Characterization of atmospheric nitrous oxide emissions from global agricultural soils

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Received: 30 August 2019 / Accepted: 13 November 2019 / Published online: 23 November 2019
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Abstract

Nitrous oxide (N_2O) is a potent greenhouse gas with an atmospheric lifetime of ~ 114 years. Agriculture activities are the main sources for N_2O emission into the atmosphere by human activities. Global N_2O emissions into the atmosphere are projected to increase in the coming years as demand for food, fibre and energy increases owing to increasing global population. Here, a statistical model (N_2O_STAT) is developed for characterizing atmospheric N_2O emissions from agricultural sources. We obtained N_2O emissions and physicochemical variables (i.e. air temperature, soil temperature, soil moisture, soil pH, and N input to the soil) from published journal articles since 2000. A statistical model was developed by expressing a multiple linear regression equation between N_2O emission and the physicochemical variables. The model was evaluated for 2012 N_2O emissions. Results of the model are compared with other global and regional N_2O models (e.g. EDGAR, EPA/USGS, and FAOSTAT). In comparison with other data sets, the model generates a lower global N_2O estimate by 9–20% (N_2O_STAT : $3.75 \text{ Tg N yr}^{-1}$; EDGAR: $4.49 \text{ Tg N yr}^{-1}$; FAO: $4.07 \text{ Tg N yr}^{-1}$), but is $\sim 25\%$ higher when compared to Bouwman et al. (Glob Biogeochem Cycles 16:1–9. <https://doi.org/10.1029/2001gb001812>, 2002) ($2.80 \text{ Tg N yr}^{-1}$). We also performed a region-based analysis (USA, India, and China) using the N_2O_STAT model. For the USA, our model produces an estimate that ranges from -13 to $+32\%$ in comparison with other published data sets. Meanwhile, the N_2O_STAT model estimate for India shows N_2O emissions between -56 and $+14\%$ when compared to other data sets. A much lower estimate is seen for China, where the model estimates N_2O emissions 38 – 177% lower than other data sets. The N_2O_STAT model provides an opportunity to predict future N_2O emissions in a changing world.

Keywords Nitrous oxide · Emissions · Agricultural soil · Statistical model

1 Introduction

The largest human influence on climate since the end of the twentieth century is the emission of greenhouse gases to the atmosphere. In addition to carbon dioxide (CO_2), nitrous oxide (N_2O) is one of the most important greenhouse gases that has a global warming potential (GWP) of ~ 300 for a 100-year timescale [1]. N_2O also contributes to the destruction of ozone in the stratosphere [2]. The

lifetime of N_2O in the atmosphere is ~ 114 years, indicating its long-term influence on a planetary scale [3].

Since 1978, globally averaged N_2O concentrations in the atmosphere have been measured at Mauna Loa, Hawaii. Prior to 1978, N_2O levels were extracted from ice cores from Antarctica. N_2O concentrations in the atmosphere were relatively stable until the start of the Industrial Revolution [4]. Since that time, N_2O concentration has increased by 18%, from ~ 270 ppb to the current value of ~ 331 ppb

Electronic supplementary material The online version of this article (<https://doi.org/10.1007/s42452-019-1688-5>) contains supplementary material, which is available to authorized users.

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SN Applied Sciences (2019) 1:1662 | <https://doi.org/10.1007/s42452-019-1688-5>

(Fig. 1). This increase is primarily due to intensive human activities, particularly related to agriculture.

Ciais et al. [5] have estimated the yearly emission of N_2O to be $17.9 \text{ Tg N yr}^{-1}$ for the period 2006–2011. N_2O emissions from natural sources are $11.0 \text{ Tg N yr}^{-1}$, which includes sources from land and oceans. Agricultural activities are the primary anthropogenic source of N_2O , contributing to 5.6 Tg N yr^{-1} [6]. With increasing food, fibre and energy production, along with climate change and agricultural intensification, N_2O emissions from soils have increased since 1990, from 3.5 Tg N yr^{-1} to 4.1 Tg N yr^{-1} [7].

During the period 1961–2010, global N_2O emissions from manure usage have grown from 1.17 to $2.03 \text{ Tg N yr}^{-1}$ at an average rate of $1.10\% \text{ yr}^{-1}$ [8]. Meanwhile during the same period, N_2O emissions from synthetic fertilizers have increased from 0.14 to $1.40 \text{ Tg N yr}^{-1}$ at an average rate of $3.90\% \text{ yr}^{-1}$ globally [9]. This indicates that synthetic fertilizers will have a greater contribution to N_2O emission than manure within less than 10 years [8]. Besides agriculture, other sources such as fossil fuel combustion, industrial processes, and biomass burning also contribute to the total N_2O emissions, but these are all relatively small sources.

Intensive fertilizer use has increased the emissions of reactive nitrogen compounds, including N_2O from soils through nitrification and denitrification processes (Supplementary Figure 1S). Nitrification is the aerobic microbial oxidation of ammonium or ammonia to nitrite followed by oxidation of nitrite to nitrate. It is an important process in the nitrogen cycle in which N_2O is generated as a by-product that leaks from microbial cells into soil and eventually into the atmosphere [6]. Denitrification is a microbially facilitated process that leads to significant N losses from

agricultural systems. Through denitrification, nitrate and nitrite are reduced, and a portion converted into N_2O [10].

The ratios of $\text{N}_2\text{O}/\text{NO}_3^-$ (nitrification) to $\text{N}_2\text{O}/\text{N}_2$ (denitrification) products are important parameters determining the change of global budget, and they are affected by various physical, chemical and biological factors and their interacting effects [11]. To develop a predictive model for N_2O emission under different agroecosystems, climate variables, soil characteristics, and cropping practices must be considered. Granli and Bockman [11] provided a review of the factors that control N_2O emissions from soil, including moisture and aeration, temperature, soluble and decomposable carbon, soil and fertilizer

Table 1 Variables that affect product ratios during nitrification and denitrification in agricultural soils [11, 34]

Process	Variable	Effect
Nitrification		<i>Will increase $\text{N}_2\text{O}/\text{NO}_3^-$ ratio</i>
	$[\text{O}_2]$	Decreasing O_2 concentration
	$[\text{H}_2\text{O}]$	Increasing H_2O above field capacity
	$[\text{NH}_4^+]$	Low NH_4^+ concentrations
	pH	Increasing or decreasing pH
Denitrification	Temperature	Increasing temperature
		<i>Will increase $\text{N}_2\text{O}/\text{N}_2$ ratio</i>
	$[\text{NO}_3^-]$ or $[\text{NO}_2^-]$	Increasing oxidant
	$[\text{O}_2]$	Increasing O_2
	Carbon	Decreasing C availability
	pH	Decreasing pH
	Temperature	Decreasing temperature
	Enzyme status	Low N_2O reductase activity
	$[\text{H}_2\text{O}]$	Decreasing between 60 and 90% WFPS

Fig. 1 Atmospheric N_2O concentration trend from the combined Global Monitoring Division data set for the period 1977–2018 [33]

nitrogen, soil pH and salinity. Table 1 summarizes the variables that affect product ratios during nitrification and denitrification in agricultural soils. In nitrification, N_2O emission will increase with decreasing O_2 concentration, increasing water above field capacity, low NH_4^+ concentrations, deviations of pH from near neutrality, and increasing temperature. The production of N_2O by denitrification is enhanced in conditions characterized by high nitrate, high C availability, low pH, high temperature, low N_2O reductase activity, and 60–90% water-filled pore space (WFPS) [12–14].

Uncertainties of estimates of sources and sinks still exist in global N_2O budget, especially from agricultural soils [15]. Inadequate understanding of the mechanisms controlling N_2O emission from agricultural soils may be responsible for limited attention to agriculture as a major contributor of the increasing atmospheric N_2O . With increasing food and energy production, along with climate change and agricultural intensification, N_2O emissions from soils and groundwater are likely to increase, indicating the need for an updated global budget for N_2O that accounts for these recent changes.

The goal of this project is to develop a statistical model to predict N_2O emissions from agricultural soils containing synthetic and organic fertilizers using physicochemical properties of the system from different regions. We also analyse the spatial distribution of N_2O emissions from agricultural soils and compare the results with other modelled emission inventories (i.e. EDGAR v.4.3.2, EPA, and FAOSTAT).

2 Methodology

Based on literature review, we found four variables of importance in controlling N_2O emissions from soil: (1) soil moisture, (2) soil and air temperature, (3) synthetic and organic fertilizer usage, and (4) soil pH [16]. The highest N_2O emissions are usually due to high temperature and ample precipitation because increasing soil temperature stimulates microbial activities related to nitrification and denitrification. We performed a series of statistical analyses utilizing the RStudio statistical software (<https://github.com/rstudio/rstudio>) to examine the distribution of data and to fit an appropriate regression model with N_2O as the response (dependent) variable and other variables as independent predictors. We then used Integrated Land and Water Information System (ILWIS) v.3.31 Academic (<https://www.itc.nl/ilwis/download/ilwis33/>), a GIS tool to prepare the global data sets and apply the statistical model to predict N_2O emissions.

2.1 Data collection

Data collection includes two parts: (1) data sets for developing the statistical model (Table 2) and (2) global data sets for extrapolating the results to larger areas (Table 3). For the statistical model, we conducted a literature review regarding agricultural soil N_2O emission (published after 2000). Data were derived from two sources: (1) field data for developing the statistical model and (2) global data for extrapolating the results to larger areas. The complete data set is compiled in Supplementary Table 1S.

2.2 Model development

Based on the statistical analysis, we found that the data distribution, shown as the histogram of N_2O emissions (Fig. 2a), was skewed to the right. To normalize the data, we transformed them to logarithmic values (Fig. 2b), which were normally distributed. Then, we used a multiple linear regression model to fit the response variable (the log of N_2O emissions), using the physicochemical variables as predictors. The statistically derived model (hereinafter $\text{N}_2\text{O_STAT}$) to predict N_2O emissions from agricultural soils is mathematically expressed as the following:

$$\text{N}_2\text{O emission} = \left(\exp \left[A + B \times T_{\text{soil}} + C \times \text{SM} + D \times \text{pH}_{\text{soil}} + E \times \text{N input} + F \times \text{Fertilizer type} \right] \right) \times \frac{28}{44}$$

where T_{soil} refers to soil temperature ($^{\circ}\text{C}$), SM soil moisture (%), and the coefficients A , B , C , D , E , and F are statistically derived parameters (Table 4). N input is differentiated by synthetic or organic fertilizer and is expressed as $\text{kg N ha}^{-1} \text{ yr}^{-1}$. The units for predicted N_2O emission are $\text{kg N ha}^{-1} \text{ yr}^{-1}$. Initially, air temperature was included as a variable in the model, but it was later omitted from the equation because it had an insignificant correlation with N_2O emission.

Table 4 summarizes the coefficients and p values of each variable. The residual standard error is 0.928, and R -squared is 0.2. The F test shows that this multivariate linear regression model is statistically significant at 90% confidence level. Based on the p value, the soil moisture, soil pH, and fertilizer type are statistically significant. Notably, the magnitude of nitrogen input does not have a significant influence on the N_2O emission rate. This may seem counterintuitive, but N_2O emissions are produced by nitrification and denitrification, and nitrogen concentrations may be the limiting factor for these reactions only when the levels of soil nitrogen are low. Other factors are likely to be limiting when soil nitrogen concentrations are at agronomic levels [6]. Yu and Zhuang [16] corroborate these findings using their trait-based biogeochemistry

Table 2 Data for statistical model development

Parameter	Unit
N ₂ O emissions	kg N ha ⁻¹ year ⁻¹
Air temperature	°C
Soil temperature	°C
Soil pH	–
Soil moisture	%
Fertilizer N content usage	kg N ha ⁻¹ year ⁻¹
Manure N content usage	kg N ha ⁻¹ year ⁻¹

Table 4 Summary of the statistical model

Variable	Parameter	Coefficient	<i>p</i> value
A	Intercept	1.3437	0.0295
B	Soil temperature	0.0291	0.0515
C	Soil moisture	0.0196	0.0003
D	Soil pH	–0.3454	0.0007
E	Nitrogen input	0.0003	0.5802
F	Fertilizer type	0.4567	0.0073

Table 3 Global data set used for prediction

Parameter	Data sets
Soil temperature; soil pH	Harmonized World Soil Database v 1.2 http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soil-database-v12/en/
Soil moisture	The Global Soil Dataset for Earth System Modeling http://globalchange.bnu.edu.cn/research/soilw
Air temperature	ERA-Interim Global Atmospheric Reanalysis https://www.ecmwf.int/en/forecasts/datasets/archive-datasets/reanalysis-datasets/era-interim
Cropland cover, fertilizer usage, manure usage	EarthStat's Cropland and Pasture Area (with modification) http://www.earthstat.org/

model to estimate global N₂O emissions that were more sensitive to temperature and precipitation and less sensitive to soil organic carbon and nitrogen contents.

2.3 Model diagnostics

After running the regression analysis, we verified that N₂O_STAT works well for fitting the data and complies with the assumptions of linear regression models. A two-step model diagnostic was performed by analysing the variance and distribution of the residuals (Supplementary Figure 2S). The equal distribution with no distinct patterns of residuals around the horizontal provides a good indication

of the likelihood of a linear relationship. Additionally, the residuals are well fitted on the straight line, indicating that the data are indeed normally distributed. The outliers indicated by residuals that are far from the line were excluded in further analysis.

We tested different model forms, i.e. linear form (classical emission factor approach) and exponential form (this study). The exponential form had $r^2 = 0.2$, and residual standard error = 0.93, which are better than in the linear model ($r^2 = 0.14$ and residual standard error = 1.02), suggesting that the exponential model is preferred in modelling the N₂O emission.

Fig. 2 **a** Histogram of N₂O emission and **b** log of N₂O emission

2.4 Other N₂O emission inventories

2.4.1 EDGAR

The Emission Database for Global Atmospheric Research compiles anthropogenic global N₂O emissions and trends from 1970 to 2012 based on international statistics and emission factors [17]. N₂O emissions from fertilizer are based on the estimation from the International Fertilizer Industry Association (IFA) and the Food and Agriculture Organization Statistics Division (FAOSTAT). The N₂O emission factor for direct soil emissions from the use of synthetic fertilizer and from manure and from crop residues is based on IPCC Guideline [7]. For the comparison purposes, we use the 2012 global N₂O data set for agricultural soils (subsector 4C + 4D).

2.4.2 EPA greenhouse gas inventory report and USGS county-level data sets

We calculated N₂O emission from agriculture soils over the continental USA based on subsectors described in the EPA report [18]. The subsector emissions are taken from the county-level information compiled by USGS from the 2012 census of agriculture [19, 20]. The county-level information consists of fertilizer usage, manure applications, and crop residue. Then we calculated the emissions which are interpolated to generate a spatial distribution of the emission for the USA.

2.4.3 FAOSTAT (<http://www.fao.org/faostat/en/>)

Food and Agriculture Organization of the United Nations develops methods and standards for food and agriculture statistics, provides technical assistance services, and disseminates data for global monitoring. It provides the N₂O global emissions from synthetic fertilizers, manure applied to soils, manure left on pasture, and crop residues in 2012.

3 Results

3.1 Global

After calculating the coefficients for all variables, we applied the N₂O_STAT model for each grid cell and generated a global map for N₂O emissions. Figure 3a gives the spatial distribution of global N₂O emission from agricultural soils calculated using N₂O_STAT in kg N yr⁻¹ grid cell⁻¹. The resolution of this map is 5 arc-minute by 5 arc-minute, which is equivalent to 8464 ha. The average N₂O emission from agricultural soils is ~9000 kg N yr⁻¹ grid cell⁻¹, which is comparable to average values of

1 kg ha⁻¹ for agricultural soils, reported by Kim et al. [21] and Shcherbak et al. [22].

Figure 3b shows spatial distribution of global N₂O emission from agricultural soil based on EDGAR. Total annual global N₂O emissions from N₂O_STAT and EDGAR are 3.75 Tg N yr⁻¹ and 4.49 Tg N yr⁻¹, respectively. It is encouraging to see that, in general, the model captures the global spatial pattern in N₂O emissions well. Figure 3c shows the absolute difference between N₂O_STAT and EDGAR. In comparison with EDGAR, N₂O_STAT gives lower N₂O emission values in North America, South America, India, and China, while higher values in Eastern Europe and mid-Africa.

3.2 Continental USA, India, and China

Figure 4 provides the comparison between the results from N₂O_STAT, EDGAR, and EPA/USGS over the continental USA (hereafter listed as USA). Total N₂O emissions from agricultural soils in the USA calculated from N₂O_STAT, EDGAR, and EPA/USGS are 0.35 Tg N yr⁻¹, 0.43 Tg N yr⁻¹, and 0.46 Tg N yr⁻¹, respectively. N₂O_STAT performs well in capturing the spatial pattern and the total annual emission. Figure 5 gives the absolute difference of N₂O emissions between N₂O_STAT model and EDGAR and between N₂O_STAT and EPA/USGS. Based on Fig. 5a, N₂O_STAT underestimates N₂O emission in the Midwest region of the USA and overestimates emissions in the south-eastern region, compared with EDGAR. Figure 5b shows that N₂O_STAT gives lower N₂O emission values in northern Texas, California, Florida, and states around Lake Michigan, while in other areas the values are comparable to EPA/USGS.

Figure 6 and Table 5 show close agreement with the N₂O_STAT estimate of agricultural soil emissions for India when compared with EDGAR (~ -14%), the finely resolved N₂O emission estimate by Aneja et al. [23] (~ 17%), and FAOSTAT (~ -7%). Moreover, Table 5 compares the finely resolved N₂O emission for India with other published studies. The Aneja et al. [23] results are higher than the results of Garg et al. [24] and Sharma et al. [25], perhaps due to the selection of higher emission factors by Aneja et al. [23]. Overall, we believe that Aneja et al. [23] is more appropriate because these researchers used the activity-level data at district levels and chose the emission factors suitable for Asian context.

Meanwhile for China, our estimate using N₂O_STAT is 2.3–2.8 times lower than those estimated by EDGAR and FAO. Our N₂O emission estimate, however, is in good agreement with Gao et al. [26] and Zhou et al. [27] being 2% higher and 38% lower, respectively. These two studies employ different methods in estimating N₂O emission from Chinese agricultural soils. Gao et al. [26] studied N₂O direct emissions from croplands by using localized

Fig. 3 Comparison between the results from **a** N₂O_STAT, **b** EDGAR, and **c** absolute difference between the two models (in ton N₂O yr⁻¹ grid cell⁻¹). The maps are generated using ILWIS v3.8.5 (<https://52north.org/software/software-projects/ilwis/ilwis-3/>)

emission factors, while Zhou et al. [27], in addition to using regional emission factors, utilized high-resolution activity data and localized parameters.

4 Discussion

We have developed a novel way to approach global nitrous oxide emissions from agricultural soils (N₂O_STAT). We have also used three case studies (USA, India,

Fig. 4 Comparison between the results from **a** N₂O_STAT, **b** EDGAR, and **c** EPA/USGS (in ton N₂O yr⁻¹ grid cell⁻¹). The maps are generated using ILWIS v3.8.5 (<https://52north.org/software/software-projects/ilwis/ilwis-3/>)

and China) to strengthen our model development. Unlike all previous N₂O emission studies, our approach relies on global emission measurements rather than emission factors and activity data.

Table 5 summarizes the data comparison between N₂O_STAT, EDGAR, EPA/USGS, and FAOSTAT for N₂O emission from agricultural soils for the USA, India, China, and globally. The FAOSTAT, EDGAR, and EPA estimates are slightly different, although consistent given the large uncertainties in the IPCC default methodologies [9]. Tubiello et al. [9] compared N₂O emission from four databases. The results

show that the EPA 2006 and EPA 2011 provided the highest values, while FAOSTAT gave the lowest, consistent with our study.

In developing N₂O_STAT, we collected data for published N₂O emissions that correspond to the use of fertilizer and manure on particular soils (Supplementary Table 15). N₂O_STAT, however, does not include ancillary emissions from leaching and surface runoff, as such information is not often available. As a result, our estimate is only driven by the direct N₂O emissions from agricultural soils. This may represent a fundamental difference when

Fig. 5 Absolute difference of N₂O emissions over CONUS between **a** N₂O_STAT and EDGAR, **b** between N₂O_STAT and EPA/USGS (in ton N₂O yr⁻¹ grid cell⁻¹). The maps are generated using ILWIS v3.8.5 (<https://52north.org/software/software-projects/ilwis/ilwis-3/>)

comparing the results across different data sets. EDGAR and FAOSTAT incorporate both direct and indirect N₂O emissions in estimating the global emissions. Additionally, the agricultural sources from which the emissions are tabulated for our model are different from other data sets. For example, EDGAR includes rice cultivation and crop residue in its estimate [28]. Another key difference between N₂O_STAT and other models lies in the methodology of collecting the model inputs. The N₂O_STAT model uses the measured N₂O emissions reported from field experiments, whereas the other approaches derive their emissions by using intermediate data sets (e.g. fertilizer production, livestock counts) and apply emission factors to the corresponding data sets. The N₂O_STAT model only considers physicochemical variables of the emissions, excluding the soil management practices that might contribute to the emissions. In addition, the methods used to measure

N₂O emissions in the field were different from one study to another; these differences are not taken into consideration in developing N₂O_STAT.

The region-based analysis (USA, India, and China) indicates that our model gives lower estimates than other modelling efforts. The global N₂O agricultural soil emission from N₂O_STAT estimate is 9–20% lower than EDGAR and FAOSTAT. The major differences, as observed in Fig. 3c, are most prominent in India and China. In India, negative differences are depicted in Fig. 6c in the northern and central regions, while the positives are mainly to the west and south of the subcontinent. However, the finely resolved agricultural emissions of N₂O in India [23], as well as from EDGAR and FAOSTAT, agree well with N₂O_STAT (< 20% differences). It is to be noted that the estimate from Aneja et al. [23] was calculated for 2003. Despite this difference, there are similarities between these data sets with respect

Fig. 6 Comparison between the results from **a** N₂O_STAT, **b** EDGAR, and **c** the absolute difference between N₂O_STAT and EDGAR (in $\text{ton N}_2\text{O yr}^{-1} \text{ grid cell}^{-1}$). The maps are generated using ILWIS v3.8.5 (<https://52north.org/software/software-projects/ilwis/ilwis-3/>)

to the areas from which high emissions are estimated. Such similarities are not observed when we compared our model estimate with EDGAR.

Our approach is subject to uncertainty. In particular, our statistical analysis was restricted to parameters which were available in the measurement literature and in global databases. Thus, the analysis did not include parameters such as soil composition and porosity, which could also influence N₂O emissions. We also do not take into account short-term changes in moisture and temperature which may result in enhanced N₂O emissions. Further, data were

not available to systematically incorporate differences in agricultural practices, such as the cultivation of more than one crop per year, or the use of multiple fertilizer applications in a year. This may account for some of the difference between our estimates and other estimates for China, where two crops are grown per year in many places.

Nevertheless, previous N₂O emissions inventory approaches are also subject to large uncertainties. Our literature survey identified N₂O emission factors from less than 0.1 to almost 10 $\text{kg N}_2\text{O-N kg}^{-1} \text{ N applied}$ [29, 30]. This demonstrates the difficulty of using an emission

Table 5 Summary of N₂O emission from different inventories

Emission inventory	N ₂ O (Tg N yr ⁻¹)			
	Global	US	India	China
N ₂ O_STAT	3.75	0.400	0.412	0.300
EDGAR	4.49	0.432	0.468	0.832
FAOSTAT	4.07	0.350	0.440	0.686
Bouwman et al. [32]	2.80	–	–	–
EPA/USGS	–	0.457	–	–
EPA Report	–	0.529	–	–
Aneja et al. [23]	–	–	0.344	–
Garg et al. [24]	–	–	0.181	–
Sharma et al. [25]	–	–	0.226	–
Gao et al. [26]	–	–	–	0.294
Zhou et al. [27]	–	–	–	0.414

factor approach to compute N₂O emissions. In fact, diagnostic tests for our model indicated that N₂O emissions are a nonlinear function of N input [22]. N₂O_STAT can be used to estimate a median value for the N₂O emission factor by calculating the ratio between N₂O emission and applied N fertilizer in every grid cell of the map. We calculated the N₂O emission factor for USA. In our calculation, we distinguished the two sources of N₂O emissions, i.e. synthetic fertilizer and organic fertilizer, and determined emission factors for each of these sources. Our results suggest that for the USA, the median values for the emission factor for synthetic fertilizer and organic fertilizer are 1.03% and 1.52%, respectively, based on the N input from the fertilizer. The emission factor for synthetic fertilizer is comparable to those from Stehfest and Bouwman [12] (0.9%) and De Klein et al. [31] (1.0%).

5 Conclusion

N₂O_STAT is a statistical model developed for characterizing atmospheric N₂O emissions from agricultural soils. We obtained N₂O emissions and physicochemical variables (i.e. air temperature, soil temperature, soil moisture, soil pH, and N input to the soil) from published journal articles since 2000. In comparison with other data sets, the model generates a lower global N₂O estimate by 9–20% (N₂O_STAT: 3.75 Tg N yr⁻¹; EDGAR: 4.49 Tg N yr⁻¹; FAO: 4.07 Tg N yr⁻¹), but is ~ 25% higher when compared to Bouwman et al. [32] (2.80 Tg N yr⁻¹). A region-based analysis (USA, India, and China) using the N₂O_STAT model produces an estimate for the USA that ranges from – 13 to + 32% in comparison with other published data sets. Meanwhile, the N₂O_STAT model estimate for India shows N₂O emissions between – 56 and + 14% when compared to other data sets. A much lower estimate is seen for China,

where the model estimates for N₂O emissions are 38–177% lower than other data sets.

The N₂O_STAT uses measured values for N₂O emissions including N content in the fertilizer to develop the model. The correlations between N₂O emissions and most physicochemical variables are at a high significance level (90%), suggesting that these variables are likely affecting the emissions despite excluding other variables. Moreover, the N₂O_STAT model provides an opportunity to predict future N₂O emissions in a changing world. This statistical model provides an innovative and relatively simple way to estimate global N₂O emission from agricultural soils.

The underestimation of N₂O emissions in comparison with other data sets and the fact that N₂O_STAT may be still missing some key N inputs to its variables should be taken into account in future work. Parameterization of soil biological activity would more fully represent the processes governing the N₂O emissions.

Acknowledgments Support for this work was provided by U.S. GFDL-NOAA project NOAA CPO AC4. We thank Dr. Larry Horowitz and Dr. Fabien Paulot for their ongoing discussions on the project. We also thank Dr. Francesco Tubiello, UN Food and Agriculture Organization, for discussions of our results.

Author contributions The five co-authors contributed equally to the work; however, VPA and WHS jointly supervised the work. AN prepared the global emission maps. All authors reviewed the manuscript. QL and AN performed the statistical analysis related to the modelling framework.

Compliance with ethical standards

Conflict of interest The authors declare no competing interests.

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