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Variance and main drivers of field nitrous oxide emissions: A global synthesis

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A R T I C L E I N F O

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A B S T R A C T

The precise estimation of global nitrous oxide (N_2O) emissions in nitrogen cycling will facilitate improved projections of future climate change. However, the geographical variations and the primary controlling factors of N_2O emissions remain elusive at the global scale. What is lacking is their specific evaluation based on field data. We compiled a new dataset of soil N_2O emission rates, including 6016 field observations from 219 articles, to synthesize N_2O emission rates for different ecosystems and to explore the key determinants of N_2O emission variations. The global mean soil N_2O emission rate was 1111.8 ± 26.6 μg N m^{-2} day^{-1}, with the largest one from humid subtropical regions and the smallest one from semi-arid areas. The soil N_2O emission rates were positively correlated with the mean air annual temperature, soil pH, cation exchange capacity, soil moisture, soil organic carbon (C), total soil nitrogen (N), dissolved organic N, ammonium, nitrate, available phosphorus concentrations, microbial biomass carbon (MBC), and microbial biomass nitrogen (MBN) at a global scale. Conversely, the soil N_2O rates were negatively correlated with soil bulk density, C:N ratio, and MBC:MBN ratio. The results of structural equation models revealed that the joint direct effects of soil nitrate, ammonium, and total N (combined standard coefficient = 0.45) accounted for most of the variability in global soil N_2O emissions (total standard coefficient = 0.84), while climate factors and other soil physicochemical properties accounted for less. This study highlights the critical roles of soil N substrates on N_2O emissions, which will facilitate the optimization of process-models for soil N_2O emissions.

1. Introduction

Global soil N_2O emissions have risen by approximately 59% from the preindustrial period to the recent decade (Tian et al., 2019) and are estimated to increase to 16 Tg N yr^{-1} by 2050 (Bouwman et al., 2013). The global warming potential of N_2O will increase by 1.7% when atmospheric N_2O concentrations reach 525 ppb in comparison with current concentration of 323 ppb (Etminan et al., 2016). To track this warming potential, the Intergovernmental Panel on Climate Change (IPCC) has been pursuing the accurate prediction of global soil N_2O emissions. However, there remain significant disparities in the projections of soil N_2O emissions (Del Grosso et al., 2010; Tian et al., 2019; Xu et al., 2020), which can range from 3.3 to 13.3 Tg N yr^{-1} using different models, with relative predictive errors of up to 235% (Zhang

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et al., 2018). Simulated N_2O emissions from models do not match the observed data well (Levy et al., 2017; Zhang et al., 2018); thus, additional N_2O field data are required to optimize the models and pinpoint the controlling factors at large spatial scales.

Since soil N_2O is generated through nitrification and/or denitrification processes, the N_2O emission rate is typically regulated by climatic factors, soil physicochemical properties, and microbial traits. Higher temperatures usually increase soil N_2O emissions in terrestrial ecosystems via denitrification (Wang et al., 2020; Zhang et al., 2019). The mean annual temperature significantly influences soil nitrification at a global scale (Li et al., 2020), which may eventually impact global soil N_2O emissions. Further, higher soil moisture generally increases soil N_2O emissions through nitrification and/or denitrification (Wu et al., 2017). Nonetheless, the effect of soil water on N_2O emissions is also dependent on other factors, such as N availability (Weitz et al., 2001). The roles of soil properties on soil N_2O emissions are complex. For example, several studies found that soil N_2O emissions peaked at pH 6.5 (Stevens et al., 1998) or pH 7.0 (Kesik et al., 2006), and then decreased at higher pH levels (Stevens et al., 1998; Van den Heuvel et al., 2011). However, other studies observed that N_2O production was constant under different soil pH levels (Cuhel et al., 2010). This indicates that our understanding on soil pH impact on N_2O emission is still very limited. The conflicting results were also reported about the effects of soil texture on N_2O emissions. Although soil texture was reported to impact soil N_2O emissions in agricultural soils (Henault et al., 2012), N_2O emissions were observed not to change with clay content in boreal agricultural clay and loamy sand soils (Syvasalo et al., 2004). This inconsistency may be due to the complex interactions between soil properties under different conditions. As for soil microbes, N_2O emissions may be positively correlated with microbial biomass nitrogen (MBN) (Zhang, C.B. et al., 2019); but soil microbes do not affect N_2O emissions in some conditions (Yin et al., 2019). In the context of these divergent findings, it remains unclear how those climatic, soil physicochemical factors, and soil microbes individually and interactively regulate soil N_2O emissions at a global scale.

In principle, the soil N content should be the main factor that determines N_2O emissions since it serves as the substrate. A recent global assessment that employed an ensemble of terrestrial biosphere models found that global N fertilization contributed 2.0 ± 0.8 Tg N_2O–N yr^{-1}, manure contributed 0.6 ± 0.4 Tg N_2O–N yr^{-1}, and N deposition contributed 26% of global soil N_2O emissions from 2007 to 2016 (Tian et al., 2019). Furthermore, decreases in N_2O emissions from China's croplands after 2003 were mainly attributed to the reduction in N fertilization (Shang et al., 2019); thus, we hypothesized that the soil N content may play an important role in regulating soil N_2O emissions at large spatial scales. The incorporation of N substrates to simulate soil N_2O emissions is important and necessary, as current models only use fertilization quantities (e.g., N fertilizer, manure, and N deposition) as input data (Tian et al., 2018). This is primarily due to the scarcity of data on soil N content, and uncertainty regarding the relationships between soil N_2O emissions and N substrates at large spatial scales. Various soil N substrates can be transformed to N_2O through N cycling. Soil ammonium and organic N are critical for soil nitrification at the global scale (Li et al., 2020), since they participate in autotrophic nitrification and heterotrophic nitrification, respectively, while soil nitrate is the substrate of nitrate reductase in the first step of denitrification. Thus, it is imperative to test the effects of soil N substrates on N_2O emission rates at a global scale.

In this study, we aimed to explore the variations and the controlling factors of field N_2O emissions across terrestrial ecosystems. We compiled the available data from field measurements on soil N_2O emissions (6016 observations from 219 articles) across croplands, forests, grasslands, and wetlands. The specific questions addressed in this study were: 1. How do soil N_2O emission rates vary globally across different terrestrial ecosystems? 2. What are the key controlling factors and how do they operate interactively to determine the global variations in soil N_2O emission rates?

2. Materials and methods

2.1. Soil N_2O emission data

We compiled data by searching published peer-reviewed articles using two platforms: Web of Science (http://apps.webofknowledge.com) and China National Knowledge Infrastructure Database (the most papers in Chinese; http://www.cnki.net) up to July 20, 2019. The search terms for the articles were 'Soil Nitrous oxide' OR 'Soil N_2O' And 'Field'. We also searched for articles using Google Scholar. All appropriate articles were composited into a single file and any article duplications were removed. We first removed the duplicated articles automatically by *Endnote*, and then we double checked one by one. The duplicated observation was removed by ourselves during data collection based on the information of author (particularly the first author and corresponding author), site, latitude, longitude, etc. The eligible articles were organized using the following the criteria: 1. The N_2O emitted from soil was collected from the field; 2. The experiment lasted for 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 rates; 4. The dataset did not include the N_2O emissions from water (e.g., river sediments or lake sediments). Finally, 219 articles were used to construct the dataset of soil N_2O emissions.

Site-specific data were also distilled from the articles, such as the geographic coordinates (i.e., latitude and longitude of experimental site), climatic variables (e.g., mean annual temperature and precipitation), soil physicochemical properties of topsoil (e.g., the contents of sand/clay, soil bulk density, pH, cation exchange capacity, soil moisture by weight). The contents 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 C:N ratio), and soil microbial biomass (i.e., microbial biomass carbon (MBC), MBN, and MBC:MBN ratio) were also derived from the articles. The replicates of experiments that were generally located within the same sites were also extracted from the articles.

2.2. Data survey

The soil N_2O emission rate dataset from the field experiments was developed based on the selected 219 articles, which included 6016 observations. It encompassed all continents except for Antarctica (Fig. 1) and was primarily comprised of four ecosystem types. The identification of ecosystem types were extracted from the original articles. Croplands included paddies and uplands; forests included tropical, temperate, and boreal forests, etc.; grasslands included steppes, prairies, and pastures, etc.; and wetlands included marshes, swamps, coastal wetlands, etc.. We grouped ambiguous ecosystems into 'unclassified ecosystem' for those articles that had no clear descriptions of 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 varied largely. For instance, 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.

2.3. Data analyses

The mean soil N_2O emission rates of each ecosystem type were calculated and compared using the ANOVA approach, and post hoc were tested using '*TukeyHSD*', as were the soil N_2O emission rates for each climate zone. Statistical analyses were conducted with the '*stats*' package. The abbreviations for the climate zones included: (A) monsoon-influenced humid subtropical climate; (B) humid subtropical climate;

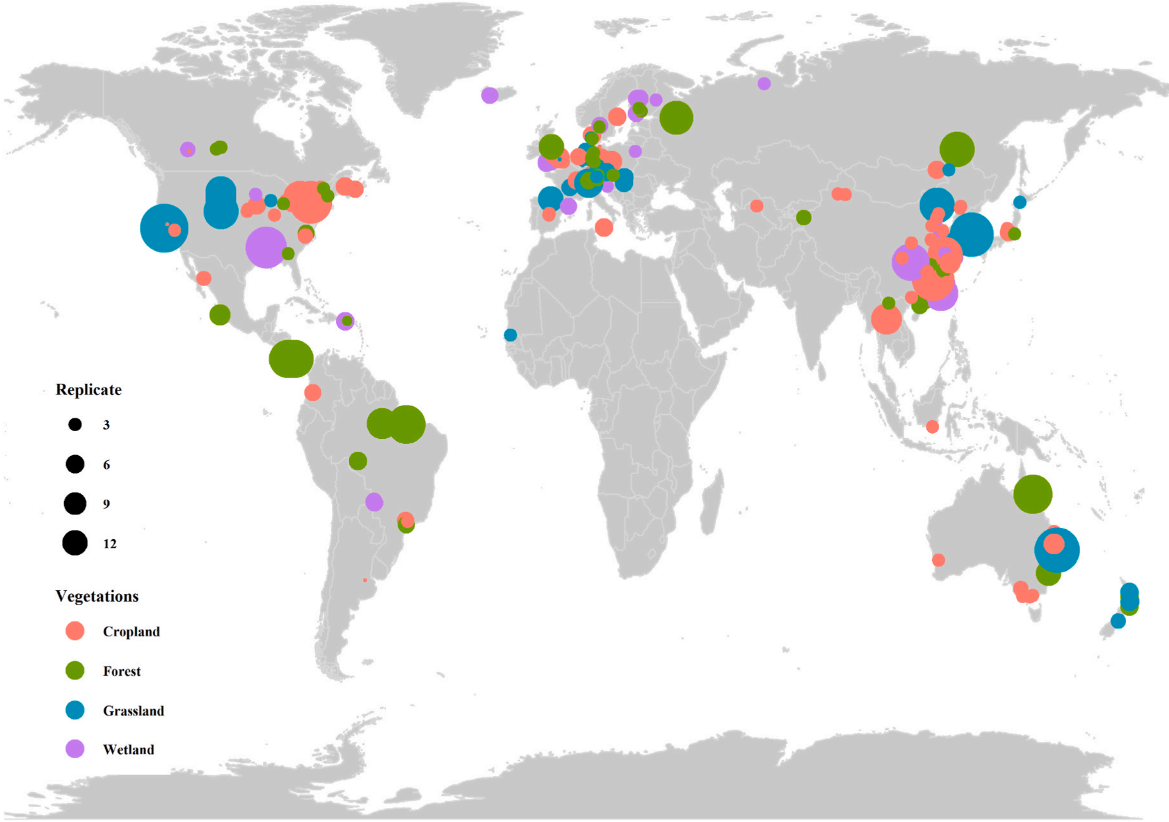

Fig. 1. Global distribution of field data on soil N_2O emission rates in this study.

(C) temperate oceanic climate; (D) tropical rainforest climate, tropical monsoon climate, and tropical wet and dry climate; (E) warm-summer humid continental climate; (F) hot-summer humid continental climate; (G) monsoon-influenced hot-summer humid continental climate and monsoon-influenced warm-summer humid continental climate; (H) hot semi-arid climate and cold semi-arid climate.

The relationships between the soil N_2O emission rates and environmental factors (e.g., climatic factors, soil physicochemical properties, soil C and nutrient contents, and microbial biomass) were tested using linear mixed-effect models. In general, the equation was:

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

where, β_0 is the intercept value, β_1 is slope value, π_{study} is the random effect, ε is sampling error, and X is the environmental factor, respectively. The random effect, 'study', considered the autocorrelation between observations within the same article. We further separately conducted analyses for each ecosystem using normalized data (Z-score normalization).

Structural equation models were used to explore the multiple relationships between the soil N_2O emission rates and environmental factors. Initially, we structured conceptual models based on the bivariate relationships between the soil N_2O emission rates and climatic factors, soil physicochemical properties, and microbial biomass. There were direct effects on the soil N_2O emissions from environmental factors; while there were indirect effects from climatic factors, soil properties, and substrates via changes in the soil microbial biomass. Environmental factors (e.g., climatic factors, soil physicochemical properties, soil N contents, and microbial biomass) were regarded as fixed effects, the 'study' was the random effect, and the replicates were the 'weight' in each structural equation model. Initially, all environmental factors were incorporated into the structural equation models; however, the models were not eligible. 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 structural equation models were developed using the '*piecewiseSEM*' package. Redundant variables were excluded from the final structural equation models.

3. Results

3.1. Global patterns of soil N_2O emission rates

The mean soil N_2O emission rate was 1111.8 (SE = 26.6, N = 6016) μg N m^{-2} day^{-1} across terrestrial ecosystems (Fig. 2a), with large variations between different ecosystem types. The soil N_2O emission rate was highest in wetlands (1433.5 ± 121.8 μg N m^{-2} day^{-1}, N = 394) but lowest in forests (850.1 ± 64.6 μg N m^{-2} day^{-1}, N = 335). Croplands exhibited a greater soil N_2O emission rate (1099.0 ± 31.9 μg N m^{-2} day^{-1}, N = 4356) than forests (850.1 ± 64.6 μg N m^{-2} day^{-1}, N = 679). There were no significant differences in the soil N_2O emission rates between forests and grasslands (p = 0.99).

In terms of climate zones, the humid subtropical climate zone had the greatest soil N_2O emission rate (1424.8 ± 116.9 μg N m^{-2} day^{-1}, N = 454) (Fig. 2b). Similarly, under the tropical climate, the soil N_2O emission rate was high (1024.0 ± 144.7 μg N m^{-2} day^{-1}, N = 177), as it was under the temperate oceanic climate (1257.4 ± 52.6 μg N m^{-2} day^{-1}, N = 1337). There were no differences among the tropical climate, monsoon-influenced humid subtropical climate, and temperate oceanic climate. The lowest N_2O emissions were observed under the semi-arid climate (188.3 ± 15.7 μg N m^{-2} day^{-1}, N = 241).

3.2. Changes in soil N_2O emission rates with environmental factors

The soil N_2O emission rate increased with the mean annual temperature (slope = 0.73, p = 0.002, N = 5404) (Fig. 3a), and increased slightly with the mean annual precipitation (slope = 0.20, p = 0.11, N =

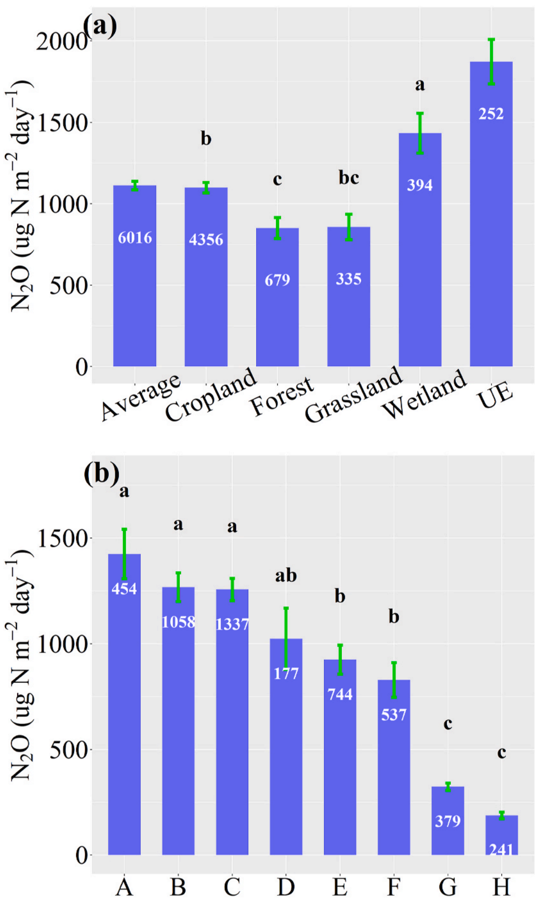

Fig. 2. The changes of soil N_2O emission rate with ecosystems (a) and climate zones (b). The green bars are standard error and the white values are the numbers of observations in ecosystems. The abbreviation of UE stands for unclassified ecosystem (a). The climate zones were classified according to Köppen Climate Classification. The mean 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.

5435, Fig. 3b). Soil physicochemical properties also markedly influenced N_2O emissions at a global scale (Fig. 3c–h). Specifically, the soil N_2O emission rates decreased with higher soil bulk densities (slope = −0.85, $p < 0.001$, N = 1828), and 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). The soil N_2O emission rates negligibly increased with the soil clay content (N = 2899, p = 0.09), whereas, it clearly did not change with the soil sand content (p = 0.32, N = 2705).

Soil N substrates, carbon, and phosphorus were found to impact soil N_2O emission rates at a global scale (Fig. 4), where higher levels of soil organic matter promoted N_2O emissions. For instance, soil N_2O emission rates 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), and soil dissolved organic N (slope = 0.81, $p < 0.001$, N = 237), while there was no significant relationship between the soil N_2O emission rate and soil dissolved organic C (slope = 0.01, p = 0.92, N = 612). The soil N_2O emission rates were decreased with higher soil C:N ratios (slope = −0.46, $p < 0.001$, N = 3385). More soil available phosphorus was likely to increase soil N_2O emissions (slope = 0.61, $p < 0.001$, N = 911). The soil inorganic N content also influenced the N_2O emission rate, that is, the soil N_2O emission rate 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.

The soil microbial biomass influenced soil N_2O emission rates as well (Fig. 5). Specifically, soil N_2O emission rates 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 was decreased with higher MBC:MBN ratios at a global scale (slope = −0.49, p = 0.04, N = 231).

3.3. Contributions of environmental factors to variations in global N_2O emissions

The soil nitrate and ammonium contents, total soil N, MBN, mean annual temperature and soil moisture directly influenced the soil N_2O emissions in structural equation models at a global scale (Fig. 6). Among these factors, the N content (i.e., nitrate, ammonium, and total N) played the most important role in explaining the variations in the soil N_2O emission rates. Specifically, higher concentrations of soil nitrate markedly accelerated N_2O emissions with a standard coefficient of 0.21 ($p < 0.001$). Moreover, soil N_2O emission rate also 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 combined direct effects (combined standard coefficient = 0.45) of the soil nitrate, ammonium, and total soil N accounted for more than half of the total direct effects (total standard coefficient = 0.84). Among the climatic factors and soil physicochemical properties, the mean annual temperature (standard coefficient = 0.17, $p < 0.001$) and soil moisture (standard coefficient = 0.18, $p < 0.001$) accounted equivalently to the geographical variations in soil N_2O emission rates.

Soil N substrates and other soil properties also indirectly influenced soil N_2O emissions through the modification of soil microbial biomass in the structural equation models. For example, although the soil pH did not directly influence N_2O emission rates (standard coefficient = 0.04, p = 0.14) at a global scale, a higher pH could increase the soil MBN (standard coefficient = 0.09, $p < 0.001$), which subsequently promoted the soil N_2O emission rate (standard coefficient = 0.04, $p < 0.001$). Moreover, soil MBN increased with higher soil ammonium (standard coefficient = 0.09, $p < 0.001$) and soil moisture (standard coefficient = 0.10, $p < 0.001$). The soil MBN was likely to be augmented with a higher total soil N (standard coefficient = 0.003, p = 0.66), which then promoted the soil N_2O emission rate.

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

3.4. Key controlling factors of soil N_2O emission rates for different ecosystems

Soil N_2O emission rates were 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) for each ecosystem type (Fig. 7). Soil N_2O emission rates were also positively correlated with the concentrations of total soil N for 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). Furthermore, the soil N_2O emission rate was positively related with MBN in croplands (weighted slope = 0.17) and forests (weighted slope = 0.20). Soil moisture played an important role for N_2O emissions 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 exhibit 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

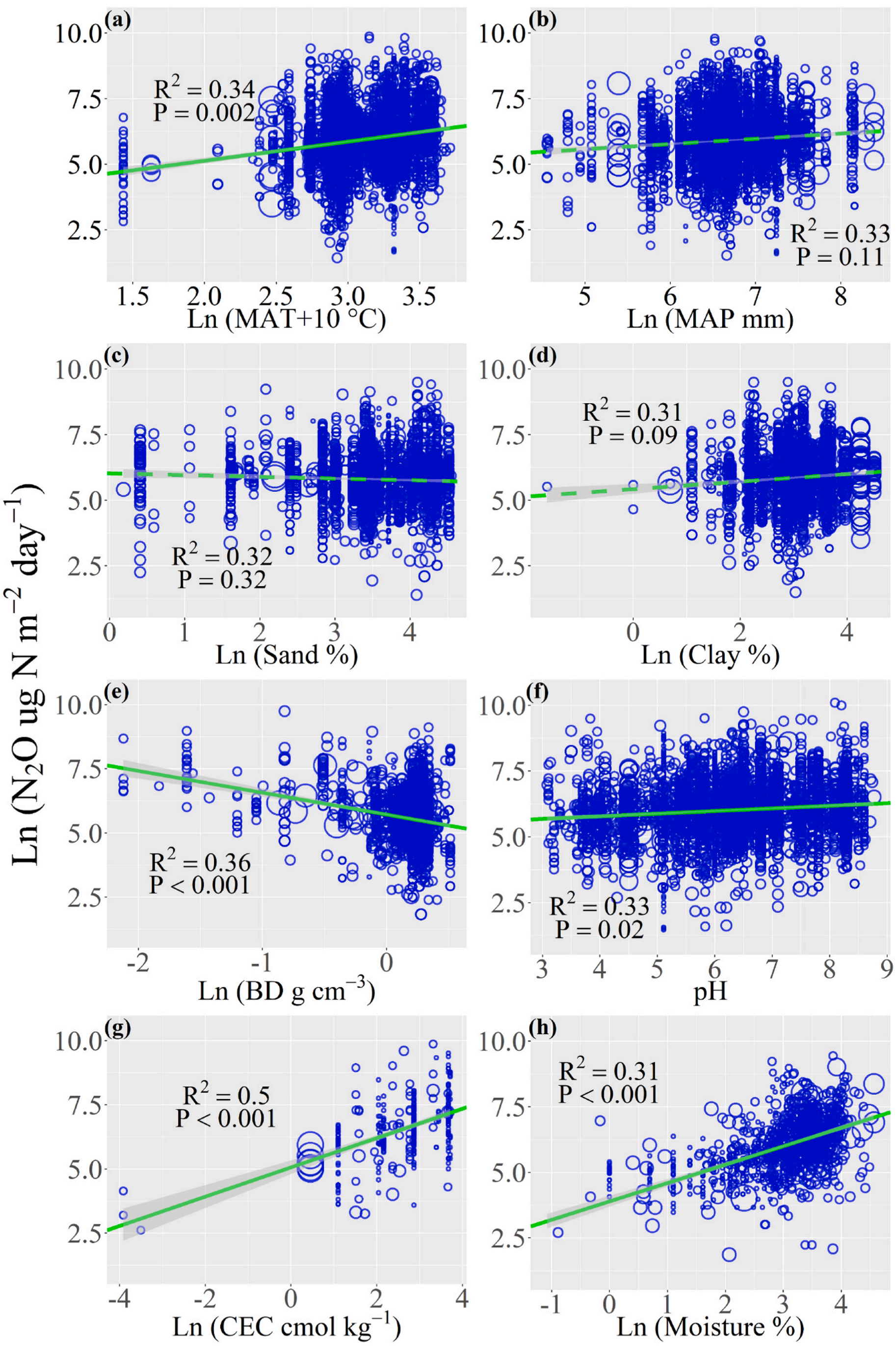

Fig. 3. The bivariate relationships between soil N_2O emission rate and mean annual temperature (MAT, a), mean annual precipitation (MAP, b), soil sand content (c), clay content (d), bulk density (BD, e), pH (f), cation exchange capacity (CEC, g), and soil moisture (h) at a global scale using the logarithmically transformed data. The green lines with grey shadings are the slopes ±95% confidence intervals. Solid lines are significant slopes and the dashed line is the insignificant one. 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.

and forests, in contrast to grasslands ($p = 0.38$) and wetlands ($p = 0.72$). Soil N_2O emission rate was significantly and positively related to mean annual precipitation in forests and grasslands, instead of in croplands ($p = 0.86$) or wetlands ($p = 0.35$).

4. Discussion

This study synthesized the geographic patterns and controlling factors of field N_2O emission rates at a global scale. The soil N content (i.e., nitrate, ammonium, and soil organic N) accounted for most of the variations in soil N_2O emissions in comparison with climatic factors and other soil physicochemical properties, which challenged traditional concepts, including the dominant roles of climate (Griffis et al., 2017) or soil pH (Wang et al., 2018) in N_2O emissions. These findings also deepen our mechanistic understanding of the recent findings that the application of N fertilizers and manure have largely accounted for the increases in N_2O over the last 140 years (Tian et al., 2019). This global synthesis enabled us to identify the controlling factors of field N_2O emissions over large spatial scales to establish a benchmark for the evaluation of N models.

4.1. *Controlling factors of variations in soil N_2O emissions at a global scale*

Soil N contents (i.e., nitrate, ammonium, and total soil N), microbial biomass, soil moisture, and mean annual temperature are key factors involved in N_2O emissions across terrestrial ecosystems. Among them, the soil N content is the most important factors behinds the variations in

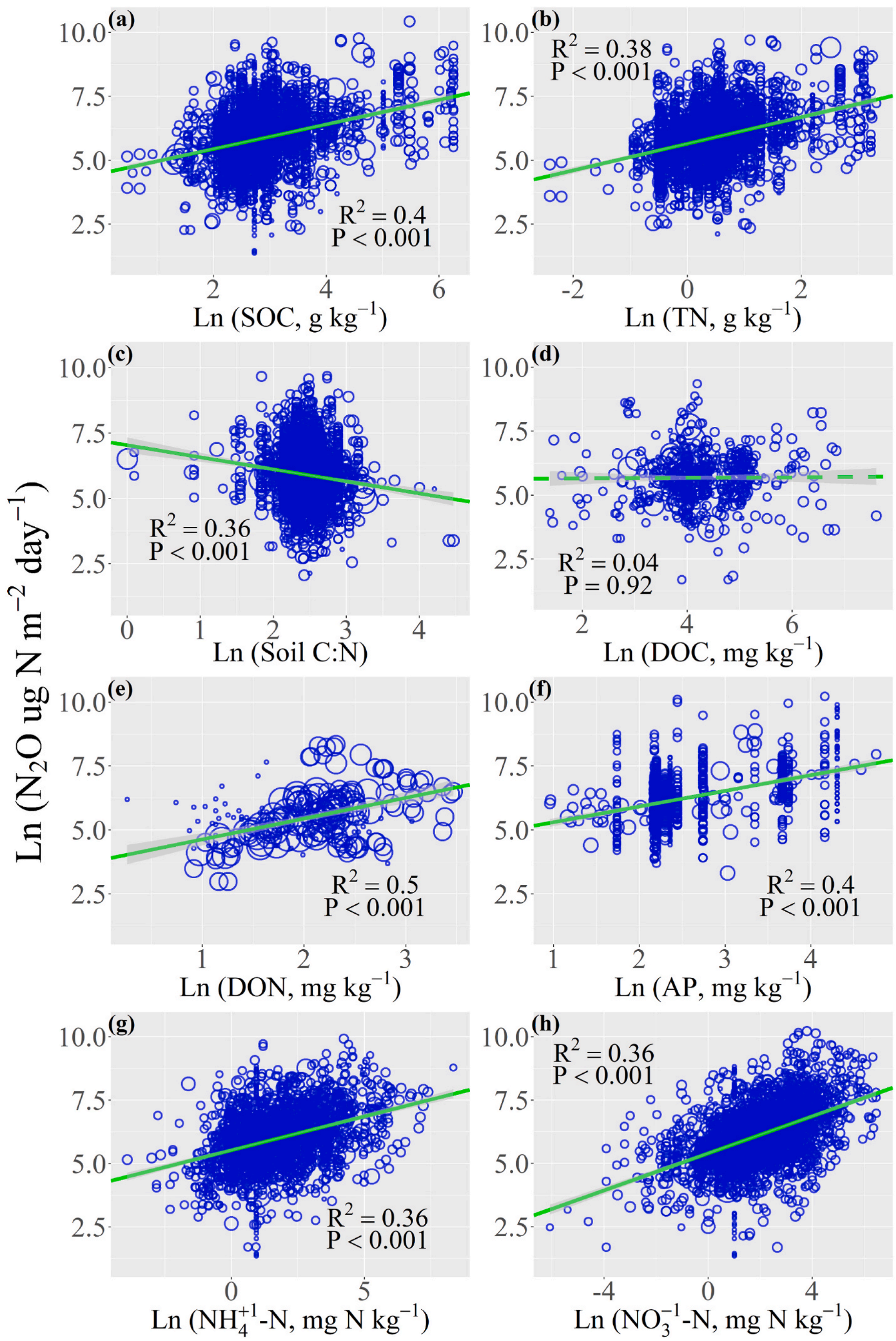

Fig. 4. The bivariate relationships between soil N_2O emission rate and carbon and nitrogen, namely, the content of soil organic carbon (SOC, a), soil nitrogen (TN, b), the ratio of soil carbon to nitrogen (soil C:N, c), soil dissolved organic carbon (DOC, d), soil dissolved organic nitrogen (DON, e), 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. Solid lines are significant slopes and the dashed line is the insignificant one. 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.

soil N_2O emissions at a global scale. This is in contrast to previous studies, which found that soil pH was the primary mediator of soil N_2O emissions at the global scale, while the soil N content was not fully considered (Wang et al., 2018). High soil pH promotes N mineralization (Li et al., 2019) and increases MBN (Fig. 6 and (Li et al., 2020), which subsequently facilitates N_2O emissions. However, when we considered the roles of the soil N content, pH was less important for the prediction of N_2O emissions (Fig. 6). Additional soil nitrate promotes denitrification, which subsequently increases N_2O emissions due to the following reasons. First, soil nitrate serves as the reactant for denitrification, where the denitrifier activity positively correlates with the nitrate content (Enwall et al., 2010). Moreover, the activities of soil denitrification enzymes are higher in soils with more nitrate (Gardner and White, 2010). For example, the activities of soil denitrification enzymes increased from 0.02 mg N kg^{-1} h^{-1} to 11.6 mg N kg^{-1} h^{-1} under the addition of nitrate in some wetlands (White and Reddy, 1999). Additionally, higher soil nitrate levels were observed to increase the N_2O:N_2 ratio during denitrification (Senbayram et al., 2012). For instance, it increased from 19% under 10 mg N kg^{-1} to 59% under 100 mg N kg^{-1} (Wang et al., 2013).

Soil ammonium and total soil N (mostly in organic form) also largely determine the global soil N_2O emission rates. High soil ammonium levels increase the abundance of ammonia-oxidizing bacteria (Tian et al., 2014), which promotes soil autotrophic nitrification. For example, soil N_2O emissions increased from 238 to 277 g N ha^{-1} yr^{-1} to 853–1301 g N ha^{-1} yr^{-1} when the aqueous ammonia was applied at from 0 to 260 kg ha^{-1} (Pittelkow et al., 2013). Soil organic N is the substrate for heterotrophic nitrification. In some cases, soil

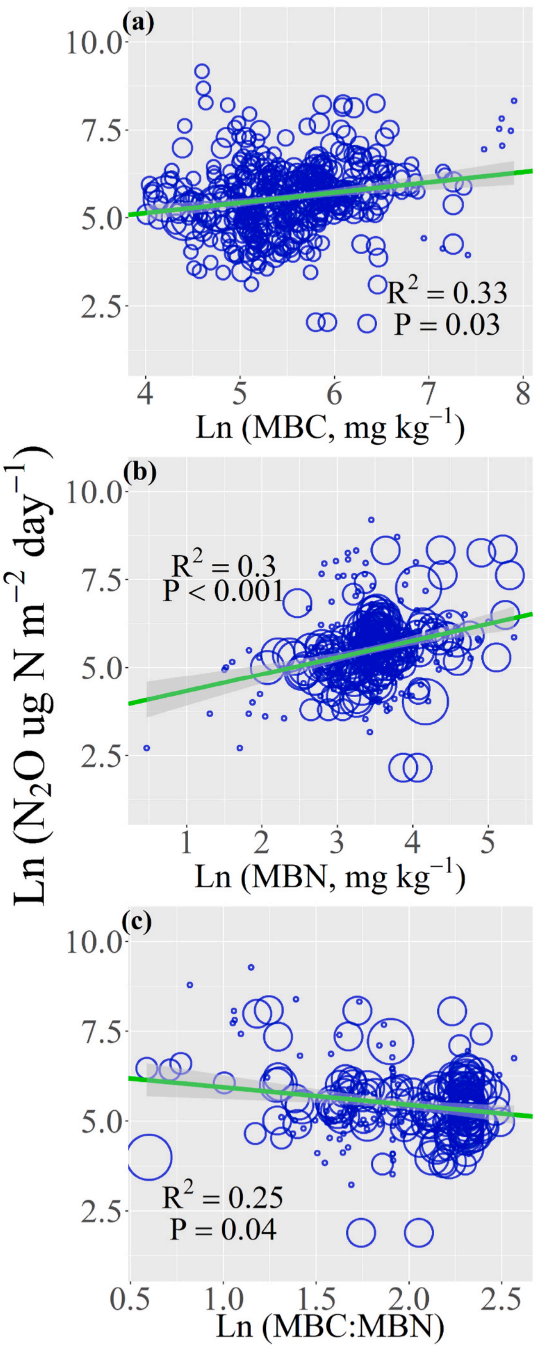

Fig. 5. The bivariate relationships between soil N_2O emission rate and soil microbial characteristics, namely, microbial biomass carbon (MBC, a), microbial biomass nitrogen (MBN, b), and the ratio of microbial biomass carbon to microbial biomass nitrogen (MBC:MBN, c) at a global scale using the logarithmically 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.

heterotrophic nitrification accounts for 7–19% of the total nitrification (Islam et al., 2007), and even more than 50% under acidic soil conditions (Liu et al., 2015). Moreover, soil organic N can increase the soil microbial biomass and subsequently increases N mineralization (Li et al., 2019). A recent study revealed that the total soil N content was the main driver for the soil nitrification rate at the global scale (Li et al., 2020). In alignment with our findings, a study revealed that the application of manure also substantially increased N_2O emissions by 5.1–58.2% (Zhou et al., 2017). The key role of soil N contents on soil N_2O emissions was also confirmed by the consistently positive relationships between the soil N_2O emission rate and soil nitrate, ammonium, and total soil N for each type of ecosystem (Fig. 7).

Soil moisture is another important controlling factor for the variations in soil N_2O emissions at a global scale, as soil moisture potentially regulated N_2O emission through the availability of substrates and the microbial activities. Low soil moisture hampers the diffusion of N substrates to microbial cells (Stark and Firestone, 1995), and can influence the dynamics of its resident microbial biomass. For instance, higher soil moisture can promote the soil MBN by 56.3–91.4% in dry ecosystems (Huang et al., 2018). Moreover, under low soil moisture microbial cell dehydration occurs, which lowers the activity of nitrifying bacteria (Stark and Firestone, 1995). Thus, the efficiency of soil processes is stimulated under higher soil moisture (Zhang et al., 2019). Finally, soil moisture alters soil nitrification and denitrification, which generates N_2O (Bollmann and Conrad, 1998). In some cases, additional N_2O emissions can be derived from denitrification when the soil moisture is >70%. It was observed that N_2O was emitted from 1 to 412 mg N m^{-2} when soil moisture increased from 40 to 90% over 15 days (Ruser et al., 2006). The important role of soil moisture in N_2O emissions was also manifested as an important predictor of its temperature sensitivity in an alpine meadow ecosystem (Zhang et al., 2020).

Higher temperatures stimulate the activities of microbes, particularly those of nitrifiers and denitrifiers, which subsequently influences soil N_2O emissions. One study showed that the assimilation of $^{13}CO_2$ by ammonia-oxidizing archaea (a type of autotrophic nitrifier) increased when the soil temperature was elevated by 3 °C (Hu et al., 2016). Similarly, warming (+3.6 °C) enhanced nirS-type denitrifiers by 38%, nirK-type denitrifiers by 82% (Qu et al., 2018), and norB-type denitrifiers by 4.3% (Zhou et al., 2012). In some meadow ecosystems with higher soil moisture, temperature changes explained up to 35% of variations in the annual soil N_2O flux (Hu et al., 2010). The bulk density of soil influences oxygen diffusion (Schjonning et al., 2003), which consequently impacts N_2O emissions through soil nitrification and denitrification. Higher soil C:N and MBC:MBN ratios may primarily impede nitrification rather than denitrification, which consequently decreases N_2O emission rates worldwide. This is because higher C:N and MBC:MBN ratios do not significantly affect denitrification rates (Li et al., 2022) but do decrease the soil nitrification rate (Li et al., 2020).

4.2. Implications for soil N_2O emissions under N inputs

Increased soil nitrate and ammonium concentrations promote soil N_2O emission. As reported, higher N_2O emissions can, for the most part, be attributed to the increased use of synthetic N fertilizers since 1960 (Davidson, 2009). A study by Chen et al. (2017) revealed that the quantity of N in croplands under current fertilization programs far exceeds crop uptake capacities; thus, surplus N in the soil is lost in the form of N_2O. Earlier studies found that N_2O emissions increased sharply with higher N inputs (Bouwman et al., 2002) or soil N_2O was exponentially emitted under N additions (Van Groenigen et al., 2010). For example, a meta-analysis reported that soil N_2O emissions increased by 90% under the application of N at 50–100 kg N ha^{-1}, and increased by up to 262% under the application of N at 250–300 kg N ha^{-1} in croplands, in contrast to those without the addition of N (Sun et al., 2016). The application of N to wetlands may also result in higher N_2O emissions since N_2O is also sensitive to nitrate/ammonium in wetlands (Fig. 7). The higher N_2O emission rates in wetlands (Fig. 2) may be the result of the higher N concentrations in the runoff from croplands, which has increased by 31–46% since 1990 in China (Hou et al., 2018). Toward addressing ever increasing global food requirements, it is likely that fertilizer inputs will increase over the next century (Erisman et al., 2008). Thus, soil N_2O emissions will rise correspondingly in the near future, which requires urgent actions to reduce soil N_2O emissions. Over the last four decades, global N deposition has increased by 8%

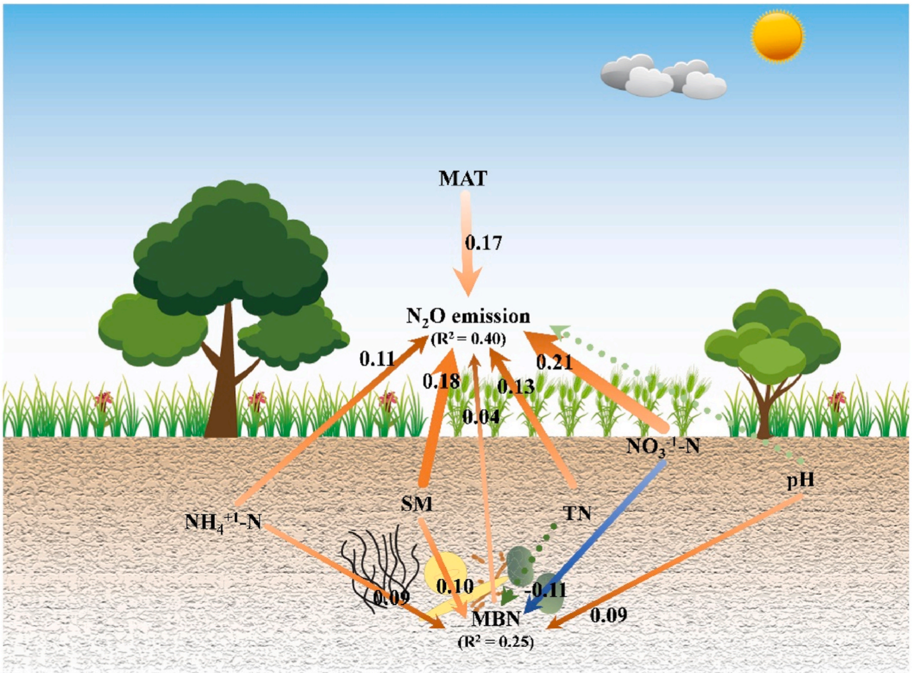

Fig. 6. The multiple relationships of soil N_2O emission rate at the global scale. The orange lines are the significantly positive relationships, blue lines are the significantly negative relationships, and the green dashed lines are the insignificant relationships, in which the statistically significant level is $\alpha \leq 0.05$. Numbers are standardized coefficients. MAT, SM, TN, and MBN represent mean annual temperature, soil moisture, total soil nitrogen, and microbial biomass nitrogen, respectively.

(Ackerman et al., 2019), which will remain a significant problem for the future (Yu et al., 2019). Therefore, more attentions should be paid to the impacts of increased N inputs on N_2O emissions, which may be exacerbated by global warming. A recent study revealed that when soil N substrates were adequate, higher temperatures significantly increased soil N_2O emissions (Zhang et al., 2020).

4.3. Implications for models and uncertainties

The dataset and findings of this study can facilitate the development of soil N_2O emissions models at large spatial scales. First, this study compiled a large quantity of data (i.e., 6016 field observations) on soil N_2O emission rates across terrestrial ecosystem types worldwide to provide a benchmark for model evaluation. Second, these data can be useful for the calibration of models. For instance, the Dynamic Land Ecosystem Model (DLEM) calculates soil N_2O emissions on the basis of nitrification and denitrification processes, which are mainly based on soil N substrates, temperature, and soil moisture (Xu et al., 2017), which are useful for calibrating the parameters of models. Third, the findings of this investigation showed that N substrates are critical for variations in soil N_2O emissions across terrestrial ecosystems, which offer insights into model development. For example, soil organic N and MBN significantly accounted for soil N_2O emission variations at a global scale, particularly in croplands, forests, and grasslands. Moreover, a recent study revealed that soil organic N explained most of the variations in soil nitrification at the global scale (Li et al., 2020). However, most land models for predicting soil N_2O have not considered the roles of soil organic N and MBN (Tian et al., 2018). Thus, the incorporation of soil N substrates and MBN may reduce model uncertainty in soil N_2O projection at large spatial scales.

There are some uncertainties in this synthesis. First, climatic factors, soil physicochemical properties, and the concentration of substrates can influence soil N_2O emissions by altering soil microbial biomass or the activities of microbes. Although we verified the roles of MBN to explain the variations in global N_2O emissions (Fig. 6), we did not test the effects of the microbial activities due to the paucity of data. For nitrification and denitrification, there are many functional microbes that participate in each specific processes. For instance, ammonia-oxidizing bacteria and archaea mediate the first step in soil nitrification, during which community dynamics may be critical (Theodorakopoulos et al., 2017). Therefore, the roles of functional microbes on soil N_2O emissions remain to be tested and verified at a global scale. Second, soil moisture may play roles in N_2O emissions by altering soil redox potentials (Rubol et al., 2012) other than microbial biomass. We did not compile sufficient data on redox potentials to test them in this study. Third, the data were mainly derived from croplands (72.4%). Although the relationships between soil N_2O emissions and environmental factors were similar for other ecosystem types (Fig. 7), the variations in weighted slopes were obviously larger when the number of observations in wetlands was small.

5. Conclusion

This study revealed the global patterns and controlling factors involved in soil N_2O emissions. Although climatic factors (e.g., mean annual temperature), soil physicochemical properties (i.e., soil pH, bulk density, and soil moisture) significantly influenced global soil N_2O emissions, the soil N content as the substrates for nitrification and denitrification (i.e., soil nitrate, ammonium, and total soil N) accounted for most of the variations (53.6%) in soil N_2O emission rates at the global scale. The crucial roles of the soil N content in soil N_2O emissions were consistent across ecosystem types. This was because more soil nitrate, ammonium, and total soil N content increased soil N_2O emissions in croplands (weighted slope = 0.36, 0.26, and 0.19, respectively), forests (weighted slope = 0.36, 0.25, and 0.24, respectively), grasslands (weighted slope = 0.30, 0.27, and 0.35, respectively), and wetlands (weighted slope = 0.27, 0.27, and 0.04, respectively). The findings highlighted the necessity that the soil N content (i.e., nitrate, ammonium, and total soil organic N) should be comprehensively incorporated into models to improve the projection accuracy of soil N_2O emissions at the global scale.

Contribution of authors

Zhaolei Li, Shuli Niu: Conceptualization, Writing- Original draft preparation. Zhaoqi Zeng, Zhaopeng Song, Dashuan Tian: Methodology, Software. Zhaolei Li, Xingzhao Huang, Sheng Nie: Data Collection. Yiqi Luo, Lifen Jiang, Jun Wang, Jun Cui: Writing-Reviewing and Editing.

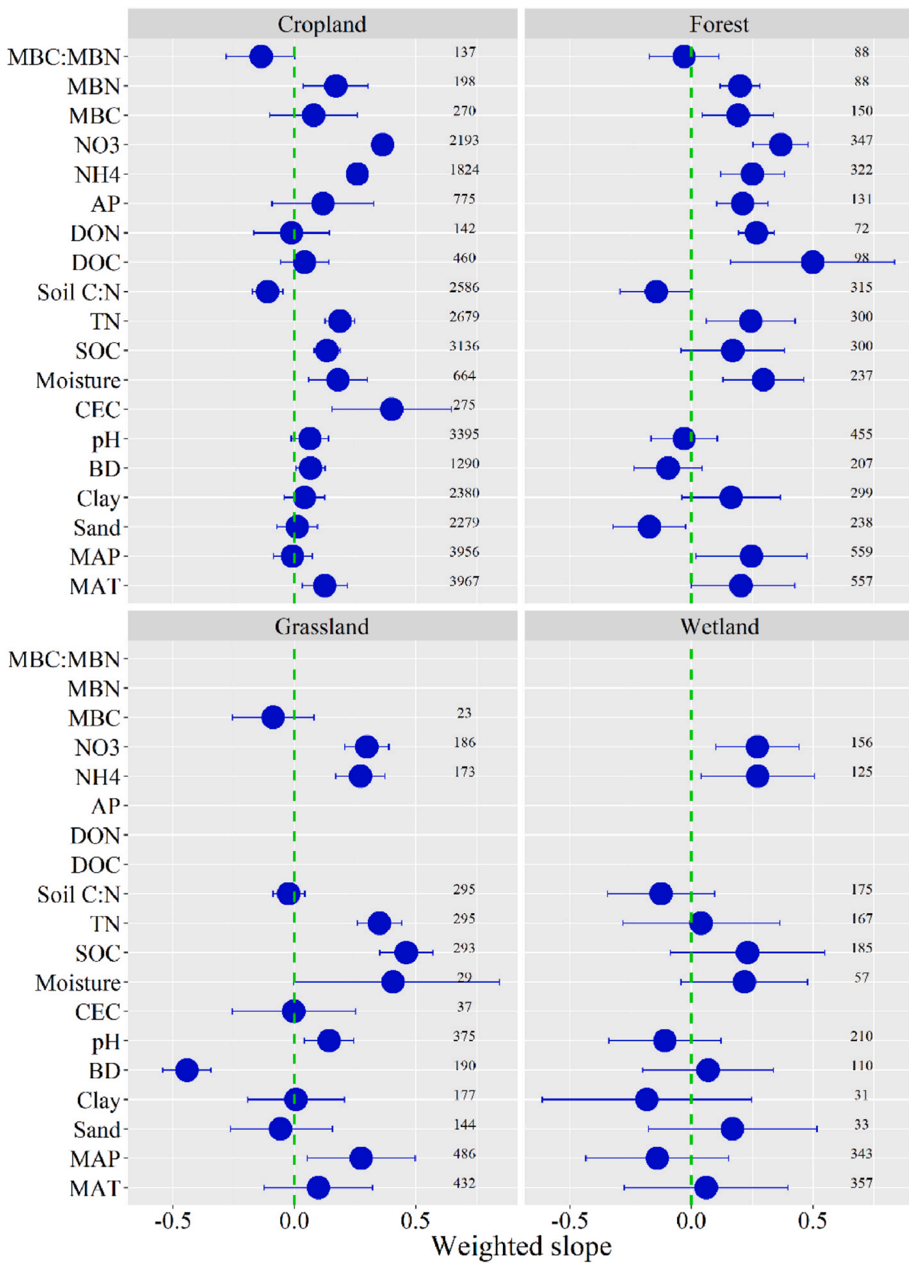

Fig. 7. The slopes of the bivariate relationships between soil N_2O emission rate and MAT (mean annual temperature), MAP (mean annual precipitation), Sand, Clay, BD (bulk density), pH, CEC (cation exchange capacity), Moisture, SOC (soil organic carbon), TN (total soil nitrogen), soil C:N, DOC (soil dissolved 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 the 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.

Data availability statement

Data supporting the results will be available after request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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