Soil nitrogen substrates determine global N_2O emission more than climate and other soil properties

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Abstract

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Abstract

Accurate estimation of N_2O emission is one of the primary objectives to project the warming potential. However, the global patterns and main controlling factors of soil N_2O emission remain elusive. We compiled a dataset with 6016 field observations from 219 articles and found that the averaged soil N_2O emission rate was 1111.8 ± 26.59 μg N m^{-2} day^{-1}. Soil N_2O emission rates were significantly influenced by climatic factors (i.e. mean annual temperature), soil physical and chemical properties (e.g. pH, nitrate, ammonium, and total nitrogen), and microbial traits (microbial biomass nitrogen) at a global scale. The combined direct effects of soil nitrate, ammonium, and total nitrogen (combined standard coefficient = 0.45) accounted for the most variance of global soil N_2O emissions (total standard coefficient = 0.84). This study highlights the critical roles of soil nitrogen substrates on N_2O emission, which will be helpful to optimize the process-models on soil N_2O emissions.

Keywords:

Nitrous oxide emission; nitrate; ammonium; organic nitrogen; microbial biomass; warming

Introduction

Nitrous oxide (N_2O) is the third most important greenhouse gas, following carbon dioxide and methane. N_2O is a long-lived gas in atmosphere with an average lifetime of 116 ± 9 years (Prather*et al.* 2015), and the radiative forcing of N_2O per unit is up to 298 times larger than that of carbon dioxide on a 100-year timescale. Soil N_2O emission dominates the total N_2O emission at the global scale (Syakila & Kroeze 2011). Global soil N_2O emission increases by approximately 59% from preindustrial period to the recent decade (Tian *et al.* 2019) and will increase to 16 Tg N yr^{-1} by 2050 (Bouwman *et al.* 2013). The N_2O forcing will increase by 1.7% when atmospheric N_2O concentrations reach 525 ppb (Etminan *et al.* 2016). To project the warming potential, we need to accurately simulate soil N_2O emission. However, there are large uncertainties in the projections of soil N_2O emission (Del Grosso *et al.* 2010; Tian *et al.* 2019), which ranges from 3.3 to 13.3 Tg N yr^{-1} using different models and the relative predictive error is up to 235% (Zhang *et al.* 2018). Moreover, the simulated N_2O emission does not match the observed data well (Zhang *et al.* 2018). To optimize the models, it is urgent to understand the drivers of soil N_2O emission at a global scale.

Soil N_2O comes from soil nitrification and denitrification, which can be regulated by climatic factors, soil physical and/or chemical properties, and microbial traits. Of climatic factors, higher temperature usually motivates soil N_2O emission in terrestrial ecosystems through denitrification (Zhang *et al.* 2019c; Wang *et al.* 2020). Mean annual temperature also significantly influences soil nitrification on the global scale (Li *et al.* 2020), which may eventually impact global soil N_2O emission. Since water condition affect both nitrification and denitrification*via* altering soil oxygen availability (Bollmann & Conrad 1998), higher soil water content significantly increases soil N_2O emission (Wu *et al.* 2017).

Comparing with climatic factors, the roles of soil properties on soil N_2O emission remain more controversial. Some studies found soil N_2O emission peaks at pH 6.5 and then decreases with increasing pH (Stevens*et al.* 1998), whereas another study showed that N_2O production remains constant with changing soil pH (Cuhel *et al.* 2010). The conflicting results are also reported about the effects of soil texture on N_2O emission. Although soil texture can impact soil N_2O emission in theory (Henault *et al.* 2012), N_2O emission does not change much with difference clay or sandy loam content in croplands (Syvasalo *et al.* 2004). Additionally, a recent study discovered soil cation exchange capacity regulates soil N_2O emission in croplands (Liu *et al.* 2019), but Kravchenko *et al.* (2002) pointed out that soil cation exchange capacity does not account for the fluctuations of soil N_2O emission.

As for soil microbes, at the local scale, soil N_2O emission may positively correlate with microbial biomass nitrogen (MBN) (Zhang *et al.* 2019a), but there is no obvious role of soil microbes on N_2O emission in arid regions (Yin *et al.* 2019). Therefore, it remains unclear how those climate and soil chemical and physical factors individually and interactively regulate soil N_2O emission, which requires a synthesis to reveal the mechanisms underlying the variations of global soil N_2O emission.

Even some ecosystem models tried to incorporate the role of climatic factors (*e.g.* precipitation) and soil properties (*e.g.*soil pH, bulk density, soil texture) (Werner *et al.* 2007), the simulated soil N_2O still fails to match the observed N_2O emission well (Dangal*et al.* 2019). For instance, Fuchs*et al.* (2020) points out the IPCC usually underestimates N_2O emission in an intensively managed grassland. The most of models may miss some important regulators, beside climate and soil properties, in driving soil N_2O emission. Theoretically, soil N content should be critical for N_2O emission since it provides substrate for producing N_2O. A recent global assessment using ensemble of terrestrial biosphere models also found that global N fertilizer application contributes 2.0 ± 0.8 Tg N_2O-N yr^{-1} during 2007-2016, manure application contributes 0.6 ± 0.4 Tg N_2O-N yr^{-1}, and N deposition contributes 26% of global soil N_2O emission (Tian*et al.* 2019). Furthermore, the deceases in cropland-N_2O emissions after 2003 are mainly ascribed to the reduction in usage of N fertilizer in China (Shang *et al.* 2019). Therefore, we hypothesized that soil N contents might play an important role on regulating soil N_2O emissions at the global scale. In fact, some models have recognized the important roles of N substrates for soil N_2O emission, but used the amounts of fertilization (*e.g.* N fertilizer, manure, and N deposition) as input data (Tian *et al.* 2018) because the data of soil N contents are scarce and the relationships between soil N_2O emission and soil N contents are unclear. There are various N substrates for soil N_2O emission because soil nitrification and denitrification are complex processes. Soil ammonium and organic N are critical for soil nitrification at the global scale (Li*et al.* 2020) since they particulate autotrophic nitrification and heterotrophic nitrification, respectively. Soil nitrate is important for denitrification because the nitrate is the substate of nitrate reductase in the first step of denitrification. It is imperative to test the roles of different soil N substrates on soil N_2O emission at a global scale.

In this study, we compiled the available data from field measurements on soil N_2O emission (6016 observations from 219 articles) across typically terrestrial ecosystems (croplands, forests, grasslands, and wetlands). The specific questions addressed in this study were: 1. What are the global patterns of soil N_2O emission rate across terrestrial ecosystems? 2. How do climatic factors, soil physical and chemical properties, soil carbon, soil N substrates, microbial characteristics influence soil N_2O emission rate at a global scale? And 3. Which factors are the main drivers on global soil N_2O emission rate?

Materials and methods

To construct dataset of soil N_2O emission

We compiled data from the published peer-view articles. First, we searched the articles taking advantage of two platform: Web of Science (*http://apps.webofknowledge.com*) and China National Knowledge Infrastructure Database (*http://www.cnki.net*) up to July 20, 2019. The terms to search articles were 'Nitrous oxide' OR 'N_2O' AND 'Soil'. We also searched articles using Google Scholar. All searched articles were composited into one file and the duplications of articles were removed, resulting in 2165 papers (1730 papers in English and 435 papers in Chinese). The eligible articles were sifted out following the criteria: 1. Soil N_2O emission was collected in situ; 2. The experiment lasted more than two days where the initial measurements were removed from dataset to eliminate the impacts of experimental disturbance; 3. There were unambiguous units for soil N_2O emission rate; 4. The dataset did not include the N_2O emission from water (*e.g.* river sediments or lake sediments). It remained 219 articles after sifting to construct the dataset of soil N_2O emission.

The site-specific information were also distilled from articles, such as the geographic coordinates (*i.e.* latitude and longitude for experimental site), climatic variables (*e.g.* mean annual temperature and mean annual precipitation), soil physical and chemical properties (*e.g.* the contents of sand/clay, soil bulk density, pH, cation exchange capacity, soil moisture by weight). The content of soil C and N (*e.g.* soil organic C, total soil N, dissolved soil organic C, dissolved organic N, available phosphorus, ammonium, nitrate, and the ratio of C to N) and soil microbial biomass (*i.e.*microbial biomass carbon (MBC), MBN, and MBC:MBN) also came from articles. The replicates of experiment were also extracted from articles.

Data overview

The dataset of soil N_2O emission rate from field experiments were constructed on the basis of 219 articles, which included 6016 observations. The dataset of soil N_2O emission rate covered all continents but Antarctica (Figure S1) and the dataset mainly encompassed four ecosystem types. Specifically, 4356 observations came from croplands, 679 observations from forests, 335 observations from grasslands, 394 observations from wetlands, and 252 observations from unclassified ecosystems. The climatic factors and soil properties covered a large scope. For example, the mean annual precipitation ranged from 95 to 4395 mm; the clay content was from 0.3 to 90%; and soil pH varied from 3.08 to 8.77.

Data analyses

All soil N_2O emission rate unified units into $\mu g\ N\ m^{-2}\ day^{-1}$. The averaged soil N_2O emission rate of each ecosystem type/climate zone were calculated and compared using ANOVA approach. The post hoc were tested using '*TukeyHSD* '. All statistical analyses were conducted with '*stats* ' package.

The relationships between soil N_2O emission rate and environmental factors (*e.g.* climatic factors, soil physical and chemical properties, the contents of soil C and nutrients, and microbial biomass) were tested using linear mixed-effect models. In general, the formula was:

$$ln(N_2O\ emission\ rate) = \beta_0 + \beta_1 \times lnX + \pi_{\text{study}} + \varepsilon \tag{1}$$

where $\beta\ _0$, $\beta\ _1$ are the intercept and slope value, and $\pi_{\sigma\tau\upsilon\delta\psi}$, $\epsilon$are the random effect and sampling error, X is the environmental factor, respectively. The random effect, 'study', could consider the autocorrelation among observations within the same article.

The structural equation models were used to test the multivariable relationships between soil N_2O emission rate and environmental factors. Initially, we structured the concept models according to the bivariable relationships between soil N_2O emission rate and climatic factors, soil physical and chemical properties, the contents of soil C and nutrients, as well as microbial biomass. There were direct effects from environmental factors on soil N_2O emission rate and indirect effects that climatic factors, soil properties, and the substrates influenced soil N_2O emission rate through changing soil microbial biomass. The environmental factors (*e.g.* climatic factors, soil physical and chemical properties, soil N contents, and microbial biomass) were viewed as the fixed effects, the 'study' was the random effect, and the replicates were 'weight' in each structural equation model. Initially, all environmental factors were incorporated into structural equation models, however, the models were not acceptable. The structural equation models were tested by reducing the number of variables one by one. Finally, the optimal models were presented with the lowest Fisher value (1.2) and Akaike information criterion value (35.1). The structure equation models were conducted using '*piecewiseSEM* ' package. The redundant variables were omitted in the final structure equation models. For example, the mean annual precipitation did not significantly influence soil N_2O emission rate and microbial biomass when soil moisture was incorporated into models, so we removed mean annual precipitation from models.

To test whether the multiple relationships were robust, we separately conducted analyses in each ecosystem. Although the structural equation model cannot be applied in ecosystem without enough data (*e.g.*wetlands), we normalized all data (Z-score normalization) and factored out the weighted slope in each ecosystem. To get a robust weighted slope, the bivariate relationship was removed while the number of observations was less than 20.

Results

The global patterns of soil N_2O emission rate

The averaged soil N_2O emission rate was 1111.79 (SE = 26.59, N = 6016) μg N m^{-2} day^{-1}across terrestrial ecosystems (Figure 1a), with large variation between different ecosystem types. The soil N_2O emission rate was the highest in wetlands (1433.47 ± 121.75 μg N m^{-2}day^{-1}, N = 394) but lowest in grassland (857.64 ± 77.89 μg N m^{-2} day^{-1}, N = 335). Croplands had significantly larger soil N_2O emission rate (1099.02 ± 31.85 μg N m^{-2}day^{-1}, N = 4356) than forests (850.05 ± 64.56 μg N m^{-2} day^{-1}, N = 679). There were no significant differences in soil N_2O emission rate between forests and grasslands (p = 0.99).

Among climate zones, humid subtropical climate zone had the greatest soil N_2O emission rate (1424.80 ± 116.84 μg N m^{-2} day^{-1}, N = 454) (Figure 1b). Similarly, the soil N_2O emission rate was high under tropical climate (1023.99 ± 144.74 μg N m^{-2}day^{-1}, N = 177) and temperate oceanic climate (1257.39 ± 52.61 μg N m^{-2} day^{-1}, N = 1337). There were no significant differences among tropical climate, monsoon-influenced humid subtropical climate, and temperate oceanic climate. The smallest N_2O emission was observed under semi-arid climate (188.33 ± 15.71 μg N m^{-2}day^{-1}, N = 241).

Bivariate relationships of soil N_2O emission rate with environmental factors

Soil N_2O emission rate significantly increased with mean annual temperature (slope = 0.73, p = 0.002, N = 5404) (Figure 2a), and slightly increased with mean annual precipitation (slope = 0.20, p = 0.11, N = 5435, Figure 2b). Soil physical and chemical properties also significantly influenced soil N_2O emission rate at a global scale (Figures 2c-h). Specifically, soil N_2O emission rate decreased with higher soil bulk density (slope = -0.85, $p < 0.001$, N = 1828), and significantly increased with higher soil pH (slope = 0.10, p = 0.02, N = 4491), cation exchange capacity (slope = 0.57, $p < 0.001$, N = 343), and soil moisture (slope = 0.70, $p < 0.001$, N = 993). Soil N_2O emission rate tended to increase with soil clay contents (N = 2899), but the relationship was not significant (p = 0.09). Soil N_2O emission rate did not significantly change with soil sand content (p = 0.32, N = 2705).

Soil N substrates, carbon, and phosphorus influenced soil N_2O emission rate at a global scale (Figure 3). Soil organic matter could promote N_2O emission. For instance, soil N_2O emission rate increased with greater soil organic C (slope = 0.40, $p < 0.001$, N = 4008), total soil N (slope = 0.52, $p < 0.001$, N = 3455), soil dissolved organic N (slope = 0.81, $p < 0.001$, N = 237), while there were no significant relationship between soil N_2O emission rate and soil dissolved organic C (slope = 0.01, p = 0.92, N = 612). Soil N_2O emission rate decreased against the higher soil C:N ratio ($p < 0.001$, N = 3385). More soil available phosphorus was likely to increase soil N_2O emission (slope = 0.61, $p < 0.001$, N = 911). Soil inorganic N contents also influenced N_2O emission rate, that is, soil N_2O emission rate significantly accelerated with greater concentrations of soil ammonium (slope = 0.27, $p < 0.001$, N = 2479) and nitrate (slope = 0.37, $p < 0.001$, N = 2919) at a global scale.

Soil microbial biomass influenced soil N_2O emission rate as well (Figure 4). Specifically, soil N_2O emission rate increased with greater soil MBC (slope = 0.29, p = 0.03, N = 449) and MBN (slope = 0.48, $p < 0.001$, N = 342). The soil N_2O emission rate decreased with higher ratio of MBC:MBN at a global scale (slope = -0.49, p = 0.04, N = 231).

Multivariable relationships between soil N_2O emission rate and environmental factors

The contents of soil nitrate, ammonium, total soil N, MBN, mean annual temperature and soil moisture directly influenced soil N_2O emission rate in structural equation models at a global scale (Figure 5). Among these factors, the N substates (*i.e.* nitrate, ammonium, total N) played the most important role in determining soil N_2O emission rate. Specially, the greater concentrations of soil nitrate significantly accelerated soil N_2O emission rate with the standard coefficient of 0.21 ($p < 0.001$). Moreover, soil N_2O emission rate increased with greater concentrations of total soil N (standard coefficient = 0.13, $p < 0.001$) and ammonium (standard coefficient = 0.11, $p < 0.001$). The joint direct effects (combined standard coefficient = 0.45) of soil nitrate, ammonium, and total soil N accounted for more than half of total direct effects (total standard coefficient = 0.84). Among climatic factors and soil physical/chemical properties, mean annual temperature (standard coefficient = 0.18, $p < 0.001$) and soil moisture (standard coefficient = 0.17, $p < 0.001$) play equivalent roles to drive the changes of soil N_2O emission rate.

Soil N substates and soil properties also influenced soil N_2O emission rate indirectly *via* changing soil microbial biomass in the structural equation models. For example, although soil pH did not directly influence soil N_2O emission rate (standard coefficient = 0.04, p = 0.14), higher soil pH could increase soil MBN (standard coefficient = 0.09, $p < 0.001$) which subsequently promoted soil N_2O emission rate (standard coefficient = 0.04, $p < 0.001$). Moreover, soil MBN increased with greater soil ammonium (standard coefficient = 0.09, $p < 0.001$) and soil moisture (standard coefficient = 0.10, $p < 0.001$), and soil MBN was likely to augment with greater total soil N (standard coefficient = 0.003, p = 0.66), and then greater soil MBN promoted soil N_2O emission rate.

Together, mean annual temperature, soil moisture, pH, MBN, and soil N substrates accounted for 40% variations of soil N_2O emission. The concentrations of soil N substrates dominated the variations of soil N_2O emission rate (total standard coefficient = 0.45) in comparison with soil moisture (total standard coefficient = 0.19) and mean annual temperature (total standard coefficient = 0.18) at a global scale.

Bivariate relationships of soil N_2O emission rate with environmental factors in different ecosystems

The soil N_2O emission rate pervasively correlated with the concentrations of soil nitrate (weighted slope = 0.36 in croplands, 0.36 in forests, 0.30 in grasslands, and 0.27 in wetlands, respectively) and ammonium (weighted slope = 0.26 in croplands, 0.25 in forests, 0.27 in grasslands, and 0.27 in wetlands, respectively) in each ecosystem type (Figure 6). Soil N_2O emission rate also positively correlated with the concentrations of total soil N in each ecosystem (weighted slope = 0.19 in croplands, 0.24 in forests, and 0.35 in grasslands, respectively) except for wetlands (weighted slope = 0.04, p = 0.81). In addition, soil N_2O emission rate positively related to MBN in croplands (weighted slope = 0.17) and forests (weighted slope = 0.20). Soil moisture played an important role in determining soil N_2O emission rate in croplands (weighted slope = 0.18), forests (weighted slope = 0.30), and grasslands (weighted slope = 0.41), whereas the relationship was insignificant in wetlands (p = 0.11). The soil N_2O emission rate did not show consistent relationships with other environmental factors across ecosystem types. For example, there were significantly positive relationships between soil N_2O emission rate and mean annual temperature in croplands and forests rather than in grasslands (p = 0.38) and wetlands (p = 0.72). Soil N_2O emission rate significantly positively related to mean annual precipitation in forests and grasslands rather than in croplands (p = 0.86) or wetlands (p =

0.35).

Discussion

This study uncovers the general patterns and controlling factors of soil N_2O emission rate at a global scale. The soil N substrates (*i.e.* nitrate, ammonium, and soil organic N) accounted for the most variations of soil N_2O emission in comparison with climatic factors and soil physical and chemical properties. The global synthesis enables us to reconcile controversial viewpoints on the controlling factors on soil N_2O emissions and set a benchmark to evaluate nitrogen cycling models.

The main drivers of soil N_2O emission rate at a global scale

Soil N substrates (*i.e.* nitrate, ammonium, and total soil N), microbial biomass, soil moisture, and mean annual temperature are the drivers of N_2O emission rate across terrestrial ecosystems. Among them, the N substrates are the most important controlling factors on soil N_2O emission rate at a global scale, which is contrast to previous studies that found soil pH is the chief controller of soil N_2O emission at the global scale while soil substrates were not considered (Wang *et al.* 2018b). High soil pH promotes N mineralization (Li *et al.* 2019) and increases MBN (Figure 5 and (Li *et al.* 2020)) which subsequently facilitates N_2O emission. However, when we considered the role of soil N substrates, soil pH played a less important role for predicting N_2O emission (Figure 5). The great soil nitrate availability promotes denitrification and therefore increases N_2O emission. There are some reasons for that soil nitrate is important for N_2O emission. Soil nitrate is the reactant for denitrification. The denitrifier activity positively correlates with nitrate contents (Enwall *et al.* 2010). Moreover, soil denitrification enzyme activity is higher in soils with more nitrate (Gardner & White 2010). For example, soil denitrification enzymatic activity increases from 0.02 mg N kg^{-1} h^{-1} to 11.6 mg N kg^{-1} h^{-1} under nitrate additions in some wetlands (White & Reddy 1999). Additionally, higher soil nitrate increases the ratio of N_2O to N_2 during denitrification (Senbayram *et al.* 2012). For instance, N_2O:N_2 increases from 19% under 10 mg N kg^{-1} to 59% under 100 mg N kg^{-1} (Wang *et al.*2013).

Soil ammonium and soil total N (almost in organic form) also significantly impact soil N_2O emission. Great soil ammonium level increases ammonia-oxidizing bacteria abundance (Tian *et al.* 2014) that can promote soil autotrophic nitrification. For example, soil N_2O emission increases from 238-277 g N ha^{-1} yr^{-1} to 853-1301 g N ha^{-1} yr^{-1} when the aqua ammonia applies from 0 to 260 kg ha^{-1}(Pittelkow *et al.* 2013).

Soil organic N is the substrate of heterotrophic nitrification. In some cases, soil heterotrophic nitrification accounts for 7-19% of total nitrification (Islam *et al.* 2007) and even more than 50% of the total nitrification in acid soil condition (Liu *et al.* 2015). Moreover, soil organic N can increase soil microbial biomass and subsequently increase N mineralization (Li*et al.* 2019). A recent study revealed that the content of soil total N is the main driver for soil nitrification rate at the global scale (Li *et al.* 2020). In line with our finding, a recent study revealed that manure application also substantially increases N_2O emission by 5.1-58.2% (Zhou *et al.* 2017). The key role of soil N contents on soil N_2O emission was also confirmed by the consistently positive relationships between soil N_2O emission rate and soil nitrate, ammonium, and total soil N in each ecosystem type (Figure 6).

Soil moisture influences soil N_2O emission directly and also indirectly through changing soil microbial biomass (Figure 5). Soil moisture regulates N_2O emission possibly through the availability of substrates and the microbial activity. Soil with low moisture hampers the diffusion of soil N substrates to microbial cells (Stark & Firestone 1995). Soil moisture can influence the dynamics of soil microbial biomass, *e.g.* the higher soil moisture promoting soil MBN by 56.3-91.4% in dry ecosystems (Huang *et al.* 2018). Moreover, at low soil moisture microbial cell dehydration occurs which lowers the activity of nitrifying bacteria (Stark & Firestone 1995). Thus, the efficiency of soil processes are stimulated under higher soil moisture (Zhang *et al.* 2019b). Finally, soil moisture can alter soil nitrification and denitrification where both processes can produce N_2O (Bollmann & Conrad 1998). In some cases, more N_2O emission comes from denitrification at a soil moisture more than 70%, in which N_2O emitted 1 to 412 mg N m^{-2} per 15 days when soil moisture increased from 40 to 90% (Ruser *et al.* 2006). The important role of soil moisture on N_2O emission is also manifested that it is the important predictor of the temperature sensitivity (Q_{10}) of N_2O emission in an alpine meadow ecosystem (Zhang*et al.* 2020).

Higher temperature can stimulate the activity of microbes and subsequently influences soil N_2O emission. High temperature stimulates the activities of nitrifier and denitrifier. A recent study showed that the assimilation of$^{13}CO_2$ by ammonia-oxidizing archaea (one type of autotrophic nitrifier) increases when soil temperature is elevated by 3°C (Hu *et al.* 2016). Similarly, warming (+ 3.6°C) enhances nirS-type denitrifiers by 38%, nirK-type denitrifiers by 82% (Qu*et al.* 2018), and norB-type denitrifier by 4.32% (Zhou *et al.* 2012). In some meadow ecosystem with higher soil moisture, the changes of temperature can explain up to 35% variations of annual soil N_2O flux (Hu *et al.* 2010).

Implications for soil N_2O emission under global change

Fertilization is a common management in croplands, which can dramatically increase soil nitrate and ammonium concentrations that will promote soil N_2O emission. As reported, the rise of N_2O emission is mainly ascribed to accelerating usage of synthetic N fertilizers after 1960 (Davidson 2009). A recent study revealed that the amount of N into croplands under the current fertilization far exceeds the capacity of crop uptake, because crop only uptake about 48.5 kg N ha^{-1} while the amount of N fertilization is 240 kg N ha^{-1} (Chen *et al.* 2017). The surplus N fertilization may lose in the form of N_2O. A meta-analysis reported soil N_2O emission increases by 90% under N application at 50-100 kg N ha^{-1} and the N_2O emission increases by up to 262% under N application at 250-300 kg N ha^{-1}in croplands (Sun *et al.* 2016). In addition, the fertilization does not only enhance soil N_2O emission in croplands, but impact soil N_2O emission of wetlands through runoff. The N is imported into wetlands that will emit in the form of N_2O since the N_2O emission rate are also sensitive to nitrate/ammonium in wetlands (Figure 6). The higher N_2O emission rate in wetlands (Figure 1) may be caused by the higher N concentrations of runoff from croplands that has increased by 31-46% since 1990 in China (Hou *et al.*2018). The increasing N concentrations of runoff (Wang *et al.* 2018a) and the higher organic N eventually enhance soil N_2O emission in wetlands. In the late century, the N application in croplands increase substantially in the form of synthetic N (Yu *et al.* 2019a), in some regions the amount of N application has been up to 550-600 kg N ha^{-1} yr^{-1}(Ju *et al.* 2009). To meet the growing food requirement, the fertilizer inputs will not decrease in the next century (Erisman *et al.*2008), therefore, soil N_2O emission will correspondingly increase under growing fertilization in the near future.

Nitrogen deposition also increases soil N_2O emission. Soil N_2O emission is increased by 91.3% (Deng *et al.* 2020) and 215% (Liu & Greaver 2009) under N deposition at the global scale. High N deposition increased the N_2O flux where average annual N_2O fluxes increased by 13.7% at 7 kg N ha^{-1} yr^{-1}, 47.6% at 20 kg N ha^{-1} yr^{-1}, and 98.7% at 40 kg N ha^{-1} yr^{-1}, respectively (Yan *et al.* 2018). In the last four decades, global N deposition increases by 8% (Ackerman *et al.* 2019), and the N deposition still is the critical question on earth, for example, N deposition (*i.e.* NH_x and NO_x) amounts up to 19.6 – 20.4 kg N $ha^{-1}yr^{-1}$ in China (Yu*et al.* 2019b). Although N deposition can contribute to global greening (by 9%) (Zhu *et al.*2016), the role of N deposition on N_2O emission should also be paid more attentions.

Warming will increase soil N_2O emission as well. The previous experimental studies showed that warming can stimulate soil N_2O emission and the rate of increase is very steep when soil denitrification is the dominant process (Smith 1997). A recent study revealed warming significantly increases soil N_2O emission when soil N substrates is adequate (Zhang*et al.* 2020), indicating that warming may enhance soil N_2O emission in croplands with fertilization.

Implications for ecosystem modeling

The dataset and the findings in this study can facilitate modeling study of soil N_2O emission. First, this study complied a big data (*i.e.* 6016 observations) of soil N_2O emission from field across main terrestrial ecosystem types to provide benchmark for model evaluation. Second, the data can be helpful to calibrate process-based model, for instance, Dynamic Land Ecosystem Model (DLEM) calculates soil N_2O emission on the basis of nitrification and denitrification processes primarily based on soil N substrates, temperature, and soil moisture (Xu *et al.* 2017). Our data can be useful for calibrating parameters of models. Third, the findings in this study that N substrates are critical for soil N_2O emission across terrestrial ecosystems will offer insights for model development. For example, soil organic N and MBN significantly influence soil N_2O emission at the global scale, particularly in croplands, forests, and grasslands. Moreover, a recent study also revealed that soil organic N can explain the most variations of soil nitrification at the global scale (Li*et al.* 2020). However, most land models in predicting soil N_2O have not considered the roles of soil organic N and MBN (Tian *et al.* 2018). Thus, incorporating soil N substrates and MBN may reduce the model uncertainty in projection of soil N_2O emission.

Uncertainties and limitations

There are some uncertainties in this synthesis. First, climatic factors, soil physical and/or chemical properties, the concentrations of substrate can influence soil N_2O emission through changing soil microbial biomass or the activities of microbes. Although we verified that soil substrates and soil properties affect soil N_2O emission rate *via* MBN (Figure 5), we did not test the effects of the microbial activities because of data paucity. In nitrification and denitrification, there are many functional genes expressing enzymes to participate the specific processes. For instance, ammonia-oxidizing bacteria and ammonia-oxidizing archaea mediate the first step of soil nitrification, and the community dynamics may be important for nitrification (Theodorakopoulos *et al.* 2017). Therefore, the roles of functional microbes on soil N_2O emission remain to be tested at a global scale. Second, soil moisture may play roles on soil N_2O emission *via* altering soil redox potential (Rubol *et al.*2012) other than soil microbial biomass. We did not compile enough data of redox potential to test in this study. Third, the data mainly came from croplands (72.4%). Although the relationships between soil N_2O emission and environmental factors were similar in other ecosystem types (Figure 6), the variations of weighted slope were obviously larger when the number of observations was small in wetlands.

This study revealed the comprehensive patterns of and identified controlling factors on soil N_2O emission rates at the global scale. Although climatic factors (*e.g.* mean annual temperature), soil physical and chemical properties (*i.e.* soil pH, bulk density, and soil moisture) significantly influenced soil N_2O emission, soil N substrates (*i.e.* soil nitrate, ammonium, and total soil N) accounted for the most variations in soil N_2O emission rates at the global scale. The critical roles of soil N contents in soil N_2O emission were confirmed by the consistently significantly positive relationships between soil N_2O emission rates and the contents of soil nitrate, ammonium, and total soil N across ecosystem types. The findings highlight the necessity that soil N substrates (*i.e.* nitrate, ammonium, and total soil organic N) should be comprehensively incorporated into models to improve the projection accuracy of soil N_2O emission at the global scale.

Data Accessibility

Data supporting the results are found in supplementary.

References

Ackerman, D., Millet, D.B. & Chen, X. (2019). Global estimates of inorganic nitrogen deposition across four decades. *Global Biogeochemical Cycles* , 33, 100-107.

Bollmann, A. & Conrad, R. (1998). Influence of O_2 availability on NO and N_2O release by nitrification and denitrification in soils. *Global Change Biology* , 4, 387-396.

Bouwman, A.F., Beusen, A.H.W., Griffioen, J., Van Groenigen, J.W., Hefting, M.M., Oenema, O. *et al.* (2013). Global trends and uncertainties in terrestrial denitrification and N_2O emissions. *Philosophical Transactions of the Royal Society B-Biological Sciences* , 368, 20130112.

Chen, F., Ameen, A., Tang, C.C., Du, F., Yang, X.L. & Xie, G.H. (2017). Effects of nitrogen fertilization on soil nitrogen for energy sorghum on marginal land in China.*Agronomy Journal* , 109, 636-645.

Cuhel, J., Simek, M., Laughlin, R.J., Bru, D., Cheneby, D., Watson, C.J. *et al.* (2010). Insights into the effect of soil pH on N_2O and N_2emissions and denitrifier community size and activity. *Applied and Environmental Microbiology* , 76, 1870-1878.

Dangal, S.R.S., Tian, H.Q., Xu, R.T., Chang, J.F., Canadell, J.G., Ciais, P. *et al.* (2019). Global nitrous oxide emissions from pasturelands and rangelands: Magnitude, spatiotemporal patterns, and attribution. *Global Biogeochemical Cycles* , 33, 200-222.

Davidson, E.A. (2009). The contribution of manure and fertilizer nitrogen to atmospheric nitrous oxide since 1860. *Nature Geoscience* , 2, 659-662.

Del Grosso, S.J., Ogle, S.M., Parton, W.J. & Breidt, F.J. (2010). Estimating uncertainty in N_2O emissions from US cropland soils. *Global Biogeochemical Cycles* , 24, GB1009.

Deng, L., Huang, C.B., Kim, D.G., Shangguan, Z.P., Wang, K.B., Song, X.Z. *et al.* (2020). Soil GHG fluxes are altered by N deposition: New data indicate lower N stimulation of the N_2O flux and greater stimulation of the calculated C pools. *Global Change Biology* , 1-17.

Enwall, K., Throback, I.N., Stenberg, M., Soderstrom, M. & Hallin, S. (2010). Soil resources influence spatial patterns of denitrifying communities at scales compatible with land management. *Applied and Environmental Microbiology* , 76, 2243-2250.

Erisman, J.W., Sutton, M.A., Galloway, J., Klimont, Z. & Winiwarter, W. (2008). How a century of ammonia synthesis changed the world. *Nature Geoscience* , 1, 636-639.

Etminan, M., Myhre, G., Highwood, E.J. & Shine, K.P. (2016). Radiative forcing of carbon dioxide, methane, and nitrous oxide: A significant revision of the methane radiative forcing. *Geophysical Research Letters* , 43, 12614-12623.

Fuchs, K., Merbold, L., Buchmann, N., Bretscher, D., Brilli, L., Fitton, N. *et al.* (2020). Multimodel evaluation of nitrous oxide emissions from an intensively managed grassland. *Journal of Geophysical Research: Biogeosciences* , 125, e2019JG005261.

Gardner, L.M. & White, J.R. (2010). Denitrification enzyme activity as an indicator of nitrate movement through a diversion wetland. *Soil Science Society of America Journal* , 74, 1037-1047.

Henault, C., Grossel, A., Mary, B., Roussel, M. & Leonard, J. (2012). Nitrous oxide emission by agricultural soils: A review of spatial and temporal variability for mitigation. *Pedosphere* , 22, 426-433.

Hou, X.K., Zhan, X.Y., Zhou, F., Yan, X.Y., Gu, B.J., Reis, S. *et al.* (2018). Detection and attribution of nitrogen runoff trend in China's croplands. *Environmental Pollution* , 234, 270-278.

Hu, H.W., Macdonald, C.A., Trivedi, P., Anderson, I.C., Zheng, Y., Holmes, B. *et al.* (2016). Effects of climate warming and elevated CO_2 on autotrophic nitrification and nitrifiers in dryland ecosystems. *Soil Biology & Biochemistry* , 92, 1-15.

Hu, Y.G., Chang, X.F., Lin, X.W., Wang, Y.F., Wang, S.P., Duan, J.C. *et al.* (2010). Effects of warming and grazing on N_2O fluxes in an alpine meadow ecosystem on the Tibetan plateau. *Soil Biology & Biochemistry* , 42, 944-952.

Huang, G., Li, L., Su, Y.G. & Li, Y. (2018). Differential seasonal effects of water addition and nitrogen fertilization on microbial biomass and diversity in a temperate desert. *Catena* , 161, 27-36.

Islam, A., Chen, D. & White, R.E. (2007). Heterotrophic and autotrophic nitrification in two acid pasture soils. *Soil Biology & Biochemistry* , 39, 972-975.

Ju, X.T., Xing, G.X., Chen, X.P., Zhang, S.L., Zhang, L.J., Liu, X.J. *et al.* (2009). Reducing environmental risk by improving N management in intensive Chinese agricultural systems. *Proceedings of the National Academy of Sciences of the United States of America* , 106, 3041-3046.

Kravchenko, I., Boeckx, P., Galchenko, V. & Van Cleemput, O. (2002). Short- and medium-term effects of ${NH_4}^+$ on CH_4 and N_2O fluxes in arable soils with a different texture. *Soil Biology & Biochemistry* , 34, 669-678.

Li, Z., Zeng, Z., Tian, D., Wang, J., Fu, Z., Zhang, F. *et al.* (2020). Global patterns and controlling factors of soil nitrification rate. *Global Change Biology* .gcb15119.

Li, Z.L., Tian, D.S., Wang, B.X., Wang, J.S., Wang, S., Chen, H.Y.H. *et al.* (2019). Microbes drive global soil nitrogen mineralization and availability. *Global Change Biology* , 25, 1078-1088.

Liu, L.L. & Greaver, T.L. (2009). A review of nitrogen enrichment effects on three biogenic GHGs: the CO_2 sink may be largely offset by stimulated N_2O and CH_4 emission. *Ecology Letters* , 12, 1103-1117.

Liu, Q., Liu, B.J., Zhang, Y.H., Hu, T.L., Lin, Z.B., Liu, G. *et al.* (2019). Biochar application as a tool to decrease soil nitrogen losses (NH_3volatilization, N_2O emissions, and N leaching) from croplands: Options and mitigation strength in a global perspective.*Global Change Biology* , 25, 2077-2093.

Liu, R., Suter, H., He, J., Hayden, H. & Chen, D. (2015). Influence of temperature and moisture on the relative contributions of heterotrophic and autotrophic nitrification to gross nitrification in an acid cropping soil. *Journal of Soils and Sediments* , 15, 2304-2309.

Pittelkow, C.M., Adviento-Borbe, M.A., Hill, J.E., Six, J., van Kessel, C. & Linquist, B.A. (2013). Yield-scaled global warming potential of annual nitrous oxide and methane emissions from continuously flooded rice in response to nitrogen input. *Agriculture Ecosystems & Environment* , 177, 10-20.

Prather, M.J., Hsu, J., DeLuca, N.M., Jackman, C.H., Oman, L.D., Douglass, A.R. *et al.* (2015). Measuring and modeling the lifetime of nitrous oxide including its variability. *Journal of Geophysical Research-Atmospheres* , 120, 5693-5705.

Qu, Y.P., Jiang, Y., Guo, L.J., Burkey, K.O., Zobel, R.W., Shew, H.D. *et al.* (2018). Contrasting warming and ozone effects on denitrifiers dominate soil N_2O emissions. *Environmental Science & Technology* , 52, 10956-10966.

Rubol, S., Silver, W.L. & Bellin, A. (2012). Hydrologic control on redox and nitrogen dynamics in a peatland soil. *Science of the Total Environment* , 432, 37-46.

Ruser, R., Flessa, H., Russow, R., Schmidt, G., Buegger, F. & Munch, J.C. (2006). Emission of N_2O, N_2 and CO_2 from soil fertilized with nitrate: Effect of compaction, soil moisture and rewetting. *Soil Biology & Biochemistry* , 38, 263-274.

Senbayram, M., Chen, R., Budai, A., Bakken, L. & Dittert, K. (2012). N_2O emission and the $N_2O/(N_2O + N_2)$ product ratio of denitrification as controlled by available carbon substrates and nitrate concentrations. *Agriculture Ecosystems & Environment* , 147, 4-12.

Shang, Z.Y., Zhou, F., Smith, P., Saikawa, E., Ciais, P., Chang, J.F. *et al.* (2019). Weakened growth of cropland N_2O emissions in China associated with nationwide policy interventions. *Global Change Biology* , 25, 3706-3719.

Smith, K.A. (1997). The potential for feedback effects induced by global warming on emissions of nitrous oxide by soils. *Global Change Biology* , 3, 327-338.

Stark, J.M. & Firestone, M.K. (1995). Mechanisms for soil moisture effects on activity of nitrifying bacteria. *Applied and Environmental Microbiology* , 61, 218-221.

Stevens, R.J., Laughlin, R.J. & Malone, J.P. (1998). Soil pH affects the processes reducing nitrate to nitrous oxide and di-nitrogen. *Soil Biology & Biochemistry* , 30, 1119-1126.

Sun, B.F., Zhao, H., Lu, Y.Z., Lu, F. & Wang, X.K. (2016). The effects of nitrogen fertilizer application on methane and nitrous oxide emission/uptake in Chinese croplands.*Journal of Integrative Agriculture* , 15, 440-450.

Syakila, A. & Kroeze, C. (2011). The global nitrous oxide budget revisited. *Greenhouse Gas Measurement and Management* , 1, 17-26.

Syvasalo, E., Regina, K., Pihlatie, M. & Esala, M. (2004). Emissions of nitrous oxide from boreal agricultural clay and loamy sand soils. *Nutrient Cycling in Agroecosystems* , 69, 155-165.

Theodorakopoulos, N., Lognoul, M., Degrune, F., Broux, F., Regaert, D., Muys, C. *et al.* (2017). Increased expression of bacterial amoA during an N_2O emission peak in an agricultural field. *Agriculture Ecosystems & Environment* , 236, 212-220.

Tian, H.Q., Yang, J., Lu, C.Q., Xu, R.T., Canadell, J.G., Jackson, R.B. *et al.* (2018). The global N_2O model intercomparison project. *Bulletin of the American Meteorological Society* , 99, 1231-1252.

Tian, H.Q., Yang, J., Xu, R.T., Lu, C.Q., Canadell, J.G., Davidson, E.A. *et al.* (2019). Global soil nitrous oxide emissions since the preindustrial era estimated by an ensemble of terrestrial biosphere models: Magnitude, attribution, and uncertainty. *Global Change Biology* , 25, 640-659.

Tian, X.F., Hu, H.W., Ding, Q., Song, M.H., Xu, X.L., Zheng, Y. *et al.* (2014). Influence of nitrogen fertilization on soil ammonia oxidizer and denitrifier abundance, microbial biomass, and enzyme activities in an alpine meadow.*Biology and Fertility of Soils* , 50, 703-713.

Wang, J.L., Fu, Z.S., Chen, G.F., Zou, G.Y., Song, X.F. & Liu, F.X. (2018a). Runoff nitrogen (N) losses and related metabolism enzyme activities in paddy field under different nitrogen fertilizer levels. *Environmental Science and Pollution Research* , 25, 27583-27593.

Wang, R., Feng, Q., Liao, T.T., Zheng, X.H., Butterbach-Bahl, K., Zhang, W. *et al.* (2013). Effects of nitrate concentration on the denitrification potential of a calcic cambisol and its fractions of N_2, N_2O and NO. *Plant and Soil* , 363, 175-189.

Wang, Y., Hu, Z., Shang, D., Xue, Y., Islam, A.T. & Chen, S. (2020). Effects of warming and elevated O_3 concentrations on N_2O emission and soil nitrification and denitrification rates in a wheat-soybean rotation cropland. *Environmental Pollution* , 257, 113556.

Wang, Y.J., Guo, J.H., Vogt, R.D., Mulder, J., Wang, J.G. & Zhang, X.S. (2018b). Soil pH as the chief modifier for regional nitrous oxide emissions: New evidence and implications for global estimates and mitigation. *Global Change Biology* , 24, E617-E626.

Werner, C., Butterbach-Bahl, K., Haas, E., Hickler, T. & Kiese, R. (2007). A global inventory of N_2O emissions from tropical rainforest soils using a detailed biogeochemical model. *Global Biogeochemical Cycles* , 21, GB3010.

White, J.R. & Reddy, K.R. (1999). Influence of nitrate and phosphorus loading on denitrifying enzyme activity in Everglades wetland soils. *Soil Science Society of America Journal* , 63, 1945-1954.

Wu, D., Cardenas, L.M., Calvet, S., Bruggemann, N., Loick, N., Liu, S.R. *et al.* (2017). The effect of nitrification inhibitor on N_2O, NO and N_2 emissions under different soil moisture levels in a permanent grassland soil. *Soil Biology & Biochemistry* , 113, 153-160.

Xu, R.T., Tian, H.Q., Lu, C.Q., Pan, S.F., Chen, J., Yang, J. *et al.* (2017). Preindustrial nitrous oxide emissions from the land biosphere estimated by using a global biogeochemistry model. *Climate of the Past* , 13, 977-990.

Yan, Y.L., Ganjurjav, H., Hu, G.Z., Liang, Y., Li, Y., He, S.C. *et al.* (2018). Nitrogen deposition induced significant increase of N_2O emissions in an dry alpine meadow on the central Qinghai-Tibetan Plateau. *Agriculture Ecosystems & Environment* , 265, 45-53.

Yin, M.Y., Gao, X.P., Tenuta, M., Gui, D.W. & Zeng, F.J. (2019). Presence of spring-thaw N_2O emissions are not linked to functional gene abundance in a drip-fertigated cropped soil in arid northwestern China.*Science of the Total Environment* , 695.

Yu, C.Q., Huang, X., Chen, H., Godfray, H.C.J., Wright, J.S., Hall, J.W. *et al.* (2019a). Managing nitrogen to restore water quality in China. *Nature* , 567, 516-520.

Yu, G.R., Jia, Y.L., He, N.P., Zhu, J.X., Chen, Z., Wang, Q.F. *et al.* (2019b). Stabilization of atmospheric nitrogen deposition in China over the past decade.*Nature Geoscience* , 12, 424-429.

Zhang, C.B., Liu, W.L., Guan, M., Wang, J., Pan, X.C., Ge, Y. *et al.* (2019a). Nitrous oxide emission rate in response to plant, soil and microbial properties in marshes impacted by alien Spartina alterniflora. *Biologia* , 74, 1087-1097.

Zhang, S.S., Zheng, Q., Noll, L., Hu, Y.T. & Wanek, W. (2019b). Environmental effects on soil microbial nitrogen use efficiency are controlled by allocation of organic nitrogen to microbial growth and regulate gross N mineralization. *Soil Biology & Biochemistry* , 135, 304-315.

Zhang, Y., Ma, M., Fang, H., Qin, D., Cheng, S. & Yuan, W. (2018). Impacts of nitrogen addition on nitrous oxide emission: Model-data comparison. *Biogeosciences Discussions* , 1-17.

Zhang, Y., Wang, J., Dai, S.Y., Sun, Y.Q., Chen, J., Cai, Z.C. *et al.* (2019c). Temperature effects on N_2O production pathways in temperate forest soils.*Science of the Total Environment* , 691, 1127-1136.

Zhang, Y., Zhang, N., Yin, J.J., Yang, F., Zhao, Y.X., Jiang, Z.Q. *et al.* (2020). Combination of warming and N inputs increases the temperature sensitivity of soil N_2O emission in a Tibetan alpine meadow. *Science of the Total Environment* , 704, 135450.

Zhou, J.Z., Xue, K., Xie, J.P., Deng, Y., Wu, L.Y., Cheng, X.H. *et al.* (2012). Microbial mediation of carbon-cycle feedbacks to climate warming. *Nature Climate Change* , 2, 106-110.

Zhou, M.H., Zhu, B., Wang, S.J., Zhu, X.Y., Vereecken, H. & Bruggemann, N. (2017). Stimulation of N_2O emission by manure application to agricultural soils may largely offset carbon benefits: A global meta-analysis. *Global Change Biology* , 23, 4068-4083.

Zhu, Z.C., Piao, S.L., Myneni, R.B., Huang, M.T., Zeng, Z.Z., Canadell, J.G. *et al.* (2016). Greening of the Earth and its drivers. *Nature Climate Change* , 6, 791-795.

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Author contributions

Zhaolei Li carried out the analyses. Zhaoli Li and Shuli Niu wrote the first draft of manuscript. All authors heavily involved in writing.

Competing interests

The authors declare no competing financial interests

Figure legends

Figure 1

The changes of soil N_2O emission rate with ecosystems (a) and climate zones (b). The green bars are standard error and the white values are the numbers of observations in ecosystems. The abbreviation of UE stands for unclassified ecosystem (a). The climate zones were classified according to Koppen Climate Classification. Cwa is Monsoon-influenced humid subtropical climate. Cfa is Humid subtropical climate. Cfb is Temperate oceanic climate. Af, Am, and Aw are Tropical rainforest climate, Tropical monsoon climate, and Tropical wet and dry climate, respectively. Dfb is Warm-summer humid continental climate. Dfa is Hot-summer humid continental climate. Dwa and Dwb are Monsoon-influenced hot-summer humid continental climate and Monsoon-influenced warm-summer humid continental climate, respectively. BSh and BSk are Hot semi-arid climate and Cold semi-arid climate, respectively. The average soil N_2O emission rate of climate zone with the observations being more than 100 was presented (b). The different letters above bars indicate significantly different soil N_2O emission rate.

Figure 2

The bivariate relationships between soil N_2O emission rate and mean annual temperature (MAT, a), mean annual precipitation (MAP, b), soil sand content (c), clay content (d), bulk density (BD, e), pH (f), cation exchange capacity (CEC, g), and soil moisture (h) at a global scale using the logarithmically transformed data. The green lines with grey shadings are the slopes +- 95% confidence intervals. The size of circles is the number of replicates from 1 to 60. The number without parentheses is the number of observations and the number with parentheses is for studies.

Figure 3

The bivariate relationships between soil N_2O emission rate and carbon and nitrogen, namely, the content of soil organic carbon (SOC, a), soil nitrogen (TN, b), the ratio of soil carbon to nitrogen (soil C:N, c), soil dissolved organic carbon (DOC, d), soil dissolved organic nitrogen (DON, e), available phosphorus (AP, f), the concentration of soil ammonium (NH_4^+-N, g), and soil nitrate (NO_3^--N, h) at a global scale using the logarithmically transformed data. The green lines with grey shadings are the slopes +- 95% confidence intervals. The size of circles is the number of replicates from 1 to 60. The number without parentheses is the number of observations and the number with parentheses is for studies.

Figure 4

The bivariate relationships between soil N_2O emission rate and soil microbial characteristics, namely, microbial biomass carbon (MBC, a), microbial biomass nitrogen (MBN, b), and the ratio of microbial biomass carbon to microbial biomass nitrogen (MBC:MBN, c) at a global scale using the logarithmically transformed data. The green lines with grey shadings are the slopes +- 95% confidence intervals. The size of circles is the number of replicates from 1 to 60. The number without parentheses is the number of observations and the number with parentheses is for studies.

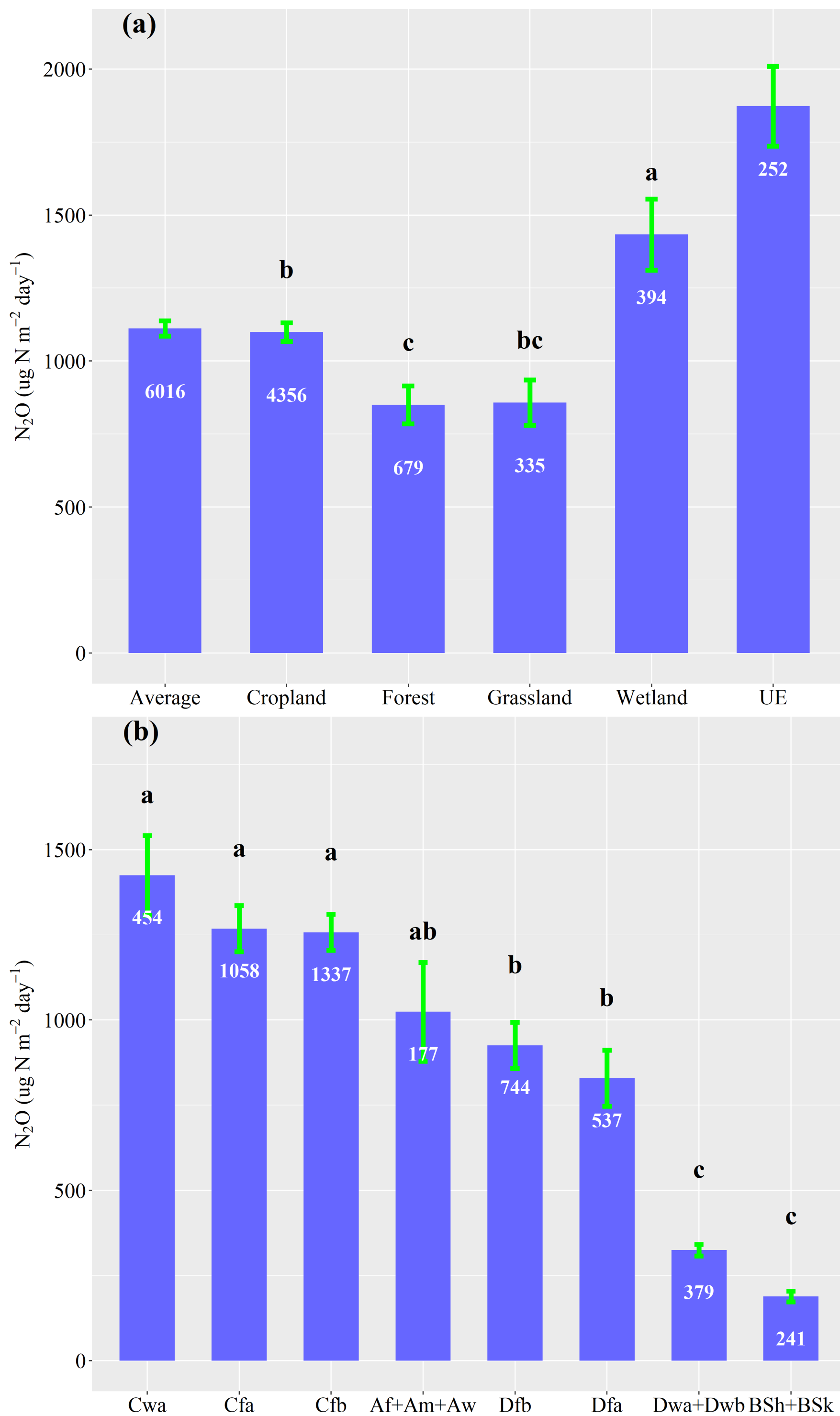
Figure 5

The multiple relationships of soil N_2O emission rate at the global scale. The orange lines are the significantly positive relationships, blue lines are the significantly negative relationships, and the green dashed lines are the insignificant relationships, in which the statistically significant level is α [?] 0.05. Numbers are standardized coefficients. MAT, SM, TN, and MBN represent mean annual temperature, soil moisture, total soil nitrogen, and microbial biomass nitrogen, respectively.

Figure 6

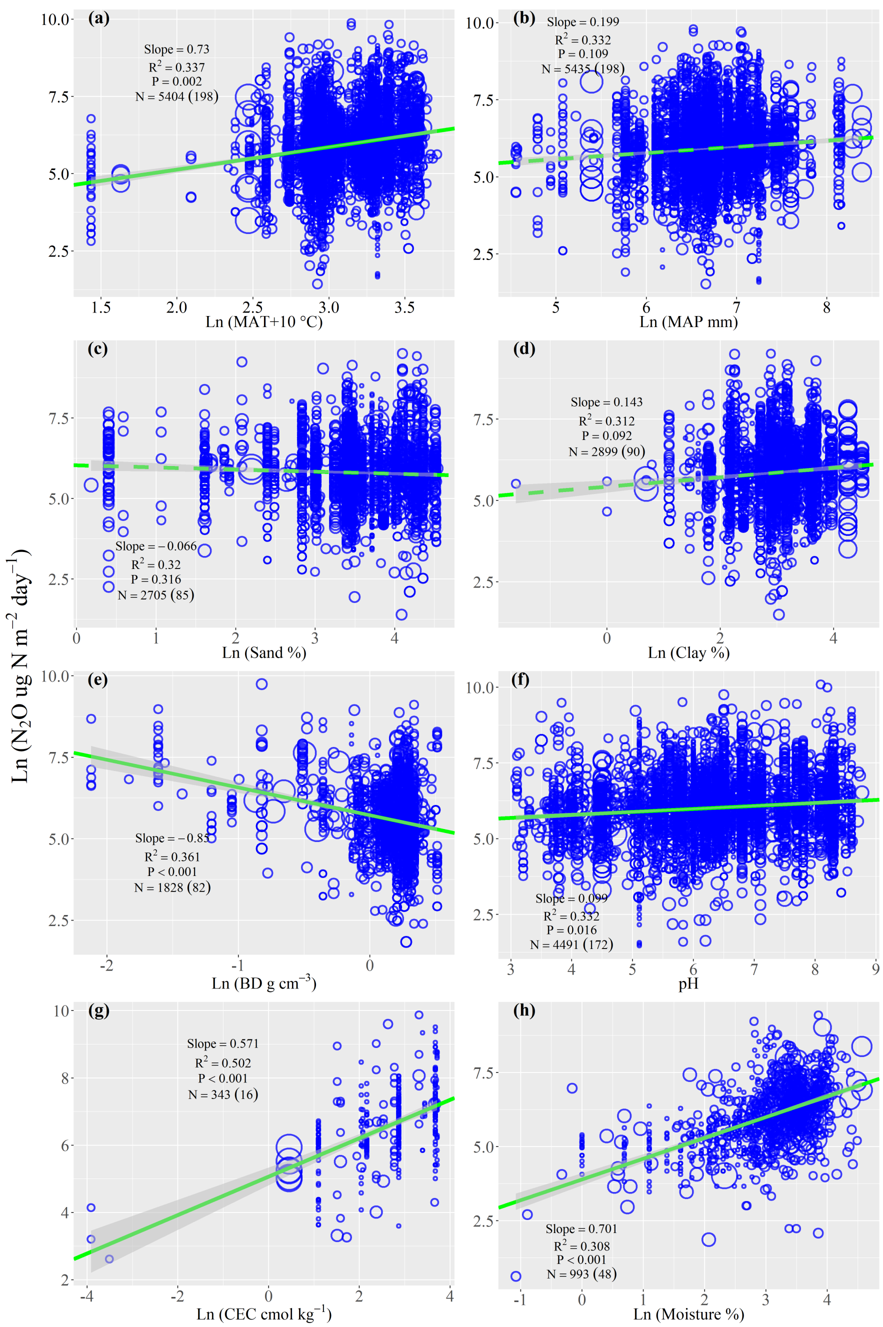
The slopes of the bivariate relationships between soil N_2O emission rate and MAT (mean annual temperature), MAP (mean annual precipitation), Sand, Clay, BD (bulk density), pH, CEC (cation exchange capacity), Moisture, SOC (soil organic carbon), TN (total soil nitrogen), soil C:N, DOC (soil dissolved organic carbon), DON (dissolved organic nitrogen), AP (available phosphorus), NH_4-N, NO_3-N, MBC (soil microbial biomass carbon), MBN (microbial biomass nitrogen), MBC:MBN across terrestrial ecosystems. The blue dot is averaged slope and the bars are 95% confidence intervals. The values in parentheses are the number of studies and values without parentheses are the number of observations.

Figure 1



(a)
N2O (ug N m-2 day-1)
2000
1500
1000
500
0
b
c
bc
a
6016
4356
679
335
394
252
Average
Cropland
Forest
Grassland
Wetland
UE
(b)
N2O (ug N m-2 day-1)
1500
1000
500
0
a
a
a
ab
b
b
c
c
454
1058
1337
177
744
537
379
241
Cwa
Cfa
Cfb
Af+Am+Aw
Dfb
Dfa
Dwa+Dwb
BSh+BSk

Figure 2



(a)
Slope = 0.73
R^2 = 0.337
P = 0.002
N = 5404 (198)
Ln (MAT+10 °C)
(b)
Slope = 0.199
R^2 = 0.332
P = 0.109
N = 5435 (198)
Ln (MAP mm)
(c)
Slope = −0.066
R^2 = 0.32
P = 0.316
N = 2705 (85)
Ln (Sand %)
(d)
Slope = 0.143
R^2 = 0.312
P = 0.092
N = 2899 (90)
Ln (Clay %)
(e)
Slope = −0.85
R^2 = 0.361
P < 0.001
N = 1828 (82)
Ln (BD g cm^{-3})
(f)
Slope = 0.099
R^2 = 0.332
P = 0.016
N = 4491 (172)
pH
(g)
Slope = 0.571
R^2 = 0.502
P < 0.001
N = 343 (16)
Ln (CEC cmol kg^{-1})
(h)
Slope = 0.701
R^2 = 0.308
P < 0.001
N = 993 (48)
Ln (Moisture %)
Ln (N_2O ug N m^{-2} day^{-1})

Figure 3

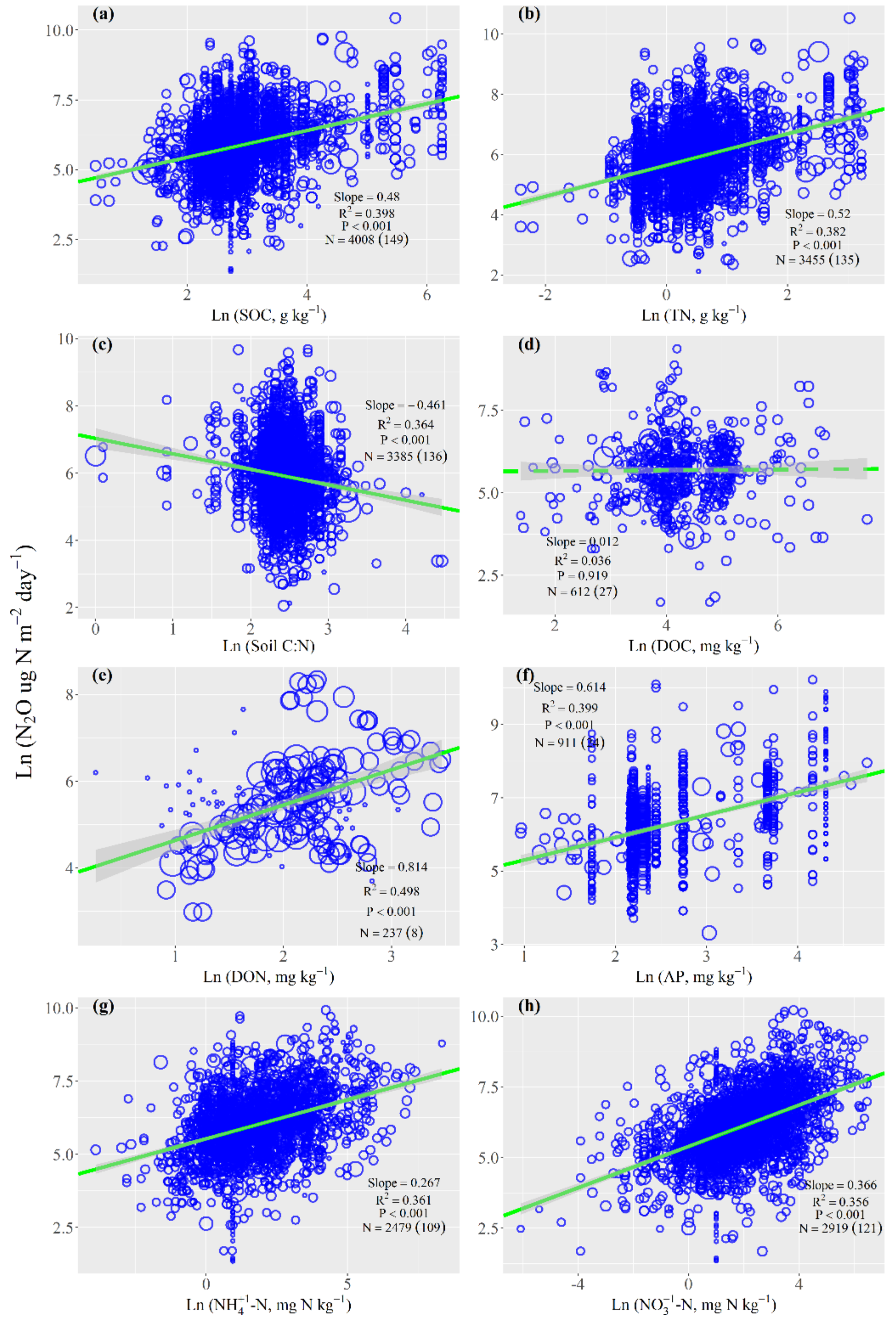

Ln (N2O ug N m-2 day-1)
(a)
Slope = 0.48
R2 = 0.398
P < 0.001
N = 4008 (149)
Ln (SOC, g kg-1)
(b)
Slope = 0.52
R2 = 0.382
P < 0.001
N = 3455 (135)
Ln (TN, g kg-1)
(c)
Slope = −0.461
R2 = 0.364
P < 0.001
N = 3385 (136)
Ln (Soil C:N)
(d)
Slope = 0.012
R2 = 0.036
P = 0.919
N = 612 (27)
Ln (DOC, mg kg-1)
(e)
Slope = 0.814
R2 = 0.498
P < 0.001
N = 237 (8)
Ln (DON, mg kg-1)
(f)
Slope = 0.614
R2 = 0.399
P < 0.001
N = 911 (34)
Ln (AP, mg kg-1)
(g)
Slope = 0.267
R2 = 0.361
P < 0.001
N = 2479 (109)
Ln (NH4-1-N, mg N kg-1)
(h)
Slope = 0.366
R2 = 0.356
P < 0.001
N = 2919 (121)
Ln (NO3-1-N, mg N kg-1)

Figure 4

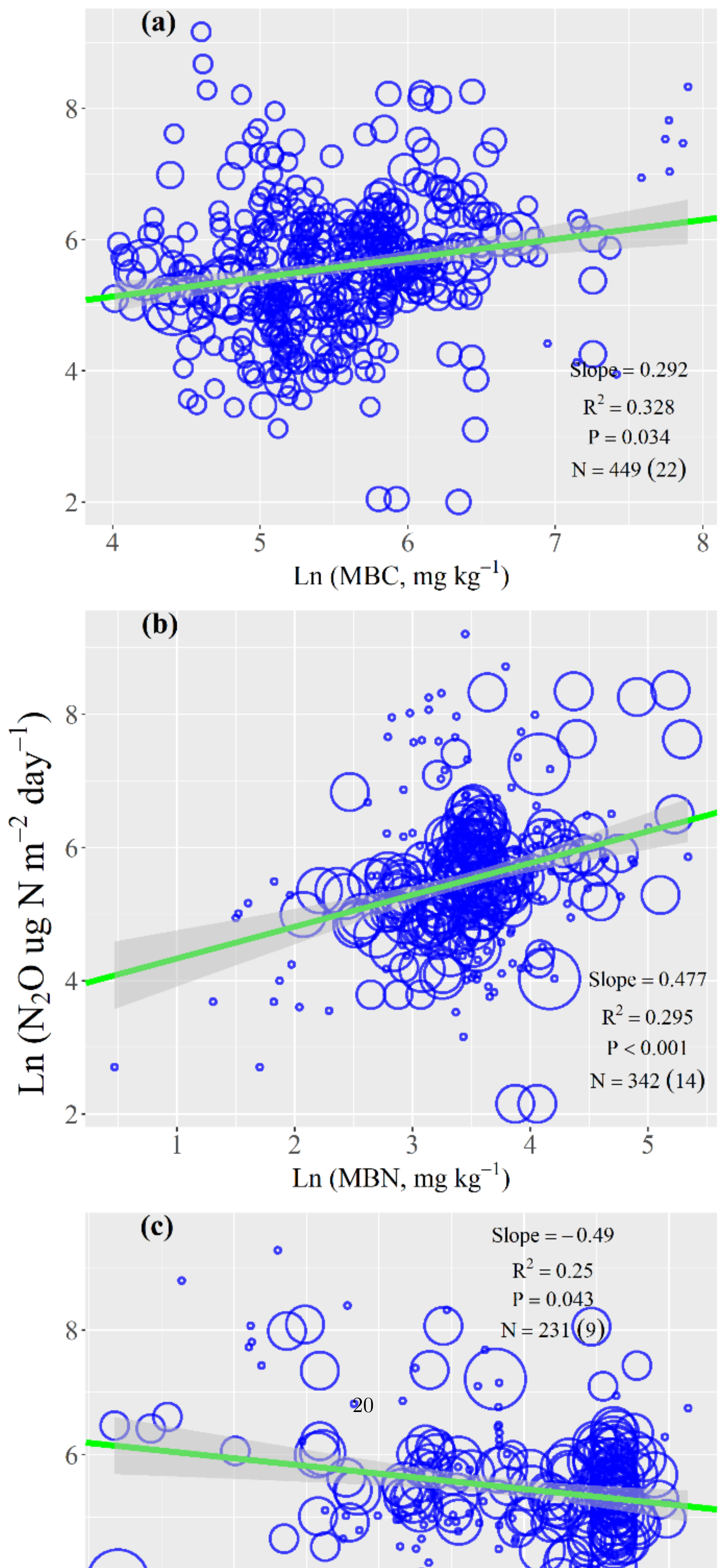

(a)
Slope = 0.292
R2 = 0.328
P = 0.034
N = 449 (22)
Ln (MBC, mg kg−1)
(b)
Ln (N2O ug N m−2 day−1)
Slope = 0.477
R2 = 0.295
P < 0.001
N = 342 (14)
Ln (MBN, mg kg−1)
(c)
Slope = −0.49
R2 = 0.25
P = 0.043
N = 231 (9)

Figure 5

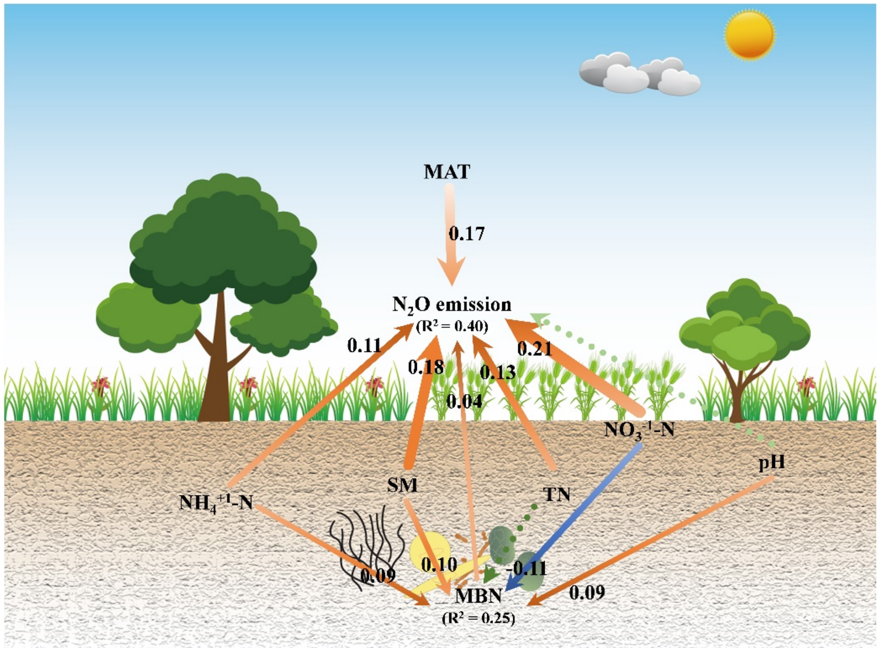


Figure 6

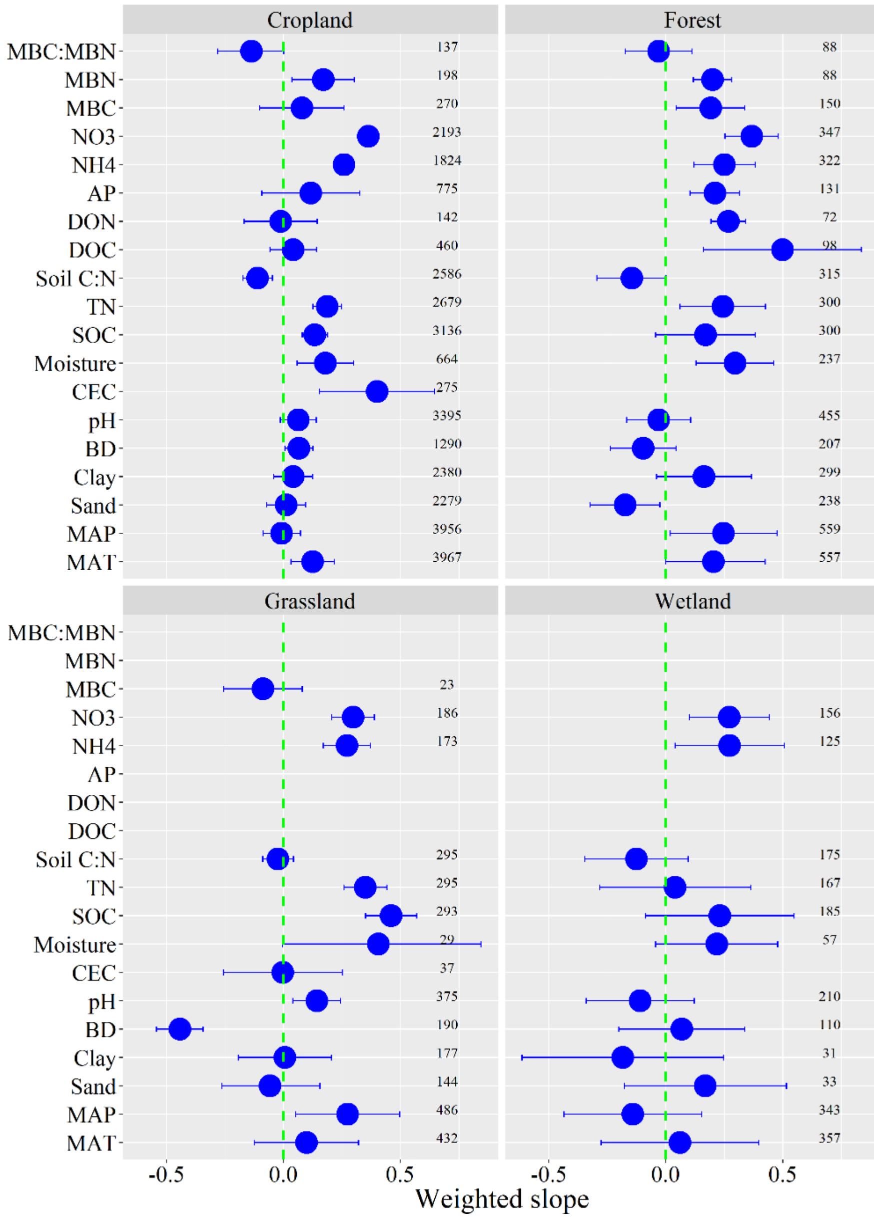
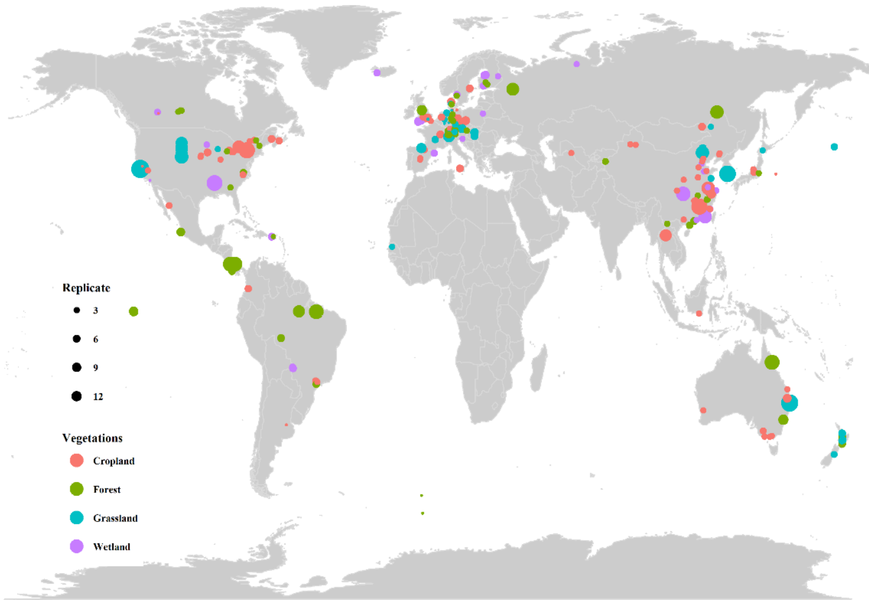


Figure S1

Global distribution of field data on soil N_2O emission rates in this study



Replicate
3
6
9
12
Vegetations
Cropland
Forest
Grassland
Wetland