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Sources of nitrous oxide emissions from agriculturally managed peatlands

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Abstract

The draining and fertilization of peatlands for agriculture is globally an important source of the greenhouse gas nitrous oxide (N_2O). Hitherto, the contribution of major sources to the N_2O emission—that is, fertilization and nitrogen (N) release from peat decomposition—has not yet been deciphered. This hampers the development of smart mitigation strategies, considering that rewetting to halt peat decomposition and reducing N fertilization are promising N_2O emission-reduction strategies. Here, we used machine learning techniques and global N_2O observational data to generalize the distribution of N_2O emissions from agriculturally managed peatlands, to distinguish the sources of N_2O emissions, and to compare mitigation options. N_2O emissions from agriculturally managed croplands were 401.0 (344.5–470.9) kt N year^{-1}, with 121.6 (88.6–163.3) kt N year^{-1} contributed by fertilizer N. On grasslands, 64.0 (54.6–74.7) kt N_2O-N year^{-1} were emitted, with 4.6 (3.7–5.7) kt N_2O-N year^{-1} stemming from fertilizer N. The fertilizer-induced N_2O emission factor ranged from 1.5% to 3.2%. Reducing the current fertilizer input by 20% could achieve a 10% N_2O emission reduction for croplands but only 3% for grasslands. Rewetting 1.9 Mha cropland and 0.26 Mha grassland would achieve the same N_2O emission reductions. Our results suggest that N_2O mitigation strategies for managed peatlands should be considered separately across land-use types and climatic zones. For croplands, particularly in the tropics, relevant N_2O mitigation potentials are achievable through both fertilizer N reduction and peatland rewetting. For grasslands, management schemes to halt peat degradation (e.g. rewetting) should be considered preferentially for mitigating N_2O and contributing to meeting climate goals.

KEYWORDS
drained peatland, fertilizer N, mitigation strategies, N_2O mitigation, organic soil, peat decomposition

1 | INTRODUCTION

Peatlands are an important component of the Earth's climate system and global carbon (C) and nitrogen (N) cycles. With only 3% of the terrestrial surface, peatland biomes store approximately 644 Gt of soil C or 25% of the global soil organic carbon and 8–15 Gt of soil nitrogen (N) (Leifeld & Menichetti, 2018; Yu et al., 2010). Human activities (i.e., draining and mining peatlands) have transformed this biome from a long-term C and N sink into a source. The greenhouse gas (GHG) release from managed peatlands is approximately 1.91 (0.31–3.38) Gt CO_2-eq $year^{-1}$ (Carlson et al., 2016; Evans et al., 2021). Given their small area of approximately 500 Mha (UNEP, 2022) and high emission rates, drained peatlands are hot spots for GHG release.

Around 20% of GHGs emitted from managed peatlands have been attributed to nitrous oxide (N_2O) (FAOSTAT, 2022; Leifeld & Menichetti, 2018), a potent GHG stemming largely from microbial denitrification and nitrification (Butterbach-Bahl et al., 2013; Davidson et al., 2000). The overall release from agriculturally managed organic soils of 122–607 kt N_2O-N $year^{-1}$ (57–284 Mt CO_2-eq $year^{-1}$), equivalent to 3.2%–16.0% of the global agricultural N_2O emissions of 3800 kt N_2O-N (Carlson et al., 2016; Conchedda & Tubiello, 2020; Frolking et al., 2011; Günther et al., 2020; Leifeld & Menichetti, 2018; Tubiello et al., 2016), and contributing 1.3%–6.4% to the global soil-borne N_2O emissions of 9400 kt N_2O-N (Tian et al., 2020). When peatlands are drained and managed, the fertility of organic soil for agricultural production improves through the aerobic decomposition of peat and the accompanying nutrient release. Consequently, N_2O emissions from drained organic soils are much higher than those from mineral soils under the same land use (Hiraishi et al., 2014; Maljanen et al., 2010). Moreover, agriculturally managed peatlands are often fertilized, which is considered necessary to maintain or improve the productivity of the land. These fertilizer inputs drive extra soil N_2O emissions from peatlands managed for agriculture (Shcherbak et al., 2014). The relatively high N_2O emissions derived from both peat decomposition and fertilizer input make managed peatland key players when seeking climate change mitigation potentials in the agricultural sector, and a substantial part of N_2O emitted from soils might be mitigated by adjusted land management practices (Butterbach-Bahl et al., 2013). Therefore, it is crucial to clarify the source and rates of N_2O released from managed peatlands to explore and develop targeted N_2O reduction strategies for agriculturally managed peatlands under different climates and land use.

The range of current estimates of the N_2O emissions from global managed peatlands cited above reflects high uncertainty due to the strong control imposed on these emissions by climate and weather conditions, fertilization, peat nitrogen content, and land use (Griffis et al., 2017; Lawrence et al., 2021; Parn et al., 2018) (i.e., the dynamism and variability of the driving forces and their interactions) (Butterbach-Bahl et al., 2013). Current limitations in quantifying peatland N cycling and climate feedback are reflected by the lack of N_2O emission models for organic soil (Farmer et al., 2011), and predicting the size of N_2O emissions from managed peatlands remains a challenge. Some previous studies showed that soil properties, such as bulk density, soil carbon-to-nitrogen ratios (C/N), and soil pH, are useful for predicting the N_2O fluxes from managed peatlands (Leifeld, 2018; Liu et al., 2019; Wang et al., 2018). These properties may all have simultaneous effects on N_2O emissions from agriculturally managed peatlands. In addition to soil biogeochemical parameters, climate conditions and land use significantly alter the N_2O emissions from agriculturally managed peatlands, making predictions based on single factors uncertain (Hiraishi et al., 2014; Leppelt et al., 2014). Combining and incorporating this knowledge into N_2O models would help to better estimate the N_2O emissions from peatlands and further distinguish the source of N_2O emissions on a regional and global scale. An improved and more reliable prediction would not only enable us to better identify the source of N_2O emissions from agriculturally managed peatlands but also enable us to develop more tailored mitigation strategies. Therefore, in this study, we assess the contribution of fertilizer and peat decomposition to the N_2O emissions from agriculturally managed peatlands globally and determine the distribution of N_2O emissions under different land-use types and climates. We do so by compiling a database of N_2O emissions (N_2O dataset) from agriculturally managed peatland sites around the world that encompasses a wide range of peatland systems under different land-use types (Figure 1a). In addition, parameters that have previously been identified as key variables for controlling N_2O emissions from organic soil are included in this database. This database is used to set up a machine learning model that enables us to predict global N_2O emissions from agriculturally managed peatlands and is upscaled using a second dataset with environmental variables of many peatland sites worldwide (soil dataset, Figure 1b).

2 | MATERIALS AND METHODS

2.1 | Data acquisition and pre-processing

2.1.1 | Database for developing the machine learning model (N_2O dataset)

The data on global N_2O emission values from peatlands, herein named N_2O dataset, were collected from peer-reviewed published literature using Google Scholar and Web of Science. The period considered was January 2000 to September 2022. The search keywords included the following: 'Peatland,' or 'Organic soil,' or 'Histosol;' and "GHGs," or "greenhouse gas," or "nitrous oxide (N_2O)". The selection criteria were as follows: First, N_2O emissions must have been observed from field experiments; laboratory incubations and greenhouse experiments were excluded. Second, the N_2O measurement period must have covered at least the entire growing season or the whole year. Third, the literature should have included basic soil properties (i.e., organic carbon content, bulk density, pH, N content, and C:N ratios, and fertilizer application rates). When soil properties were unavailable from the original literature, the information was collected from the supplementary literature, where the study site was the same as that of the original study. Studies using nitrification or denitrification inhibitors were excluded. Overall, 364 data points (Table S1) from 63 references (covering 28 countries and 68

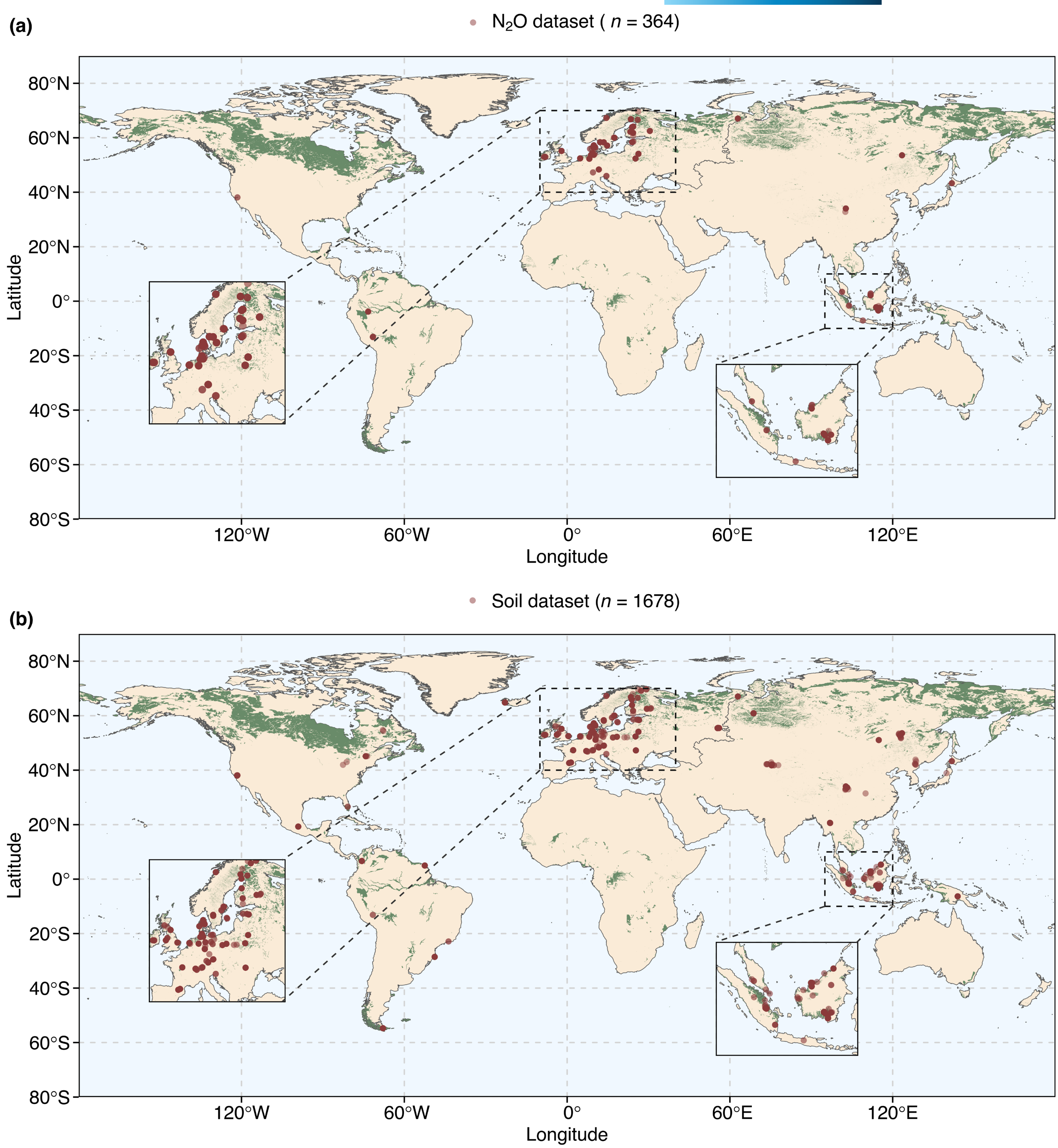

FIGURE 1 Spatial distribution of N_2O data points (a) and soil data points (b) from the literature used in this study. Green areas indicate the area of peatland (Leifeld & Menichetti, 2018). Southeast Asian and European regions were zoomed in for better optical resolution of the data points. Map lines delineate study areas and do not necessarily depict accepted national boundaries.

sites) were used to set up the machine learning model. Among the collected N_2O emissions, 15% were from the growing season, while 85% covered the entire year. Since the N_2O emissions outside the growing season were low or nearly zero, we argue that including these data will not significantly influence the overall results. Each data point includes one N_2O observational value from a single measurement year or site.

2.1.2 | Database for simulating N_2O distributions (soil dataset)

To place our model into a broader context, we collected a second set of published data obtained from C-exchange measurements, or soil property measurements from peatlands, hereafter referred to as the soil dataset. We extended the data from a previous study (Leifeld

& Menichetti, 2018) for tropical sites and collected more data on peatland soil properties from published papers. We included studies that could provide the following soil property data: organic carbon and N content, bulk density, pH, C:N ratios, and fertilizer input. In the end, 1678 data points (covering 27 countries and 195 sites) were included in the soil dataset. Due to the limited number of soil data from agriculturally managed peatlands without fertilization, data from natural peatlands, where no agricultural activities were reported or recorded, were also included. The three soil properties that contributed the most to the machine learning model (N content, C:N ratio, and pH) in unfertilized but managed peatlands and natural peatlands were compared. We found no significant differences in soil N content and soil C:N ratios between agriculturally managed peatlands without fertilizer N application and natural peatlands (Figure S2). The soil pH differed between these two subsets of soil data; however, this contributed only about 4% to explaining the soil N_2O emissions in our machine learning model. Moreover, the trend of N_2O emission response to soil pH was not consistent (Figure S5; details of the calculations can be found in the Methods subsection, "Assessing variables importance"). We also included soil properties from natural peatlands in the soil dataset for simulating N_2O emissions from agriculturally managed peatlands. In the soil dataset, each data point included one soil observation from a single measurement location.

2.1.3 | Database complementation

Climate and N deposition

Missing specific climate data and data on N deposition for both the N_2O and soil datasets were extracted from gridded global data. Missing annual precipitations and air temperatures from the measurement year were extracted from a high-resolution gridded climate dataset (Harris et al., 2020), and missing N deposition data from the measurement year were extracted from a previous study (Ackerman et al., 2019). To determine the climate zone for each data point, long-term (1961–2010) climate data from the same dataset used for determining the missing annual precipitations and air temperatures (Harris et al., 2020) were extracted for each data point, and the climate zone was determined by the method reported in the IPCC (Bickel et al., 2006). We prioritized the consideration of this particular classification because it represents a standard for studies dealing with greenhouse gas emissions and climate mitigation. However, we are aware that this choice has important implications for aggregated results, an issue that we will resume and discuss in more detail later.

Soil data

Missing soil bulk density was filled using the correlation between bulk density and soil organic carbon content from the soil dataset, as follows:

$$BD = \ln\left(\frac{SOC}{691.2}\right) / -2.2. \quad (1)$$

The collected soil pH values, which were either measured with potassium chloride (KCl) or calcium chloride ($CaCl_2$) solution or in pure water, were corrected to the soil pH measured in pure water using the following equation (Lierop, 1981):

$$pH_{H_2O} = 0.98 * pH_{CaCl_2} + 0.53, \quad (2)$$

$$pH_{H_2O} = 0.97 * pH_{KCl} + 0.84. \quad (3)$$

Fertilizer application

For the collected data points in which the fertilizer application rate was unavailable (614 data points; 36% of the soil dataset), country-specific fertilization recommendations and country-specific FAO nitrogen input (synthetic N fertilizer and manure) rates were used to represent the N application rate (FAOSTAT, 2022). For countries where the calculated N input rate was outside the 95% confidence interval (CI) of the collected N input rate (37–1065 kg N ha^{-1}), the average N input of the respective climate zone and land-use type was used to represent the N application rate of a site.

2.2 | Machine learning model

2.2.1 | Selection of variables

In this study, climate, soil chemical, soil physical, and land-use type data were included for each soil point from the N_2O dataset to explain the measured N_2O emissions. Environmental factors and soil properties have been reported to jointly influence the response of N_2O emissions to fertilizer N input (Stehfest & Bouwman, 2006). Soil C:N ratios have been reported to be negatively correlated with N_2O emissions from managed peatlands (Leifeld, 2018; Yao et al., 2022). Soil bulk density has been reported to be positively related to N_2O emissions from peatland ecosystem (Liu et al., 2019), and soil pH is considered the main modifier of regional N_2O emissions (Wang et al., 2018). Environmental factors, such as temperature and precipitation, have also been reported to influence the N_2O response to fertilizer input (Parn et al., 2018). Consequently, we selected the following variables, which were reported to significantly influence soil N_2O emissions, as the original input variables in this study: soil N content, C:N ratios, bulk density, and pH; N input (i.e., fertilizer N input and N deposition); and environmental factors (i.e., annual mean temperature and precipitation). Furthermore, rainfall (20–60 mm) is known to induce soil moisture changes that could affect the magnitude of soil N_2O emissions (Li et al., 1992). Therefore, we selected daily rainfalls higher than 20, 30, 40, and 50 mm to test the performance (the coefficient of determination from the validation data) of the model (R^2 = 0.56, 0.56, 0.59, and 0.58, respectively), and we chose days with daily rainfalls higher than 40 mm as the input parameters for the model. The rainfall data were extracted for each data point from the gridded dataset (Xie et al., 2010). In the next step, we identified multicollinearity among the predictors using the "ellipse" package in R software (version R 4.1.2) and visualized all pairwise Pearson correlation coefficients of the predictors. The results showed that soil organic carbon and soil bulk density were highly correlated (Figure S1b). Therefore, we dropped the collinear predictor soil organic carbon (SOC) from the input variables because SOC could be reflected by soil N content and C:N ratios. For the soil dataset, the results were reported for different depths. Therefore, we converted all properties to a depth of 0–10 cm based on conversion ratios calculated from a database of soil properties in different land-use types and for different soil depths. To determine the conversion ratios of soil parameters, including C:N ratios, SOC, N content, and soil bulk density, we gathered data from publications containing soil core data from various depths in organic soils. In total, 1719 data points from eight different countries (details in Table S3) were compiled. Initially, we normalized the soil core data from different depths to the surface. Subsequently, we calculated conversion ratios from 0–10 cm to various depths for each soil core, averaging the results based on land-use type—croplands, grasslands, and forest. Details on the conversion ratio can be found in Table S4.

2.2.2 | Predictive modelling

The final machine learning model was set up using the attributes of soil bulk density, pH, N content, C:N ratios, land-use type, atmospheric N deposition, and climate variables, including annual mean air temperature, average annual precipitation, and the number of days with rainfall higher than 40 mm. The annual N_2O emissions (kg N ha^{-1} year^{-1}) was set as the target variable. Using the selected variables, we used k-fold cross validation ($k=10$) to test the performance (root mean square error [RMSE] and *R* square [R^2]) of six different machine learning models, including random forest (RF), extreme gradient boosting (XGBoost), Cubist, support vector machines (SVM), Bayesian regularized artificial neural networks (BRANNs), and lasso regression (LASSO). For each model, observations from 80% of the data points randomly selected (i.e., 300 data points from the N_2O dataset) were used for model calibration, and the remaining 20% of the data were used for validation. Here, it is worth mentioning that the data from the forest were exclusively utilized to train the model. Achieving optimal performance in machine learning models often requires a relatively large dataset for training. Due to the limited observations of N_2O emissions from agriculturally managed peatlands, we found it necessary to include N_2O emissions data from forests in our training set. This inclusion, especially under low fertilizer conditions, is anticipated to enhance the model's performance. To test each model's performance on the entire dataset, this process was performed 10 times. To avoid the influence of selection bias during data splitting (to test and train data), the model testing process was applied 100 times (each with different random seed values). The mean value of the model RMSE, the R^2, and the ratio between the observed and simulated N_2O emissions were used to determine the model with the best performance (see Figures S3 and S4). We found that the XGBoost model performed best during model calibration, although it was not ranked the best regarding the RMSE and R^2 during model validation. However, the ratio of observed to simulated N_2O emissions was around 1, indicating that the XGBoost model could predict the N_2O emissions without bias. Therefore, we chose XGBoost for simulating N_2O emissions for this study.

2.2.3 | Assessing variable importance

The relative importance of the variables in the machine learning model indicates the influence of each variable in predicting N_2O emissions. We assessed the variable importance of XGBoost by using importance scores for each predictor in the model. These assessments were conducted using the packages “xgboost” and “caret” in the R software (version R 4.1.2).

2.2.4 | Partial dependence analysis

To identify the relationship between each single variable and N_2O emissions, partial dependence analysis and associated partial dependence plots (PDPs) were used (Figure S6). Partial dependence analysis is a particularly effective method to state the relationship between the independent controls and the response while accounting for the average effect of the other predictors in the model, and isolating the effect of the target independent variables. Moreover, the PDPs can visualize the average marginal effect of the independent variables on the predicted parameters of the machine learning model. By applying PDPs, the linear, nonlinear, monatomic, or complex relationship between the predictors and the outcome was easily accessed through the shape of the PDP curve. The knick points of the PDP curve can also be used to identify where the controls of each single predictor on the predicted outcome are stronger and more indirect. In our study, we employed the “pdp” package in R to apply partial dependence analysis.

2.3 | N_2O response to fertilization input and fertilization contribution analysis

To evaluate how the N_2O fluxes respond to fertilizer N input in managed peatlands, we set up different fertilizer input scenarios using the range of collected fertilizer input data with an N input step width of 50 kg N ha^{-1} over a range of 0–500 kg N ha^{-1} year^{-1}. We then applied the XGBoost model to simulate the N_2O emissions for the soil dataset under different fertilization scenarios. To generate statistically valid CIs of N_2O emissions for different climate zones, we performed a stratified bootstrapping procedure with the total N_2O emissions. The simulated N_2O emissions were resampled (repeated) 1000 times. We then obtained the average of the N_2O emissions and used the lower 2.5% to the upper 97.5%

range as the CI of the N_2O emissions for different climate zones in different N input scenarios. We applied a linear regression between the fertilizer N input and the corresponding soil N_2O emissions to obtain the growth rate of N_2O emissions to fertilizer N (i.e., the fertilizer-induced emission factor).

To determine the global N_2O emissions from agriculturally managed peatlands under the current fertilizer N addition, the soil dataset was used to predict the N_2O emissions using the XGBoost model. The fertilizer contribution to N_2O emissions $Contri_{fer}$ was determined as Equation (4). The confidence interval of the simulated N_2O emissions for different climate zones was determined using the same resampling process mentioned above

$$Contri_{fer} = \frac{Emission_{fer} - Emission_0}{Emission_{fer}} \times 100\%. \quad (4)$$

$Emission_{fer}$, ($kg\,N_2O\text{-}N\,ha^{-1}\,year^{-1}$) was the simulated N_2O emissions with actual or prescribed fertilizer N input, and $Emission_0$, ($kg\,N_2O\text{-}N\,ha^{-1}\,year^{-1}$) was the simulated N_2O emissions without fertilizer N input.

2.4 | Upscaling N_2O emissions with globally managed peatland data

We combined the resulting N_2O emissions with the area of managed peatlands as reported from the peatland map (Leifeld & Menichetti, 2018) by climate zone and land-use type. It should be noted that we acted on the assumption that peatlands drained for forestry do not receive any fertilizer; therefore, forest ecosystems were excluded when estimating the fertilizer N contribution to N_2O emissions from managed peatlands. To calculate the mean N_2O distribution and the CI from different land-use types and climate zones, we performed a bootstrapping procedure with the simulated N_2O emissions from all soil sites under different land-use types and climate zones, with a 1000-times bootstrapping iteration. Doing so allowed us to generate a mean and a statistically robust 95% CI.

2.5 | Future scenarios and managed peatland area reduction potential

To estimate the future N_2O mitigation potential, we considered a 20% fertilizer N reduction scenario for all the collected soil points (reduction scenario) based on the European Commission's agricultural policy, which envisages a reduction in fertilizer use by at least 20% by 2030 (European Commission, 2020). N_2O emissions from the reduction scenario were simulated using the XGBoost model. We then averaged and upscaled the N_2O emissions for different climate zones using the same process mentioned above. Based on the resulting N_2O mitigation potential, we further estimated how much of the area of managed peatlands should be reduced to achieve the same N_2O emission reduction as reducing fertilizer N input by 20%.

3 | RESULTS AND DISCUSSION

3.1 | Sources of N_2O emissions from managed peatlands

Our results revealed that background emissions, which are predominantly driven by peat decomposition and, to a smaller extent, by atmospheric N deposition (~3% of the fertilizer N input), were the main source of soil N_2O from agriculturally managed peatlands. Globally, they contributed 72.8% (63.2–82.9) of the soil N_2O from agriculturally managed peatlands (grasslands and croplands). The average contribution of N fertilization was 27.2% (19.8–36.3) (Table 1, Figure 2a). Our analysis categorized managed peatlands by climatic zones (i.e., tropical, temperate, and boreal) and by land-use type (i.e., cropland and grassland), both based on the definition from the Intergovernmental Panel on Climate Change (IPCC) (Bickel et al., 2006). The contribution of fertilizer N input to soil N_2O emissions differed substantially across the categories. It was higher in croplands than in grasslands on managed peatlands. In croplands, on average, 23.5% (21.0–26.0) of the N_2O emissions were derived from fertilizer N input; this share made up even 27.6% (24.8–30.7) of the soil N_2O emissions in tropical zones (Figure 2b), which might be explained by the highest fertilizer N input of 229 (186–274) $kg\,N\,ha^{-1}$ per year (Figure 2c). Compared to croplands, the contribution of fertilizer N input to soil N_2O emissions was substantially lower in grasslands, where it contributed only 5.4% (4.6–6.3) of the soil N_2O emissions (Figure 2b). We interpret that the lower contribution of fertilizer to the N_2O emitted from grasslands compared to croplands was primarily attributed to the overall lower fertilizer N input (Figure 2c). Only a few study points were located in the boreal zone, mainly in Canada and Siberia (Figure S8), and that data indicated that N_2O emissions from boreal agricultural areas were low and contained only limited contributions from fertilizer N (Figure 2a).

3.2 | Distribution of N_2O emissions from agriculturally managed peatlands by climate zone and land use

3.2.1 | Agriculturally managed peatlands in tropical zones

Agricultural production in tropical peatlands is by far the largest hotspot of N_2O emissions. For agriculturally managed tropical croplands, the calculated emission factors were 34.8 (30.2–41.1) $kg\,N_2O\text{-}N\,ha^{-1}\,year^{-1}$ (Figure 2d), of which 12.1 (8.8–16.3) $kg\,N_2O\text{-}N\,ha^{-1}\,year^{-1}$ were fertilizer-derived (Table 1). This is much higher than the IPCC default of 5.0 (2.3–7.7) $kg\,N_2O\text{-}N\,ha^{-1}\,year^{-1}$ for tropical croplands (except rice) (Hiraishi et al., 2014). Hence, our study and the underlying literature data (Figure S7) suggest that upscaling soil N_2O

TABLE 1 Overview of actual N_2O emissions by source and associated uncertainty ranges for croplands and grasslands in managed peatlands by climatic zone.

	Cropland			Grassland		
	Boreal[d]	Temperate	Tropical	Boreal	Temperate	Tropical
Background N_2O emissions (kg N ha^{-1} $year^{-1}$)						
Mean	1.49	14.45	22.68	1.99	6.70	9.65
Low[a]	1.49	12.03	20.40	1.34	6.03	8.20
High[b]	1.49	17.08	25.28	2.63	7.35	11.54
Background emissions (kt N $year^{-1}$)[c]						
Mean	10.66	53.47	213.19	4.29	17.42	37.64
Low[a]	10.66	44.51	191.76	2.73	15.68	31.98
High[b]	10.66	63.20	237.63	5.98	19.11	45.01
Equivalent to CO_2 (Mt CO_2-eq $year^{-1}$)[e]						
Mean	4.97	24.93	99.43	2.00	8.13	17.55
Low[a]	4.97	20.76	89.43	1.27	7.31	14.91
High[b]	4.97	29.48	110.83	2.79	8.91	20.99
Fertilizer-induced N_2O emissions (kg N ha^{-1} $year^{-1}$)						
Mean	n.d.	2.22	12.06	0.00	0.74	0.67
Low[a]	n.d.	1.68	8.76	0.00	0.63	0.52
High[b]	n.d.	2.77	16.28	0.00	0.86	0.85
Fertilizer-induced emissions (kt N $year^{-1}$)[c]						
Mean	n.d.	8.21	113.36	0.00	1.92	2.61
Low[a]	n.d.	6.22	82.34	0.00	1.64	2.03
High[b]	n.d.	10.25	153.03	0.00	2.24	3.32
Equivalent to CO_2 (Mt CO_2-eq $year^{-1}$)[e]						
Mean	n.d.	3.83	52.88	0.00	0.90	1.22
Low[a]	n.d.	2.90	38.41	0.00	0.76	0.94
High[b]	n.d.	4.78	71.37	0.00	0.94	1.55

[a]Low values indicate the lower 95% CI. The 95% CI was calculated by performing a bootstrapping for the N_2O emissions for each land-use type and climatic zone 1000 times.

[b]The high values indicate the upper 95% CI.

[c]The areas used for upscaling for crop production were 7.2, 3.7, and 9.4 Mha for boreal, temperate, and tropical managed peatlands, respectively, while for grass production, the areas were 2.2, 2.6, and 3.9 Mha for boreal, temperate, and tropical managed peatlands, respectively.

[d]In the boreal zone, cropland N_2O emissions could not be distinguished between background and fertilizer-induced N_2O emissions due to a lack of experimental data.

[e]The equivalent to CO_2 was calculated based on the 100-year global warming potential of N_2O, which was 265 from the fifth assessment report of the IPCC (Bickel et al., 2006).

emissions using IPCC default values may substantially underestimate the N_2O emissions of agriculturally managed croplands in tropical zones. Based on the global peatland map (Leifeld & Menichetti, 2018), we calculated soil N_2O emissions of 328.8 (284.2–386.2) kt N_2O-N $year^{-1}$ from agriculturally managed croplands in the tropics. Of these emissions, approximately 113 kt N_2O-N $year^{-1}$ were derived from fertilizer N (Table 1), which accounted for approximately 9% of the GHG emissions from all agriculturally managed peatlands in the tropics (Evans et al., 2021). With the same amount of fertilization of 229 (186–273) kg N ha^{-1} $year^{-1}$ (Figure 2c), crop production on mineral soil in the same area would only emit 21.6 kt N_2O-N $year^{-1}$ [calculated using the IPCC 1% default emission factor of the applied fertilizer N (Stocker, 2014)], corresponding to about 20% of those from fertilizing organic soils. These findings reflect a substantial potential for mitigating N_2O emissions from agriculturally managed croplands in tropical zones (e.g. by moving a larger share of crop production to mineral soils).

N_2O emissions from tropical grasslands were smaller than those from tropical croplands (Figure 2d). The calculated soil N_2O emissions were 10.3 (8.7–12.2) kg N_2O-N ha^{-1} $year^{-1}$, and the mean N fertilization was 75 (66–91) kg N ha^{-1} $year^{-1}$ (Figure 2c). Fertilizer-derived N_2O emissions accounted for 0.67 (0.52–0.85) kg N_2O-N ha^{-1} $year^{-1}$. The calculated annual N_2O emissions were 40.3 (34.0–47.7) kt N_2O-N $year^{-1}$, of which 2.6 (2.0–3.3) kt N_2O-N $year^{-1}$ were attributed to fertilizer N (Table 1).

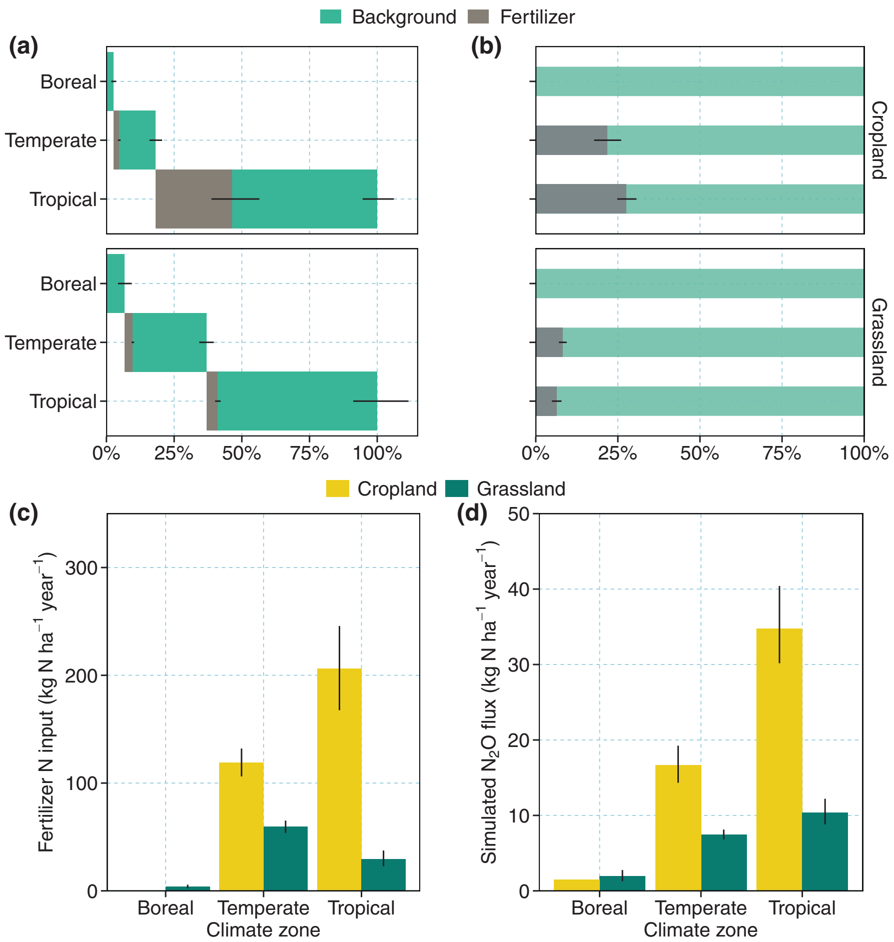

FIGURE 2 Simulated N_2O emissions of managed peatlands and fertilizer contribution by land-use type and climatic zones: Contribution of fertilizer N and background emissions to global N_2O emissions (a), where background N_2O emissions are defined as derived from peat decomposition and atmospheric N deposition. Relative contribution of both source types to the N_2O emissions across land-use types and climatic zones (b), fertilizer N addition rate (c), and simulated per hectare N_2O emissions (d). The peatland map (Leifeld & Menichetti, 2018) was used for the upscaling of soil N_2O emissions in (a). Data are shown as mean ± 95% confidence interval (CI). The 95% CI was calculated by performing a 1000-times bootstrapping procedure.

3.2.2 | Agriculturally managed peatlands in temperate zones

Soil N_2O emissions were 16.6 (14.4–19.0) kg N_2O-N ha^{-1} year^{-1} and 7.5 (6.8–8.2) kg N_2O-N ha^{-1} year^{-1} for croplands and grasslands, respectively (Figure 2d). These rates are within the range of previously reported values for Europe [0.7–39 kg N_2O-N ha^{-1} year^{-1} (Liu et al., 2020)]. The contribution of N_2O from fertilization was greater in croplands than in grasslands, with 2.2 (1.7–2.8) kg N_2O-N ha^{-1} year^{-1} and 0.74 (0.63–0.86) kg N_2O-N ha^{-1} year^{-1}, respectively. The corresponding fertilization rates were 117 (104–130) kg N ha^{-1} in croplands and 67 (61–72) kg N ha^{-1} in grasslands (Table 1, Figure 2c). Temperate peatlands, particularly in Europe, are often intensively managed for agricultural production, mainly as grasslands (Leifeld & Menichetti, 2018; Tiemeyer et al., 2016; UNEP, 2022; Vasander et al., 2003). However, the average fertilizer N input on peaty grasslands remains low compared with agricultural production on mineral soils (Cui et al., 2021), which leads to a smaller fertilizer contribution to the N_2O release. Smaller N application rates might be related to the increasing awareness of peatland protection and national-specific strategies for managing peatland more sustainably. Several European countries with high GHG emissions from organic soils have implemented actions for peatland protection since the beginning of the 21st century (UNEP, 2022), which may reduce the intensity of peatland utilization for agricultural production and, in turn, limit the fertilizer N supply. Together, the average contribution of fertilizer N to N_2O emissions from agriculturally managed peatlands remains low in the temperate zone.

3.2.3 | Agriculturally managed peatlands in boreal zones

In the boreal zone, which was mainly allocated to Canada and Siberia by the classification used in our study (Figure S8), the calculated soil N_2O emissions were 1.5 kg N_2O-N ha^{-1} year^{-1} and 2.0 (1.3–2.6) kg N_2O-N ha^{-1} year^{-1} for croplands and grasslands, respectively. In both land-use types, fertilizer N addition was much smaller than in the temperate or tropical zones (Figure 2c). A significant limitation of our analysis is the very small observational data for N_2O emissions in boreal zones, particularly croplands, where productivity was limited by low temperatures. Moreover, we were unable to identify the fertilizer-derived N_2O emissions from crop production in boreal peatlands (Table 1) because of the limited fertilizer N input information. With a sufficient number of annual N_2O observations in boreal regions, we would be better able to generalize the source of soil N_2O emissions with higher confidence. We suggest that more research should focus on the boreal zone, where peatlands account for approximately 78% of the global total (Leifeld & Menichetti, 2018).

3.3 | Response of N_2O emissions to different fertilizer N input rates

Our modelled soil N_2O emissions were consistent with the field N_2O observation (RMSE = 8.3 kg N_2O-N ha^{-1} year^{-1}, R^2 = 0.98; Figure S5). The results show that the variability of N_2O emission was mainly driven by a combination of three factors, namely fertilizer N input, soil N content, and annual precipitation. Fertilizer N input was the dominant driver (57%) of the variability in soil N_2O emissions (Figure S6). To quantify the role of fertilization on soil-borne N_2O emissions, we applied the model to different fertilization rates (from 0 to 500 kg N ha^{-1} year^{-1}, with a step width of 50 kg N ha^{-1} year^{-1}) and simulated the response of soil N_2O emissions. Without fertilization, when soil N_2O emissions mainly stemmed from N released from peat decomposition and, to a minor extent, atmospheric N deposition, N_2O release increases in order of the lowest to the highest (boreal < temperate < tropical, Figure 3). The simulated soil N_2O emissions were highest, 22.7 kg N ha^{-1} year^{-1}, for croplands in managed peatlands in the tropics (Figure 3). This is probably related to the higher microbial activity under a warmer climate, leading to faster peat decomposition, faster N cycling and, therefore, higher soil N_2O production (Parn et al., 2018). A similar observation can be made for grasslands in managed peatlands, where the tropical zone again has the highest soil N_2O emissions without any N input.

With the addition of fertilizer, N_2O emissions tend to increase with N input. The response of soil N_2O emissions to fertilizer N input was strongly dependent on the climate and land use (Figure 3). For croplands on managed peatlands, the response of soil N_2O emissions to N addition is stronger in the temperate zone (3.2 ± 0.2 kg N_2O-N ha^{-1} per 100 kg N ha^{-1} input) than in the tropical (2.7 ± 0.2 kg N_2O-N ha^{-1} per 100 kg N ha^{-1} input) and boreal zones (1.9 ± 0.1 kg N_2O-N ha^{-1} per 100 kg N ha^{-1} input). For peatlands managed as grasslands, the response of soil N_2O emissions to N addition is stronger in the tropics (3.0 ± 0.2 kg N_2O-N ha^{-1} per 100 kg N ha^{-1} input) than in the temperate (1.9 ± 0.1 kg N_2O-N ha^{-1} per 100 kg N ha^{-1} input) and boreal (1.5 ± 0.1 kg N_2O-N ha^{-1} per

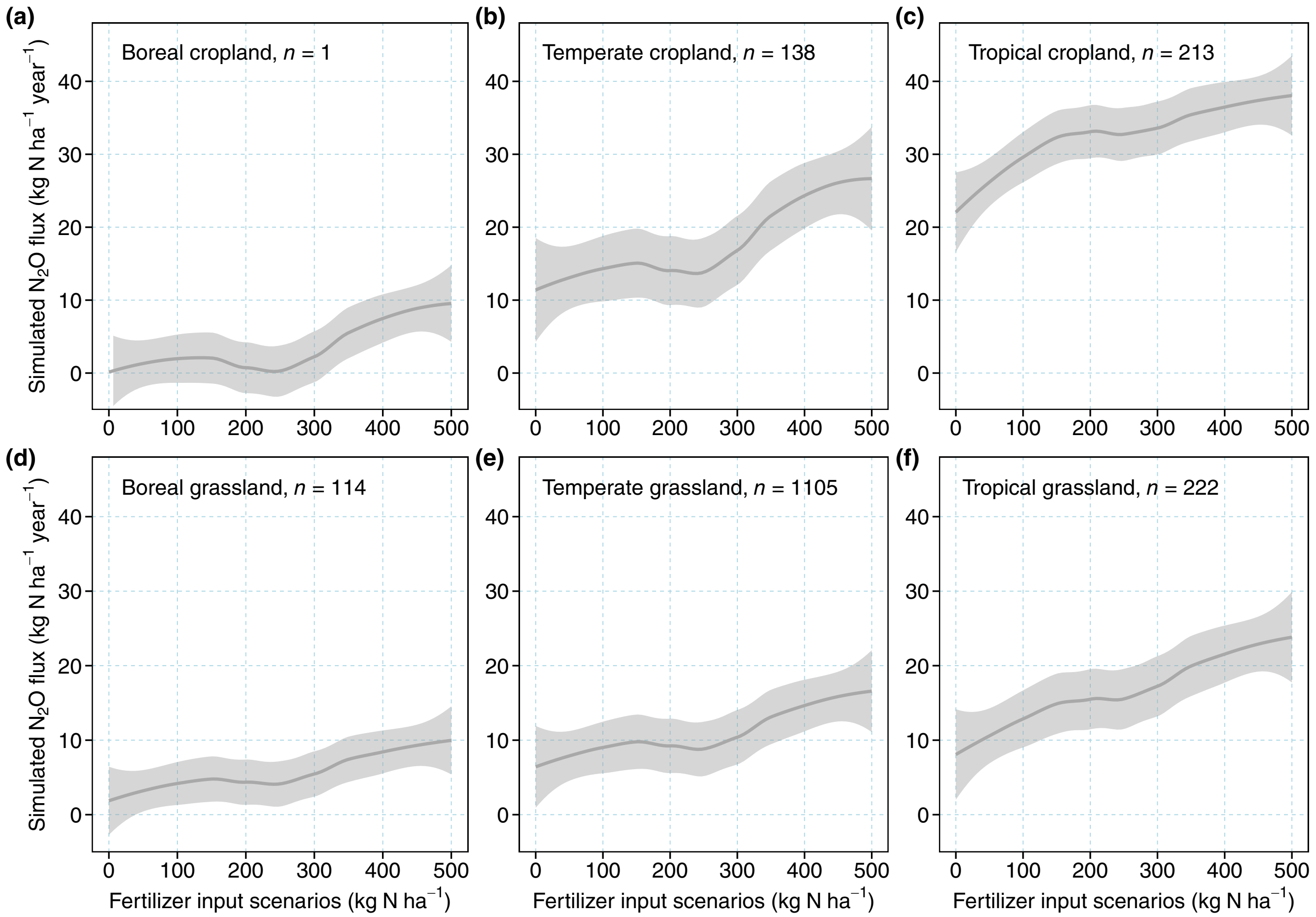

FIGURE 3 Response of N_2O emissions to different fertilizer nitrogen (N) inputs for agriculturally [croplands (a), (b), and (c); grasslands (d), (e), and (f)] managed peatlands in different climatic zones [boreal, (a), (d), temperate (b), (e), and tropical (c), (f)]. The *n* value on each panel indicates the number of data points included in the soil database. Data are shown as mean ± 95% confidence interval (CI), where the 95% CI is calculated by performing a bootstrapping procedure for simulated N_2O fluxes under each fertilizer N input scenario 1000 times. Please note that the results for boreal croplands relied on one study point.

100 kg N ha^{-1} input) climatic zones. The range of 1.5%–3.2% for the added N reflects the emissions caused by fertilization. This implies higher fertilizer-induced N_2O emissions as currently suggested by IPCC, where fertilizer emission factors are in the range of 0.5%–1.6% for mineral and organic fertilization (IPCC, 2019), respectively. The implied fertilizer-induced emissions shown above insinuate an overall lower fertilizer N-use efficiency in managed peatlands compared with mineral soils. When these findings are combined with the current amount of fertilizer N used in practice (Figure 2b), stronger N_2O mitigations can be achieved by reducing economical fertilizer N applications (with respect to crop/grass yield) in regions where fertilizer N is currently being applied at a high rate (i.e., croplands in tropical and temperate peatlands).

3.4 | N_2O reduction potential from agriculturally managed peatlands

To the best of our knowledge, we present herein the most comprehensive study on N_2O emissions from agriculturally managed peatlands, with a detailed attribution of emissions to sources. Our study revealed a release of 399–545 kt N_2O-N $year^{-1}$ from peatlands used for agricultural production, which was mainly derived from N becoming available through drainage and associated peat decomposition (Figures 2 and 4). Peat decomposition due to peatland drainage plus atmospheric N deposition together induced 337 kt N_2O-N $year^{-1}$, accounting for 73% of the overall N_2O flux from managed peatlands, and fertilizer N input induced 27% (126 kt N_2O-N $year^{-1}$). Our estimated N_2O emissions are in the upper half of the range for previous studies (122–607 kt N_2O-N $year^{-1}$), which mainly used IPCC default values to estimate soil N_2O emissions from agriculturally managed peatlands (Figure 4; Carlson et al., 2016; Frolking et al., 2011; Leifeld & Menichetti, 2018; Tubiello et al., 2016). The relatively high N_2O emissions found in this study were based on the consideration of multiple sources of N_2O emissions and a large database. Together, our findings indicate that the emission factors used hitherto may be too small in many cases.

Compared to the two other main biological GHGs, CO_2, and CH_4, there is no significant sink for atmospheric N_2O in terrestrial systems. Therefore, abatement is best achieved by attenuating known sources of N_2O emissions, particularly those from soils (Paustian et al., 2016). Our study underpins that agricultural production on peatlands is a hotspot of N_2O emission, with at least five times the N_2O flux than using the same area of mineral soil with the same fertilizer N input (Figure 2c) and the corresponding N_2O emission factor of 1% of the fertilizer N input (Bickel et al., 2006). However, worldwide, approximately 20.3 Mha of peatlands are managed for croplands and approximately 8.7 Mha for grasslands (Leifeld & Menichetti, 2018), thereby contributing greatly to feeding the growing population and to economic incomes and livelihoods. Restoring peatlands by rewetting is considered a silver bullet for overcoming their high GHG emissions (Günther et al., 2020; Humpenöder et al., 2020; Page et al., 2008). However, full restoration of all of these areas seems difficult to achieve in the short term because of economic incomes, social habits, or political strategies (Cooper et al., 2020; Goldstein, 2015; Tonks et al., 2017). Hence, lowering the fertilizer N input should be a priority for N_2O mitigation when drained agricultural use is to be continued. It is likely that fertilizer N input in cropped peatlands is in excess, owing to the large amount of N released via peat decomposition (Schothorst, 1977; Sonneveld & Lantinga, 2010; Wang, Paul, Alewell, & Leifeld, 2022) and the higher implied N_2O emission factors from fertilization, as found in this study. If the current fertilizer N input were to be reduced by, for example, 20% (as suggested by the Farm to Fork strategy of the European Commission, 2020), N_2O levels of the tropical and temperate zones could be reduced by 22.8 (11.9–35.2) and 2.3 (1.9–2.8) Mt CO_2-eq $year^{-1}$, respectively, in agriculturally managed croplands (Figure 4a) and by 0.15 (0.08–0.22) and 1.1 (0.9–1.2) Mt CO_2-eq $year^{-1}$, respectively, in agriculturally managed grasslands (Figure 4a). The cropland area on managed peatlands would have to be reduced by 1.9 Mha, or approximately 10%, to achieve the same N_2O reduction as by reducing N fertilization by 20% (Figure 4a), assuming that this would occur with rewetting, which could lower the N_2O emissions to zero (Liu et al., 2020). However, a N_2O emission reduction corresponding to the effect of a 20% fertilizer N reduction could be achieved with only about 3% of the grassland area (Figure 4b). Our research clearly indicates that efficient N_2O mitigation potentials are achievable through fertilizer N reduction in croplands, especially in tropical zones. However, for effective mitigation of N_2O emissions from temperate and boreal peatlands, reducing fertilization has a smaller potential, and management strategies for reducing peat decomposition are required (e.g. rewetting of managed peatlands, paludiculture, or mineral soil coverage) (Günther et al., 2020; Lin et al., 2022; Liu et al., 2020; Wang, Paul, Jocher, et al., 2022). These were reported to be efficient in reducing peat decomposition and N_2O emissions.

3.5 | Uncertainties of the study

Our literature-based machine learning simulation has made it possible to estimate the distribution and shares of measured N_2O emissions from managed peatlands, providing a baseline for informing N_2O mitigation policies. However, the results remain uncertain. For instance, approximately 80% of the collected N_2O data points were located in Southeast Asia and Europe, where peatlands are intensively drained for agriculture (Dohong et al., 2017; Evans et al., 2021; Tiemeyer et al., 2016). For other regions where C storage is potentially large but unknown because of the lack of data, such as the Congo Basin and Amazonia in the tropical zones or the Siberian peatlands in the boreal zone (Dargie et al., 2017; Smith et al., 2004), soil N_2O emissions remain largely unspecified. This creates uncertainty in estimating the source and distribution of soil N_2O emissions for these important peatland biomes. Another relevant issue is the location of the transition between the temperate and boreal zones, which hinges on the chosen classification. This is notably true for countries in Scandinavia. To underscore the challenges associated with the climate classification, we recalculated

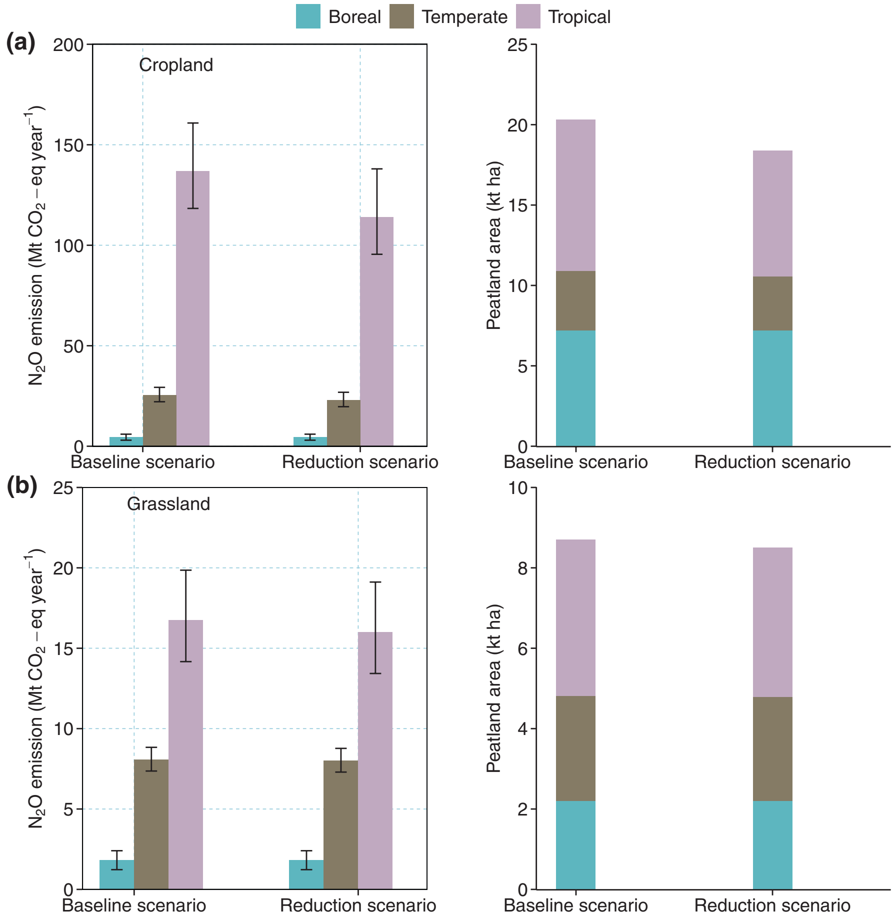

FIGURE 4 Comparison of N_2O emissions from croplands (a) and grasslands (b) for two different emission reduction options, reducing fertilizer N input by 20% (left panels), or reducing the managed peatland area to achieve the same emission reduction but without reducing fertilization on the remaining managed peatlands area (right panel). For both options, the baseline scenario denotes a constant area of managed peatlands and the current fertilizer N input; the reduction scenario denotes a constant managed peatland area and a 20% reduction of fertilizer N input. The results are shown separately for croplands (a) and grasslands (b).

the results depicted in Figure 2 using the Köppen-Geiger climate classification (Kottek et al., 2006). This recalculation led to the redefinition of 550 data points (primarily from Finland, Norway, and Sweden—see details in Table S6) from the temperate zone to the boreal zone. As illustrated in Figure S9, the recalculated N_2O emissions were significantly higher in the boreal zone (2.5 and 9.8 kg N ha year^{-1} for grasslands and croplands, respectively, as compared to 1.5 and 2.0 kg N ha year^{-1} based on IPCC classification) and the temperate zone (11.3 and 28.1 kg N ha year^{-1}) for grasslands and croplands, respectively, compared to 7.5 and 16.6 kg N ha year^{-1} obtained using the IPCC climate classification. A similar trend was also observed for the fertilizer N input.

3.6 | Outlook

The above considerations highlight two main fields for further development. First, the indicated N_2O emission reduction potential via reduced N fertilization in agriculturally managed croplands, particularly in the tropical zone, calls for targeted experiments to evaluate whether lowering fertilization levels has undesired repercussions on crop yield and quality. Second, we have shown that the aggregated results are very sensitive to the choice of underlying climate classification. For instance, high emissions at sites in southern Scandinavia would, depending on climate classification, be allocated either to the boreal or temperate zones (Figure 2; Figure S9). This can lead to diverging interpretations and, eventually, suggest different actions to mitigate N_2O emissions in countries such as Finland, Sweden, or Norway. To preclude potential misunderstandings, it is imperative to reconsider climate classification in more detail and establish an updated consensus scientific community.

AUTHOR CONTRIBUTIONS

Yuqiao Wang: Conceptualization; data curation; formal analysis; methodology; resources; visualization; writing – original draft. **Pierluigi Calanca:** Formal analysis; methodology; validation; writing – review and editing. **Jens Leifeld:** Conceptualization; methodology; supervision; validation; writing – review and editing.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data and R-script that support the findings of this study are openly available in Zenodo at https://doi.org/10.5281/zenodo.10411079.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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