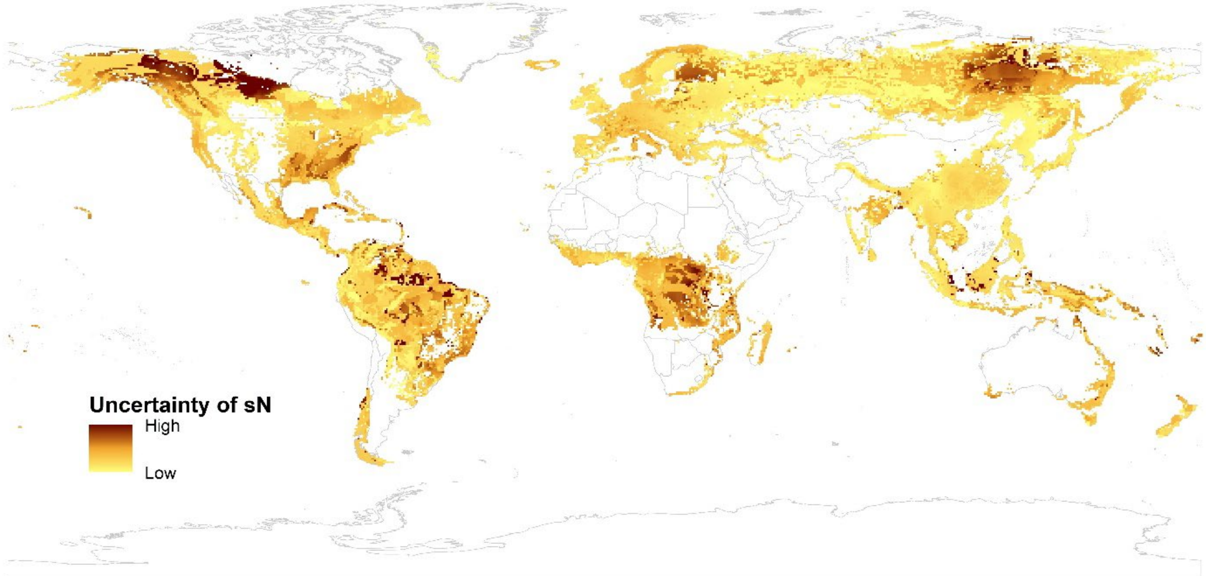


Fig. S9. Uncertainty of modeled sensitivity of soil N_2O emission to N deposition (s_N).

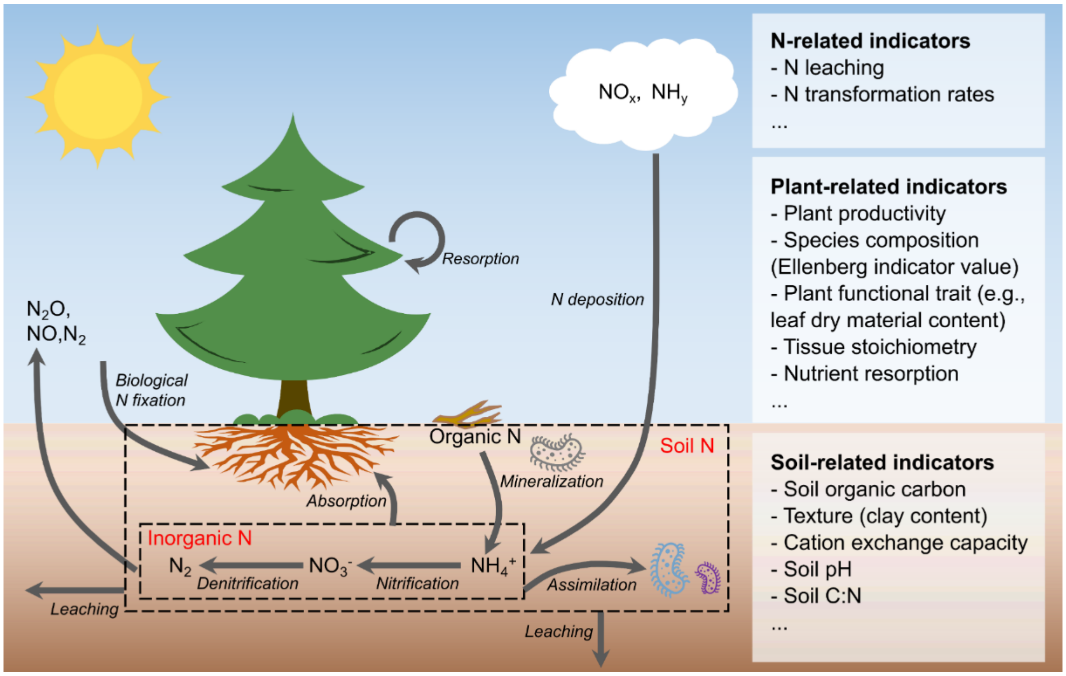


Fig. S10. Simplified illustration of the nitrogen (N) flows in forest ecosystems, and indicators of N saturation status. NH_x: reduced nitrogen; NO_y: oxidized nitrogen.

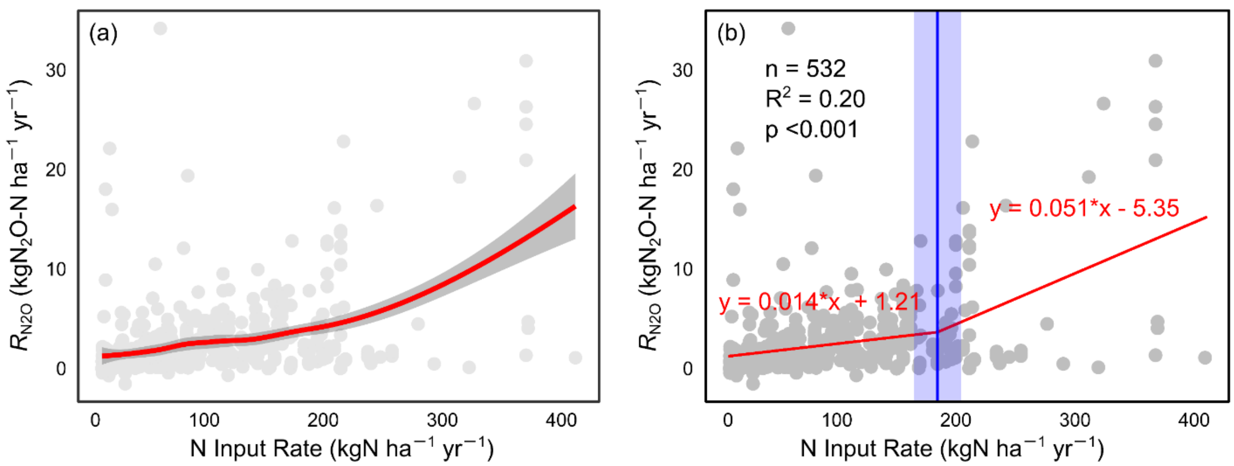


Fig. S11. Locally weighed regression model (a) and segmented linear regression model (b) on soil N_2O emission rate (R_{N2O}) and N input rate. The blue vertical line shows the estimated change point (174.70 kgN ha^{-1} yr^{-1}). The blue shading represents the standard error of the estimated change point. The red lines and fonts represent the fitted models (model: R_{N2O} ~ N input rate).

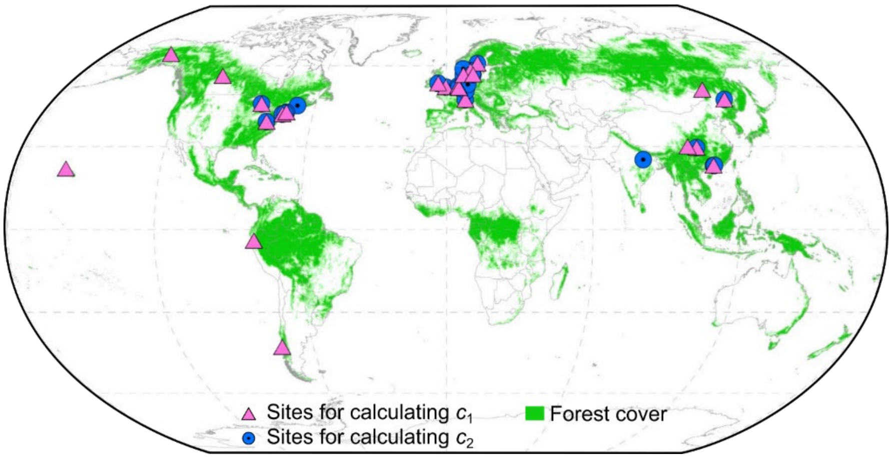


Fig. S12. The spatial map of N addition experiment sites for calculating c_1 and c_2. c_1: sensitivity of total N loss to N deposition (kgN kgN^{-1}); c_2: sensitivity of N leaching to N deposition (kgN kgN^{-1}).

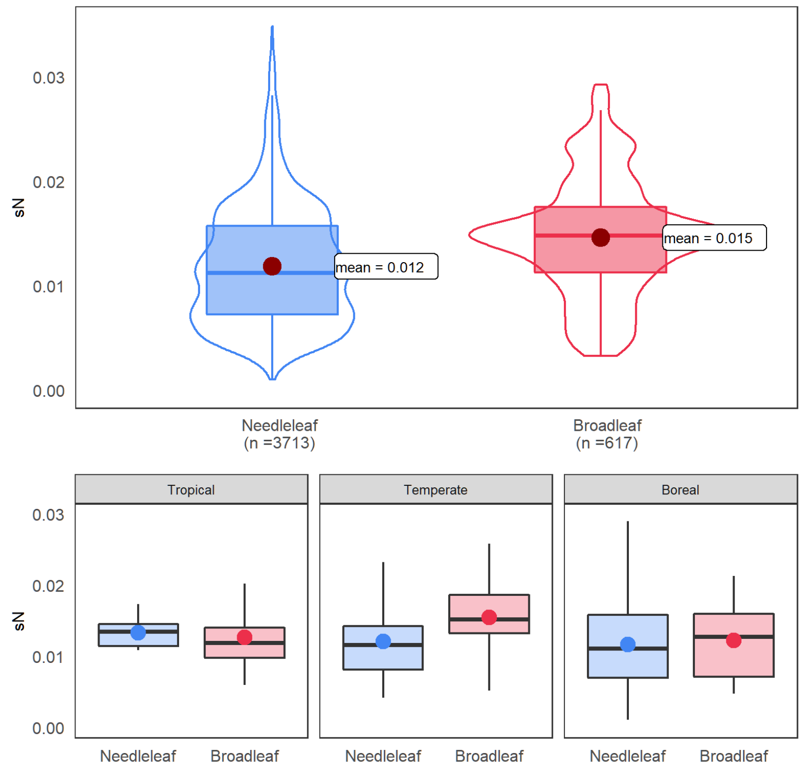


Fig. S13. Comparing the sensitivity of soil N_2O emission to N deposition (s_N) of broadleaf and needleleaf forests. Of the 4330 spatial grids where more than 50% of the area were covered by deciduous broadleaf or needleleaf forests, 3713 were needleleaf forest grids, and 617 were deciduous broadleaf forest grids.

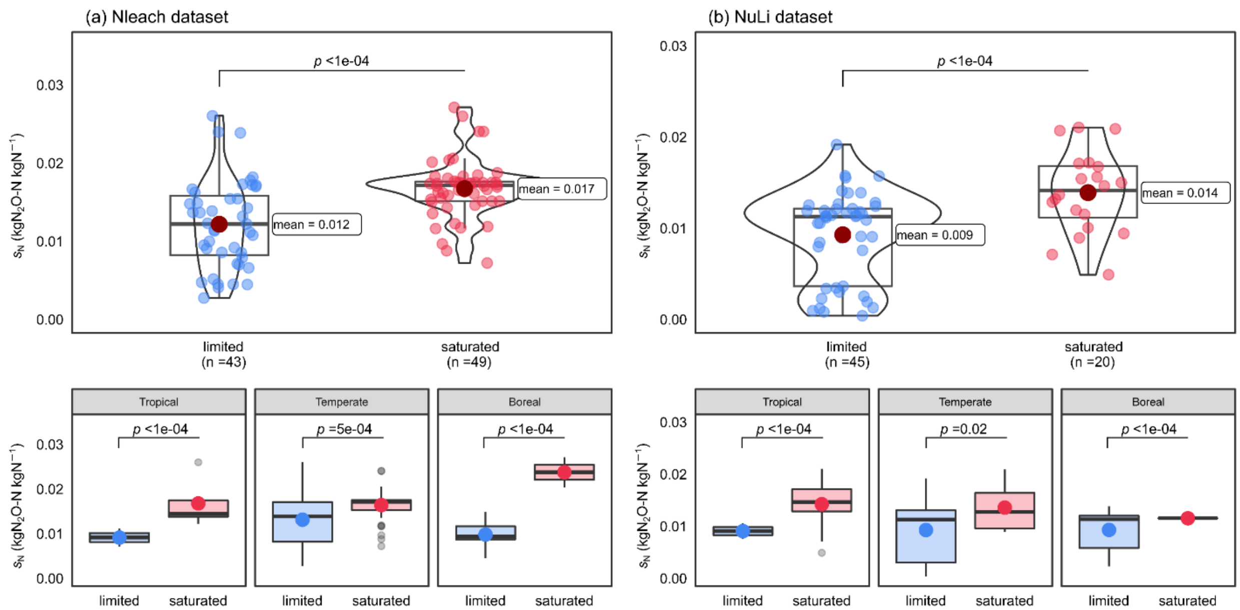


Fig. S14. Comparing the sensitivity of soil N_2O emission to N deposition (s_N) of N-saturated and N-limited forests in Nleach dataset (Data S4) and NuLi dataset (Data S5). The N limitation or saturation status of forests were determined by researchers in field observations, which we compiled from published literature.

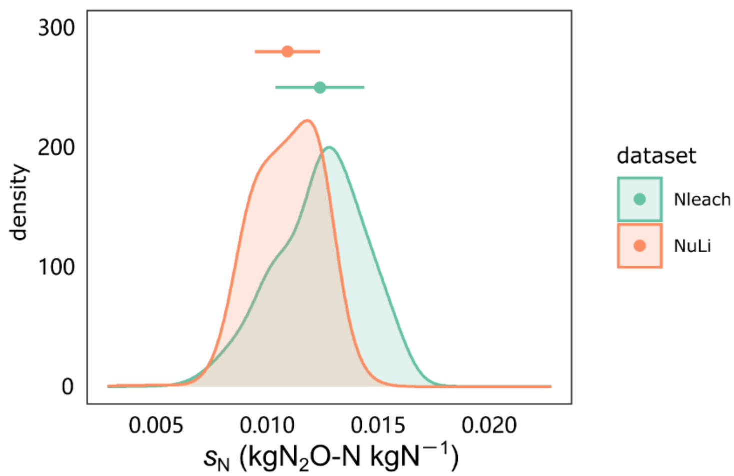


Fig. S15. Statistical distribution of the optimal cutoff values of s_N determined from field-observed N saturation status using Nleach and NuLi datasets (Data S4 and Data S5), separately. The curves represent the density of distribution of the cutoff values. The points and error bars above the curves of the corresponding color are the mean values and standard deviation of the optimal cutoff values.

Supplementary Tables

Table S1. Linear models on soil N_2O emission rate (R_{N2O}) and N input rate (model: R_{N2O} ~ N input rate) built with low N input data (N addition rate ≤ 150 kgN ha^{-1} yr^{-1}) from global forest experiment sites, and the derived sensitivity (s_N) of soil N_2O emission to N deposition and background N_2O emission rate (R_0).

No.	Longitude range	Latitude range	Biome	s_N	R_0	n	adj.R^2	p value	References
1	(19,19.5)	(64,64.5)	Boreal	0.002	0.045	2	NA	NA	[32]
2	(30.5,31)	(62.5,63)	Boreal	0.025	5.132	4	0.14	0.347	[33]
3	(22.5,23)	(62,62.5)	Boreal	0.013	0.538	2	NA	NA	[34]
4	(8,8.5)	(58.5,59)	Boreal	0.026	0.343	6	0.57	0.052	[35,36]
5	(-3.5,-3)	(55.5,56)	Temperate	0.02	0.258	6	0.18	0.224	[37]
6	(-3,-2.5)	(55.5,56)	Temperate	0.006*	-0.009	6	0.73	0.019	[37,38]
7	(1.5,2)	(52.5,53)	Temperate	0.004	0.233	2	NA	NA	[37]
8	(9.5,10)	(51.5,52)	Temperate	0.042*	0.51	10	0.48	0.015	[39-41]
9	(128.5,129)	(47,47.5)	Boreal	0.015	0.777	11	0.02	0.300	[42-44]
10	(8.5,9)	(47,47.5)	Temperate	0.003	-0.062	4	0.63	0.134	[45]
11	(-80.5,-80)	(43.5,44)	Temperate	0.009	1.374*	4	0.79	0.073	[46]
12	(-72.5,-72)	(43,43.5)	Temperate	0.012	-0.216	2	NA	NA	[47]
13	(141,141.5)	(43,43.5)	Temperate	0.025	1.647	2	NA	NA	[48]
14	(-72.5,-72)	(42.5,43)	Temperate	0.001	0.074	6	0.05	0.323	[49]
15	(128,128.5)	(42,42.5)	Temperate	0.01	0.67	2	NA	NA	[50]
16	(127.5,128)	(41.5,42)	Temperate	0.029	2.287	13	0.11	0.141	[51-53]
17	(-80.5,-80)	(41.5,42)	Temperate	0.003	0.217	2	NA	NA	[54]
18	(-4,-3.5)	(40,40.5)	Temperate	0.001*	0.026*	4	0.95	0.017	[55]
19	(112,112.5)	(36.5,37)	Temperate	0.056	2.754	3	0.98	0.068	[56]
20	(111,111.5)	(31.5,32)	Temperate	0.013**	0.483	27	0.28	0.003	[57-60]
21	(110,110.5)	(31.5,32)	Temperate	0.023	-0.31	4	0.54	0.166	[61]
22	(120.5,121)	(30.5,31)	Temperate	0.017	1.135	4	0.51	0.181	[62]
23	(119.5,120)	(30,30.5)	Temperate	0.003	1.238***	16	0.01	0.308	[63-67]
24	(120,120.5)	(30,30.5)	Temperate	0.012**	0.834*	12	0.64	0.001	[68,69]
25	(106.5,107)	(29.5,30)	Temperate	0.025*	0.875*	3	1	0.018	[70]
26	(115.5,116)	(29.5,30)	Temperate	0.012	2.025	6	0.14	0.248	[71]

27	(116.5,117)	(28,28.5)	Temperate	0.013	0.16	2	NA	NA	[72]
28	(118,118.5)	(27,27.5)	Tropical	0.015	1.948	9	0.12	0.190	[73]
29	(115,115.5)	(26.5,27)	Tropical	0.026***	-0.092	54	0.47	<0.001	[74-83]
30	(117,117.5)	(26,26.5)	Tropical	0.007	0.5	3	0.55	0.313	[84]
31	(118,118.5)	(25.5,26)	Tropical	0.012	0.601	4	0.33	0.257	[85]
32	(113,113.5)	(23.5,24)	Tropical	0.014	-0.226	3	0.77	0.220	[86]
33	(112.5,113)	(23,23.5)	Tropical	0.027*	0.19	22	0.15	0.041	[87-89]
34	(112.5,113)	(22.5,23)	Tropical	0.004	1.919***	14	0.11	0.129	[90]
35	(106.5,107)	(22,22.5)	Tropical	0.012***	-0.038	8	0.84	0.001	[91]
36	(107,107.5)	(22,22.5)	Tropical	0.043*	-0.089	10	0.51	0.013	[92-95]
37	(107.5,108)	(22,22.5)	Tropical	0.007**	0.589**	4	0.98	0.007	[96]
38	(101,101.5)	(21.5,22)	Tropical	0.037	2.101*	9	0.18	0.144	[97,98]
39	(110.5,111)	(21,21.5)	Tropical	0.018	3.195	3	0.69	0.256	[99]
40	(-80,-79.5)	(9,9.5)	Tropical	0.021**	0.674	8	0.71	0.005	[100,101]
41	(-82.5,-82)	(8.5,9)	Tropical	0.019	1.063	8	0.32	0.083	[100,101]
42	(116.5,117)	(6,6.5)	Tropical	0.007**	0.517**	10	0.61	0.005	[102]
43	(31.5,32)	(1.5,2)	Tropical	0.018***	1.756***	4	1	0.001	[103]
44	(102,102.5)	(-1.5,-1)	Tropical	0.022**	0.919*	7	0.84	0.002	[104]
45	(-79.5,-79)	(-4,-3.5)	Tropical	0.005	0.135	3	0.44	0.356	[105]
46	(-79,-78.5)	(-4.5,-4)	Tropical	0.006	0.471	3	0.5	0.333	[105]
47	(-79.5,-79)	(-4.5,-4)	Tropical	0.006	-0.11	3	0.95	0.106	[105]

* p <0.05; ** p <0.01; *** p <0.001; NA, not applicable

Table S2. Generalized linear models on environmental factors and the sensitivity (s_N) of soil N_2O emission to N deposition and the background N_2O emission rate (R_0). Models were refined from full models using environmental factors (MAT, MAP, N_{depo}, MAT.cv, MAP.cv, N_{depo}.cv, Clay, Sand) and their interactions as predictors[†].

	Estimate	**SE**	**t**	***p***
Refined model on s_N[‡] (family = "gaussian", deviance explained = 91.1%, n=46)				
Clay	4.77E-03	1.83E-03	2.605	0.013*
Sand	3.15E-03	9.20E-04	3.419	0.001**
log(N_{depo})	2.01E-02	1.14E-02	1.769	0.085
Clay × log(N_{depo}.cv)	2.13E-03	9.35E-04	2.282	0.028*
Sand × log(N_{depo}.cv)	1.17E-03	3.82E-04	3.056	0.004**
Clay × Sand	-1.90E-04	6.94E-05	-2.735	0.009**
Clay × Sand × log(N_{depo}.cv)	-1.14E-04	3.66E-05	-3.112	0.003**
Refined model on R_0[§] (family = "quasipoisson", deviance explained = 43.2%, n = 45)				
log(N_{depo}.cv)	1.99E-01	9.56E-02	2.084	0.043*
MAT × Sand × Clay	3.04E-06	5.99E-07	5.072	0.000***
MAP × MAP.cv × log(N_{depo})	-8.31E-04	2.91E-04	-2.854	0.007**

[†] These variables were selected based on availability of global datasets (for extrapolation), and mechanistic relevance. Climate is an important state factor that shapes ecosystem properties; N deposition is an important driving force of ecosystem N dynamics; soil texture is indicative of soil structure and aeration status, which is critical for nitrification and denitrification processes. MAT: mean annual temperature; MAP: mean annual precipitation; N_{depo}: mean annual N deposition; Sand: soil sand content; Clay: soil clay content.

[‡] s_N ~ (Clay + Sand + log(N_{depo}) + Clay × log(N_{depo}.cv) + Sand × log(N_{depo}.cv) + Clay × Sand + Clay × Sand × log(N_{depo}.cv))^2

[§] R_0 ~ EXP(log(N_{depo}.cv) + MAT × Sand × Clay + MAP × MAP.cv × log(N_{depo})) – 0.5

* p <0.05; ** p <0.01; *** p <0.001

Table S3. Change points of the relationship between N input rate and soil N_2O emission rate used or estimated in previous research

Change point estimated/used (kgN ha^{-1} yr^{-1})	Reference
101	[19]
135	[20]
140	[21]
100–150	[22]
150–200	[23]

Table S4. Comparing segmented regression models based on Bayes factor (BF)

Models (M_x)	Number of change points estimated	BIC	BF_{x0}*	Pr(M_0 is better)
M_0	1	2915.87	/	/
M_1	2	2928.20	474.90	> 0.99
M_2	3	2925.06	98.94	> 0.95
M_3	4	2951.56	56122954	> 0.99

*$BF_{x0} = \exp((BIC(M_x)-BIC(M_0))/2)$

Table S5. Comparing the biome-mean sensitivity (s_N) of soil N_2O emission to N deposition from calculation and the s_N estimated with generalized linear model.

Biome	c_1	c_2	c_3*	Calculated s_N	Modeled s_N
Tropical	0.42 (0.04)	0.29 (0.01)	0.20	0.026 (0.011)	0.015 (0.005)
Temperate	0.46 (0.05)	0.36 (0.05)	0.19	0.019 (0.018)	0.014 (0.004)
Boreal	0.41 (0.08)	0.37 (0.08)	0.19	0.008 (0.030)	0.010 (0.005)
All	0.44 (0.05)	0.35 (0.05)	0.19	0.017 (0.019)	0.013 (0.005)

Values in the parentheses are the standard errors of the estimates.
* Biome mean values of c_3 were calculated from modeled nitrification and denitrification end-product ratios by Bai, et al. [27].

Data S1. (separate file)

Compiled dataset on soil N_2O emission rate from N addition experiments in global forests (N_2O_exp dataset in main text).

Data S2. (separate file)

Compiled data on soil N_2O emission rate under natural conditions in global forests (N_2O_obs dataset in main text).

Data S3. (separate file)

Compiled dataset on total N loss rate, N leaching rate and change rate of soil N pool from N addition experiments in global forests (Ncycle_exp dataset in main text).

Data S4. (separate file)

Compiled dataset on global forest N saturation status (limited or saturated) indicated by N leaching rate (Nleach dataset in main text).

Data S5. (separate file)

An existing dataset from Du, et al. [12] on global forest N saturation status (limited or saturated) indicated by plant growth response to N input (NuLi dataset in main text).

Data S6. (separate file)

GDP per capita data of global countries, downloaded from World Bank Open Data portal (https://data.worldbank.org/).

Data S7. (separate file)

Data on environmental factors (MAT, MAP, N deposition rate, etc.) in global forests, extracted from spatial datasets mentioned in Methods section.

Code S1. (separate file)

R code script used to carry out the data analysis processes, and produce the figures.

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