Measurement of N_2O emissions over the whole year is necessary for estimating reliable emission factors

Ziyin Shang[a*], Mohamed Abdalla[a], Matthias Kuhnert[a], Fabrizio Albanito[a], Feng Zhou[b], Longlong Xia[c], Pete Smith[a]

[a] Institute of Biological and Environmental Sciences, University of Aberdeen, 23 St Machar Drive, Aberdeen AB24 3UU, UK.

[b] Sino-France Institute of Earth Systems Science, Laboratory for Earth Surface Processes, College of Urban and Environmental Sciences, Peking University, Beijing, 100871, P.R. China.

[c] Institute for Meteorology and Climate Research (IMK-IFU), Karlsruhe Institute of Technology, Garmisch-Partenkirchen 82467, Germany.

*Corresponding Author:

Ziyin Shang, Phone: +44 (0)1224 272702, Fax: +44 (0)1224 272702, Email: ziyin.shang@abdn.ac.uk

Author Emails:

ziyin.shang@abdn.ac.uk (Ziyin Shang), mabdalla@abdn.ac.uk (Mohamed Abdalla), matthias.kuhnert@abdn.ac.uk (Matthias Kuhnert), f.albanif@abdn.ac.uk (Fabrizio Albanito), zhouf@pku.edu.cn (Feng Zhou), longlong.xia@kit.edu (Longlong Xia), pete.smith@abdn.ac.uk (Pete Smith)

Abstract

Nitrous oxide emission factors (N_2O-EF, percentage of N_2O-N emissions arising from applied fertilizer N) for cropland emission inventories can vary with agricultural management, soil properties and climate conditions. Establishing a regionally-specific EF usually requires the measurement of a whole year of N_2O emissions, whereas most studies measure N_2O emissions only during the crop growing season, neglecting emissions during non-growing periods. However, the difference in N_2O-EF (ΔEF) estimated using measurements over a whole year (EF_{wy}) and those based on measurement only during the crop-growing season (EF_{gs}) has received little attention. Here, we selected 21 studies including both the whole-year and growing-season N_2O emissions under control and fertilizer treatments, to obtain 123 ΔEFs from various agroecosystems globally. Using these data, we conducted a meta-analysis of the ΔEFs by bootstrapping resampling to assess the magnitude of differences in response to management-related and environmental factors. The results revealed that, as expected, the EF_{wy} was significantly greater than the EF_{gs} for most crop types. Vegetables showed the largest ΔEF (0.19%) among all crops (0.07%), followed by paddy rice (0.11%). A higher ΔEF was also identified in areas with rainfall ⩾600 mm yr^{-1}, soil with organic carbon ⩾1.3% and acidic soils. Moreover, fertilizer type, residue management, irrigation regime and duration of the non-growing season were other crucial factors controlling the magnitude of the ΔEFs. We also found that neglecting emissions from the non-growing season may underestimate the N_2O-EF by 30% for paddy fields, almost three times that for non-vegetable upland crops. This study highlights the importance of the inclusion of the non-growing season in the measurements of N_2O fluxes, the compilation of national inventories and the design of mitigation strategies.

Capsule

Fallow-season N_2O emissions must be included when calculating emission factors (EFs); neglecting them lowers the EFs by 30% for paddy rice and 10% for non-vegetable crops.

Key words: nitrous oxide, greenhouse gas, fallow, residual fertilizer N, nitrogen use efficiency

1 Introduction

Nitrous oxide (N_2O) is a long-lived greenhouse gas (GHG) with a mean atmospheric lifetime of ~120 years and has a global warming potential (GWP) of ~300 times that of CO_2 over a 100-year period (Myhre et al., 2014). N_2O is the most significant ozone-depleting substance and is predicted to remain the largest during the 21st century (Ravishankara et al., 2009). About 50% of global anthropogenic N_2O emissions are from agricultural soils, and the percentage has been rising since the 1950s, due to the widespread application of synthetic nitrogen (N) fertilizers (Myhre et al., 2014; Shang et al., 2019). Microbial nitrification and denitrification in managed and natural soils contribute approximately 70% of globalN_2O emissions (Braker and Conrad, 2011). Previous studies have shown that these two processes are regulated mainly by available N pools (synthetic or organic), soil characteristics and environmental conditions (e.g., soil temperature, water content, bulk density and pH) (Abdalla et al., 2009; Butterbach-Bahl et al., 2013; Zhou et al., 2015). An inventory framework was devised by the Intergovernmental Panel on Climate Change (IPCC) to quantify the impacts of N availability and other environmental factors on N_2O emissions from agricultural soils using a N_2O emission factor (N_2O-EF) approach at regional scale (IPCC, 2000, 2006).

Emission factors (EFs) are a pragmatic approach, widely used for the compilation of national GHG inventories. The N_2O-EF is the percentage of N_2O-N emissions arising from applied N from synthetic and organic fertilizers. The IPCC Tier 1 approach uses a global default EFs, but at Tier 2 these default values can be replaced by country-specific EFs , based on local measurements covering an entire year, including growing and non-growing (fallow) seasons, reflecting the varying impacts of environment and management over time (IPCC, 2000, 2006; Wang et al., 2019). The non-growing period, or fallow season, is a period of the year when no crop is growing in arable lands and occurs between crop harvest and the sowing or transplanting of the following crop. Since there can be multiple cropping seasons within a year, e.g., rice-wheat rotation during a year in the Chinese Taihu Lake region (Zhao et al., 2012), the non-growing season is the sum of the multiple fallow periods for each crop of the rotation. However, emission measurements from most field studies, from which the EFs are derived, often only cover a crop growing season (EF_{gs}), and only a few studies have noted differences (ΔEF) between EF_{gs} and those based on emissions measured over a whole year (EF_{wy}): these cases being, e.g. vegetable fields in Spain (Sanchez-Martin et al., 2010) and paddy rice in China (Liu et al., 2016). Although the ΔEF should not be neglected, many current regional N_2O inventories (Bouwman et al., 2002b; Cayuela et al., 2017; Stehfest and Bouwman, 2006) are based on the EF_{gs} rather than the EF_{wy}. None of these studies provide an assessment of whether the difference, ΔEF, exists ubiquitously in global agroecosystems.

The difference between EF_{gs} and EF_{wy} depends on residual fertilizer N, and other management and environmental factors affecting nitrification and denitrification processes during fallow periods. Vegetables generally have lower nitrogen use efficiency (NUE, yield N/fertilizer N) compared to other crops (e.g., maize, wheat and paddy rice) (Garnett et al., 2013), which may contribute to high residual fertilizer-induced N_2O emissions during the fallow periods, accounting for 15%-50% of the annual total (Pfab et al., 2011; Sanchez-Martin et al., 2010). Field drainage after rice harvest may change soil conditions from anaerobic to aerobic (Hou et al., 2012; Peng et al., 2011; Zou et al., 2005), stimulating N_2O emissions during fallow periods through the inhibition of N_2O reduction in denitrification (Butterbach-Bahl et al., 2013). Other management and environmental factors, such as fertilizer type, rainfall, temperature, soil organic carbon content, total N content and texture, can also affect nitrification and denitrification processes (Bouwman et al., 2002a; Butterbach-Bahl et al., 2013). However, it is not yet known whether these factors play crucial roles in any observed differences between EF_{gs} and EF_{wy}.

The objectives of this study are to evaluate the differences between EF_{gs} and EF_{wy}, and to identify the key factors responsible for any differences at global scale. Here we conducted a global meta-analysis of 123 ΔEFs from 21 studies where each experiment contained both EF_{gs} and EF_{wy}. The overall mean ΔEF and mean ΔEFs for subgroups, with respect to management and environmental factors, were statistically compared to zero to detect differences between EF_{gs} and EF_{wy}. Key factors influencing ΔEFs were identified by identifying significant differences of ΔEFs within the subgroup. Finally, the implications of ΔEFs on the estimation of annual N_2O emissions were quantified with respect to EF_{gs} ($\Delta EF/ EF_{gs}$) for upland crops and paddy rice.

2 Materials and methods

2.1 Data selection and collection

To locate all relevant papers that have reported measurements of N_2O for crop growing seasons and whole years, we performed a comprehensive search on Web of Science, Google Scholar and the China National Knowledge Infrastructure database using the keywords: nitrous oxide or N_2O, non-growing or fallow, upland crops or paddy rice, and soil or fertilizer. To ensure comprehensive coverage, we also checked all references cited in the papers found.

We selected studies from 21 peer-reviewed papers and dissertations where N_2O emissions with at least two different N application rates, including a zero control, were measured both for whole year, and for the growing season and fallow period. Studies with the following measurements were excluded: (i) measurements made in laboratories or greenhouses, (ii) measurements conducted in organic (peaty) soils where N_2O-EFs are much higher than those in mineral soils (IPCC, 2006), and (iii) measurements with the use of controlled-release fertilizers, or nitrification or urease inhibitors, which may reduce N_2O emission rates. The final dataset contains 123 paired EF_{gs} and EF_{wy} at 20 sites globally (Fig. 1 and Table S1).

For each site, the N_2O emissions and related variables were sorted into four categories: (i) N_2O emissions, (ii) climatic factors, (iii) soil properties, and (iv) management parameters. The N_2O emissions for the whole year and growing season were obtained from the studies identified. The averages of these emissions by replicated measurements were then used to calculate N_2O EF_{gs} and EF_{wy}. For the climatic factors, climatic zones based on thermal and moisture regimes (cool, warm, dry and moist zones) were identified according to the locations of sites to represent the variations of soil water content and temperature, following the method in Smith et al. (2008) and Albanito et al. (2016). Mean annual air temperature (MAT) and mean annual precipitation (MAP) for field sites were obtained from the original papers. Mean annual evapotranspiration (MAET) values for 1980-2010 were extracted from the Climatic Research Unit (CRU) TS v. 3.23 database (https://crudata.uea.ac.uk/cru/data/hrg/). Presence of freeze-thaw cycles was characterized by the minimum soil temperature during fallow periods. When the minimum soil temperature was less than zero, we assumed that the soil water was subject to freeze-thaw in winter during the fallow periods. Soil organic carbon content (SOC), pH, total N content, bulk density (BD), and clay content were used to account for substrate availability and soil aeration conditions, which together with climate conditions, determine rates of nitrification and denitrification (Bouwman et al., 2013; Butterbach-Bahl et al., 2013). For the management parameters, crop type, fertilizer type, N fertilizer application rate, residue return, irrigation, and fallow duration were selected, because of their known impacts on soil C and N cycling and transport in the root zone. Multiple cropping seasons of different upland cereals (e.g., maize-wheat rotation) in a full year were included in the category “other crops”. Single or double cropping seasons of paddy rice were both categorized as paddy rice, and the category “vegetables” contained multiple vegetable cultivations. Information on fertilization methods (e.g. broadcast, injection, or deep placement) and tillage practices were not available in the original papers, so these factors were not considered for further analysis.

Missing values of MAT and MAP (32% and 19% of total 123 ΔEFs, respectively) for 1980-2010 were extracted from the CRU climate database; BD, clay content, SOC and pH (58%, 36%, 7% and 0% of the total ΔEFs, respectively) were supplemented from the 1-km Harmonized World Soil Database (HWSD v1.2) (http://www.iiasa.ac.at/) using site latitudes and longitudes. Data from CRU and HWSD were validated through observations from literature at known latitudes and longitudes (Fig. S1 and S2). Although total N could not be added from external datasets, we found that missing data (7% of observations) did not impact our results greatly. Details of these variables can be found in Table S2.

2.2 ΔEF

The ΔEF (%) was calculated as the difference in N_2O-EFs between the whole year and growing season for a non-zero N application level under the same environmental and management conditions. We did not average the ΔEF for a specific site if management practices, such as crops, fertilizer types, and tillage, or other critical factors were different. The N_2O ΔEF for each pair of whole year and growing season was evaluated using the following equations:

$$\Delta EF = EF_{wy} - EF_{gs} \tag{1a}$$

where

$$EF_{wy} = \left(E_{wy} - E_{0wy} \right) / N \tag{1b}$$

$$EF_{gs} = \left(E_{gs} - E_{0gs} \right) / N \tag{1c}$$

and the indices *wy* and *gs* represent whole year and growing season; E is the N_2O emission from the fertilized treatment (kg N ha^{-1}); E_0 is the N_2O emission under zero-N control (without N application, kg N ha^{-1}); *EF* is emission factor, %; *N* is fertilizer N application rate (kg N ha^{-1}).

2.3 Statistical analyses

Analyses of N_2O ΔEF were conducted using statistics based on resampling. We used a Kolmogorov-Smirnov test to determine if the distribution of the dataset differed from normality, and given that it was not normally distributed ($p<0.001$), we applied the bootstrapping resampling method to estimate the means of the ΔEFs. Bootstrapping resampling (i.e., random sampling with replacement of the equal size of the initial dataset repeated n=100,000 times) was performed using the MATLAB bootstrapping function to generate the normal distributions of the means of ΔEFs, and then to compare 95% confidence intervals (CIs) of the means with zero to identify the difference in EFs observed during whole year and growing season. Differences between subgroups of potential factors were then tested using bootstrap confidence intervals and analysis of variance (ANOVA) on bootstrapped values for two and multiple subgroups, respectively.

We removed 1 outlier ΔEF with the largest value (1.03%) from further analysis due to its undue influence on the means of subgroups, since it was nearly 7 times larger than the standard deviation of the dataset. The remaining 122 ΔEFs were then categorized into 16 groups: crop type, climatic zone, MAT, freeze-thaw cycles, MAP, potential net water input (MAP−MAET), SOC, pH, total N content, BD, clay content, fertilizer type, N application rate, residue return, irrigation, and fallow duration. For the groups with continuous variables (e.g. total N content and SOC), ΔEFs were split into two subgroups based on the responses of ΔEFs to the factors.

We used a contingency table to show the interrelation between different environmental factors to avoid assigning the same influence to two or more factors. For each pair of soil properties or climatic factors, we calculated the phi coefficient (ϕ), the degree of association between two variables of two categories. In the contingency table, $\phi = \pm\sqrt{\chi^2/\mathrm{N}}$, where χ^2 is from Pearson's χ^2 test, and the total number of observations, N, was given.

2.4 Impact of ΔEF on N_2O-EF

The percentage of ΔEF of the mean EF_{gs} was used to indicate the relative impact of ΔEF on EF_{gs} for N_2O emission inventories. We estimated mean ΔEFs and their 95% CIs by the bootstrapping resampling method for paddy rice and non-vegetable upland crops. The mean EF_{gs} was then calculated based on the data collected in this study. Moreover, we used the proportional upper and lower boundaries of the 95% CI to estimate the uncertainty of the mean EF_{gs}. To compare EF_{gs} with other studies, N_2O datasets from Cayuela et al. (2017) and Akiyama et al. (2005) were also collected.

3 Results

An analysis of all data together showed significantly greater EF values for a whole year than for a growing season. ΔEFs were positive in 86% of the data and negative in only 14% (17 cases) under certain circumstances (Text S1). Based on the bootstrap resampling, both the mean (0.08) and median (0.03) of the overall ΔEFs were significantly positive ($p < 0.001$), with 95% confidence intervals of 0.06-0.11 and 0.02-0.05, respectively. Removing 1 outlier from the dataset decreased the mean from 0.081 to 0.073 but had no significant effect on the median value (Fig. 2).

3.1 Impact of crop type on ΔEF

Three main cereal crops (paddy rice, n=35; maize, n=23, and wheat, n=33) dominated other crops (vegetables, n=10; legume, n=4, and other upland crops, e.g. barley, maize and wheat rotations, n=21) on the perspective of ΔEF data availability. Except for legume crops, for which the data were insufficient, all crops showed significant positive ΔEF values ($p<0.01$). However, differences among crop types showed that mean ΔEF for paddy rice was significantly larger ($p<0.05$) than that for all upland crops, except for vegetables (Fig. 2). The mean ΔEFs for paddy rice (0.11) and vegetables (0.19) were about 2 to 7 times those for maize (0.03), wheat (0.07) and other upland crops (0.04).

3.2 Impact of climate on ΔEF

The ΔEFs for the moist climatic zones (warm-moist and cool-moist) were significantly ($p<0.001$) positive (Fig. 3a). The cool-moist zone had the highest mean ΔEF (0.10), followed by warm-moist (0.08) and warm-dry (0.01). Significant ($p<0.05$) differences were also found between moist (cool-moist and warm-moist) and dry (warm-dry) zones. The averaged ΔEF for moist regions was 0.09, ~6 times more than that of the dry region. The subgroup for water condition also had significantly ($p<0.001$) positive ΔEF values. The ΔEF was much larger when the MAP reached 600 mm per year, however the effect of the difference between precipitation and evapotranspiration (MAP-MAET) was not significant. Higher (⩾15°C) or lower (<15°C) MAT, and the occurrence of freeze-thaw cycles during the fallow period, showed no significant impacts on the magnitude of the ΔEF values ($p<0.001$).

3.3 Impact of soil properties on ΔEF

Among soil conditions, ΔEFs were all significantly higher ($p<0.001$) than zero in relation to SOC, pH, total N content, BD and clay content. The ΔEFs were also higher where SOC contents were relatively high (SOC ⩾1.3%), and where soil was acidic (pH <7; Fig. 3b). The total N content, BD, and clay content had no significant impact on the ΔEF at the 95% confidence level.

3.4 Impact of management on ΔEF

All N fertilizer types (Urea (U), Organic (O), mixture of synthetic and organic fertilizers (OS) and other synthetic fertilizers (other SNs)) and application rates had significantly positive impacts on ΔEFs ($p<0.05$, Fig. 3c). The mean ΔEFs for U (0.08) and other SNs (0.10) were ~3 times more than that for O (0.03) and OS (0.04), showing significant ($p<0.05$) differences. Although the mean ΔEF increased with increasing N fertilizer application rate, the differences between them were not significant ($p>0.05$).

For other agricultural management, i.e., residue management, irrigation and length of fallow period, the mean ΔEFs for all subsets were significantly positive ($p<0.05$) (Fig. 3d). The mean ΔEF was higher ($p<0.05$) for residue return (0.12) after harvest than that for residue removal (0.03). Irrigated cropland had a higher mean ΔEF (0.09, n=75) compared with the mean of all data, whereas rain-fed cropland (n=7) had substantially smaller mean ΔEF (0.01). Among three categories of fallow duration, the mean ΔEF grew significantly ($p<0.05$) with increasing length of fallow periods and significantly ($p<0.05$) positive correlation was found between the ΔEF and the duration of fallow period. The mean ΔEF for fallow periods of ⩾200 days (0.11) was ~2 and ~6 times higher than the mean ΔEF for fallow periods of 100-200 days and <100 days.

Relatively greater factor associations ($\phi>0.4$ or <-0.4) were primarily found between climatic zone and other environmental factors in a contingency table (Table S3). Other large associations were between total N and SOC (0.64), between pH and MAT (−0.65), pH and MAP (−0.44), and between total N and freeze-thaw cycles (0.58). High levels of relatedness were also found between other climatic factors, e.g., MAT and MAP (0.48), MAT and freeze-thaw cycles (−0.57), and MAP and MAP-MAET (0.86).

3.5 Impact of ΔEF on N_2O-EF

Paddy rice and non-vegetable upland crops both had positive ($p<0.05$) mean proportional ΔEFs and corresponding 95% CIs (Fig. 4). The mean proportional ΔEF for paddy rice was 30% (95% CI: 16%-45%, n=31), nearly 3 times that for non-vegetable upland crops (11%, 95% CI: 7%-14%, n=81). The proportional upper and lower boundaries of 95% CI of mean EF_{gs} in this study were 26% and −23% for upland crops (n=81), and 49% and −40% for paddy rice (n=31), respectively.

4 Discussion

Our results show that the N_2O-EF for a whole year is greater than that for the growing season; that is, positive mean ΔEFs were found for the overall dataset and for most subgroups by crop type, climatic factor, soil property, fertilization practice, and other management practices (Figs. 2 and 3).

4.1 Effect of crop type on ΔEF

Vegetables showed significantly greater differences between whole year EF and growing season EF compared to other upland crops (e.g., wheat, maize, legumes) (Fig. 2). The nitrogen use efficiency (NUE; yield N/fertilizer N) for vegetables has been reported to be 14%, substantially lower than those for wheat (42%), maize (46%), paddy rice (39%), legume (80%) and other cereal crops (53%) (Zhang et al., 2015). This is related to high fertilizer N inputs for intensive cropping vegetable systems (Li et al., 2017; Zhang et al., 2012). Globally, vegetables use 7% of global synthetic N fertilizer (Patrick et al., 2017), but account for only ~4% of harvested cropland area (FAO, 2019), leading to an application rate that is more than 30% than for other crops (Fig. S3). As reported by Gerber et al. (2016), vegetables had a slightly higher EF than other crops (e.g., 2% and 12% higher than maize and wheat, respectively). The high N application rate and the low NUE would be expected to lead to more N substrate being available for N_2O production during the fallow period (see Eq. S1 and Text S2), which is supported by a significant and positive relationship (r=0.3) between N application and N_2O emissions during the fallow season found in this study.

Paddy rice showed a significantly larger ΔEF compared with other non-vegetable upland crops (Fig. 2). Given that N application rates for non-legume crops are similar (210±28 kg N ha^{-1}, mean ± standard deviation) in our dataset, the magnitude of the ΔEF is determined only by residue fertilizer-induced N_2O emissions, i.e., the difference in N_2O emissions between fertilized and unfertilized plots during the fallow period (Eq. S1 and Text S2). The residual fertilizer-induced N_2O flux during the fallow period was 6 μg N m^{-2} h^{-1} (n=32) for paddy rice, which is about twice that of wheat (n=33) and about 5 times that of maize (n=23) (Table S4). The N_2O fluxes for these upland crops decreased significantly from the growing season (23 μg N m^{-2} h^{-1}, n=82) to the fallow period (9 μg N m^{-2} h^{-1}, n=82), which may be due to lower N availability in soils, while the N_2O fluxes for paddy rice did not decrease during fallow period (19 *vs.* 16 μg N m^{-2} h^{-1}, p=0.52). This coincides with a change in soil water and oxygen conditions after flood drainage that favor N_2O emissions during the non-growing period (Majumdar, 2013; Wang et al., 2013; Zheng et al., 2010). N_2O emissions in paddy rice systems are impacted greatly by flooding and drainage cycles. For example, the meta-analysis of Akiyama et al. (2005) reported that the practice of midseason drainage led to a larger EF than continuous flooding. Though paddy rice is cultivated mostly in regions with a moist climate and upland crops are grown both in moist and dry areas, our results do not suggest that the higher ΔEF for paddy rice resulted from climatic factors. Instead, we propose that it was most likely due to residual N fertilizer, since the residual fertilizer-induced N_2O flux for paddy rice (6 μg N m^{-2} h^{-1}, n=32) was still significantly (2 and 4 times) greater than those for wheat (n=32) and maize (n=9) in moist areas (Table S4). For other factors with high associations ($\phi>0.4$ or <-0.4, Table S3), such as pH, MAT and freeze-thaw cycles, significantly larger residual fertilizer-induced N_2O flux was also found for paddy rice than for other non-vegetable crops

(Table S4). Hence water management factors, such as flooding and drainage, are dominant over other factors in affecting the ΔEF for paddy rice.

4.2 Effect of climate on ΔEF

Our results showed that precipitation was the dominant climatic factor over temperature, showing significant differences in ΔEF: moist areas had greater ΔEF than dry areas (Fig. 3a). Higher precipitation was found to significantly promote greater N_2O emissions in the fallow season and consequently resulted in greater ΔEF values in this study, as evidenced by the significant and positive relationship (r=0.3) between the amount of rainfall during the fallow period and the ΔEF (Fig. S4). Higher precipitation is associated with higher soil water content, which is known to be a major driver of N_2O emissions, by regulating oxygen availability to microbes in the soil (Butterbach-Bahl et al., 2013; Davidson et al., 2000; Song et al., 2019). Rising soil water content has been reported to increase N_2O emissions (Smith et al., 2003; Bateman and Baggs, 2005), before extreme soil anaerobic conditions favor the reduction of N_2O through denitrification (Butterbach-Bahl et al., 2013; Davidson et al., 2000). A recent meta-analysis conducted by Xia et al. (2018) also reported a positive relationship between precipitation and N_2O emissions. Although MAT and MAP-MEAT had relatively large associations with MAP ($\phi > 0.4$ or < -0.4, Table S3), only MAP had a significant impact on ΔEF.

4.3 Effect of soil properties on ΔEF

Our results show that SOC and pH have important effects on ΔEFs (Fig. 3b), which appear to be related to their impacts on N_2O-EF from residual fertilizer N during non-growing periods. A positive relationship between N_2O emissions and SOC content was also found in other global meta-analyses (Bouwman et al., 2002a; Charles et al., 2017). Lower soil pH is generally known to depress the activity of N_2O reductase enzymes and the reduction of N_2O to N_2 in the denitrification process (Bakken et al., 2012; Čuhel et al., 2010; Wang et al., 2018). Soil pH may also affect other biotic or abiotic processes (e.g., nitrification and chemical denitrification) and the microbial community and may thereby affect N_2O emissions, but the mechanisms remain unclear (Wang et al., 2018). A negative relationship between pH and soil N_2O emission has been observed in laboratory studies with soils from acidic tea fields (Tokuda and Hayatsu, 2001), paddy rice fields (Shaaban et al., 2014; Shaaban et al., 2018) and in a recent meta-analysis (Wang et al., 2018). The association between SOC and pH was relatively low ($\phi=-0.1$, Table S3) in this study, suggesting that SOC and pH may be independently affecting N_2O emission during fallow periods.

4.4 Effect of management on ΔEF

Our results showed that the ΔEF under organic fertilizer (livestock manure) application was significantly lower than that under urea application (Fig. 3c). As discussed in Section 4.1 and Text S2, it appears that the residue fertilizer-induced N_2O flux during fallow period has the greatest impact on the ΔEF, given that N application rates for organic fertilizer and urea in our dataset were comparable (166 v.s. 172 kg N ha^{-1}, p=0.16). The residue fertilizer-induced N_2O flux for organic fertilizer (2 μg N m^{-2} h^{-1}, n=32) was one third that for urea application (n=45). Similarly, a meta-analysis conducted by Xia et al. (2017) reported that, compared to urea application, organic fertilizer also reduced N_2O emissions by 11.4%, attributed to the significant promotion of microbial N immobilization (by 36.4%), thereby reducing the availability of N for N_2O productions (Zhou et al., 2016).

The combination of crop residue return with synthetic N fertilizer led to a significantly higher ΔEF compared to a single synthetic N fertilizer application at comparable N application rates (194 v.s. 186 kg N ha^{-1}, p=0.78) (Fig. 3c). Straw degradation provides additional N substrates for nitrification and denitrification, which stimulates N_2O emissions in the fallow crop season (Liu et al., 2014). The ΔEF for paddy rice with crop residue return (0.15%, n=20) was three times greater than that for non-vegetable upland crops with crop residue return (n=31).The N_2O fluxes for upland crops decreased significantly from the growing season (29 μg N m^{-2} h^{-1}, n=31) to the fallow period (16 μg N m^{-2} h^{-1}, n=31), which may be due to lower availability of N in soils, while the N_2O fluxes for paddy rice did not decrease during the fallow period (14 v.s. 10 μg N m^{-2} h^{-1}, p=0.33). It is coincident with the change of soil water and oxygen conditions that favor N_2O emissions resulting from drainage after harvest in paddy fields (Akiyama et al., 2005; Majumdar, 2013; Wang et al., 2013; Zheng et al., 2010). The meta-analysis of Xia et al. (2018) reported that the return of crop residue significantly decreased N_2O emissions (by 17.3%_ in the flooded rice-growing season while it increased emissions by 21.5% for upland crops, supporting the findings reported here.

Fallow duration is significantly and positively correlated to ΔEF (Fig. S5 and Fig. 3d), because a longer non-growing period means a shorter growing season within a year, which also represents more residual fertilizer N available for N_2O production from both nitrification and denitrification during fallow periods.

4.5 Effect of ΔEF on N_2O-EF

The 95% CIs of mean EF_{gs} in this study were similar to those from two meta-analyses for growing-season Mediterranean upland crops (n: 186; upper: 20%, lower: 26%) (Cayuela et al., 2017) and global paddy rice (n=50; upper: 33%, lower: 31%) (Akiyama et al., 2005) (Fig. 4). The mean proportional ΔEFs for upland crops and paddy rice were 11% and 30% (Figs. 4a and b), which means that an EF_{gs}-based emission inventory, using growing season measurements only, could underestimate N_2O emissions by one tenth and one third, respectively. Moreover, for paddy rice, the mean proportional ΔEF and its upper boundary of 95% CI (45%) were close to, or even exceeded, the upper boundaries of the mean EF_{gs} from this study (49%) and Akiyama et al. (2005) (33%). Neglecting N_2O emissions from the non-growing season will lead to an underestimation of cropland N_2O emissions for both crop types, especially for paddy rice, so emission mitigation for non-growing periods also needs to be considered.

4.6 Limitations

The main limitation of the analysis is the lack of available whole-year measurements, because most measurement campaigns have focused only on cropping seasons. Geographical coverage is also an issue; with more ΔEFs from Africa, South America and East Europe, we would be better able to capture the magnitude and important factors for ΔEF with higher confidence. Additional studies are especially needed in cool-dry and warm-dry climatic zones, for vegetables and legumes and under different irrigation regimes. With more ΔEFs for vegetables, interdependences of environmental and management factors can be tested to determine their relative importance. In addition, more studies with two or more non-zero N application levels are required for studying the impacts of N input rate on ΔEF. Soil amendments, such as controlled-release fertilizer and nitrification inhibitors, may potentially lead to an increase in fallow N_2O emissions, due to the prolonged release of nitrogen. Further knowledge of the factors controlling the differences in EF between whole years and growing seasons, and their magnitude, is crucial for reducing the uncertainties of N_2O inventories and the corresponding greenhouse gas balance of croplands.

5 Conclusions

This meta-analysis showed that the inclusion of non-growing season N_2O emission significantly increased cropland N_2O-EF, indicating that residual fertilizer-induced N_2O emission during the non-growing season cannot be neglected for national inventories. In particular, ignoring emissions from the non-growing season can underestimate the N_2O-EF by 30% for paddy rice and by ~10% for non-vegetable upland crops. Areas with high precipitation, high soil organic carbon content, or low pH experience higher risks of residual fertilizer-induced N_2O emissions. For national cropland N_2O emission estimates and mitigation strategies, frequent measurements of N_2O emission should be taken both during the crop growing and non-growing periods. In the future, attention should be paid to the fate of residual fertilizers and their effects on the environment.

Declaration of interests

The authors declare no competing interests.

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Author contributions

Z.S., P.S. and M.A. conceived and designed the research; Z.S. and M.A. collected data; Z.S. performed the analysis; Z.S., M.A., M.K., F.A., and L.X interpreted the results; Z.S. wrote the paper with contributions from M.A., M.K., L.X and P.S.; All revised the paper.

Supplementary material

Additional Supplementary Information can be found in the online version of this article.

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Figure captions

Fig.1 Map showing the locations of experimental sites and numbers of observations used in this paper (123 paired N_2O EF_{gs} and EF_{wy} for whole year and growing season at 20 sites). Green area represents global croplands.

Fig.2 Overall ΔEF and ΔEF grouped by crop types. Data are presented as mean ± SEM, with n noted at the base of each bar. Asterisks indicate significant differences from zero (***p< 0.001; **p < 0.01; *p<0.05). Different letters indicate significant differences between mean ΔEFs for groups within each category. “Others” represent upland crops except wheat, maize and legume.

Fig.3 ΔEFs by climatic factors (a), soil attributes (b), fertilization (c), and other managements (d). Data are presented as mean ± SEM, with n noted at the base of each bar. Asterisks indicate significant differences from zero (***p< 0.001; **p < 0.01; *p<0.05). Different letters indicate significant differences between mean ΔEFs for groups within each category. [1]: The minimum soil temperature is presumably an indicator for the occurrence of freeze-thaw cycles: if the minimum soil temperature is below 0 °C, then the freeze-thaw cycle is assumed to occur. [2]: The potential net water input is defined as the difference between mean annual precipitation and evapotranspiration.

Fig.4 Impact of ΔEF on EF_{gs} for non-vegetable upland crops (a) and paddy rice (b). The effect of ΔEF is represented by the ratio of its mean and 95% confidence interval (CI) boundaries to the mean EF_{gs} in this study (excluding 1 outlier). 95% CIs of the mean EF_{gs} in this study were in comparison with those from Cayuela et al. (2017) and Akiyama et al. (2005).

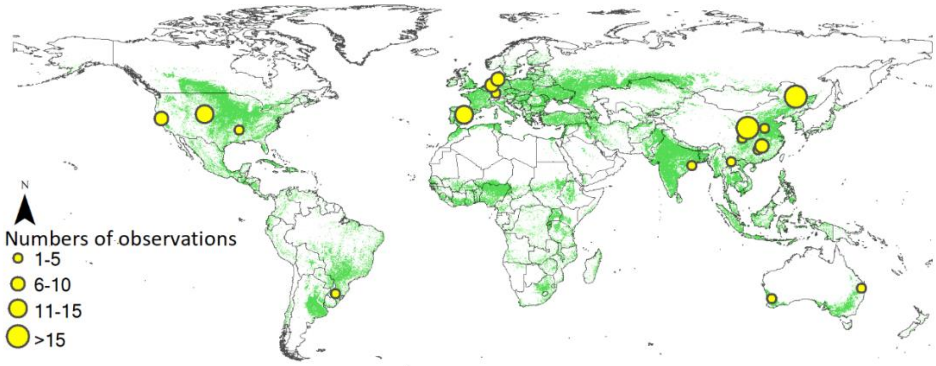


Fig.1

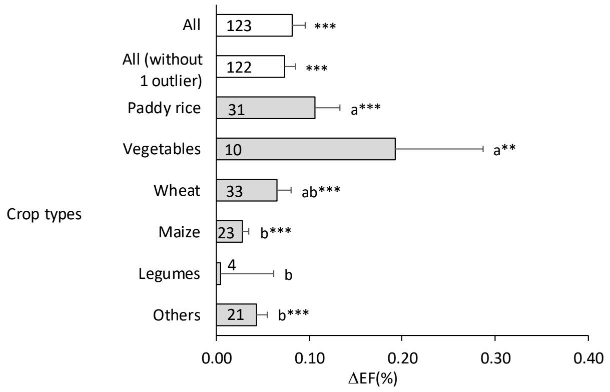

All
All (without 1 outlier)
Paddy rice
Vegetables
Wheat
Maize
Legumes
Others
Crop types
123
***
122
***
31
a***
10
a**
33
ab***
23
b***
4
b
21
b***
0.00
0.10
0.20
0.30
0.40
ΔEF(%)

Fig.2

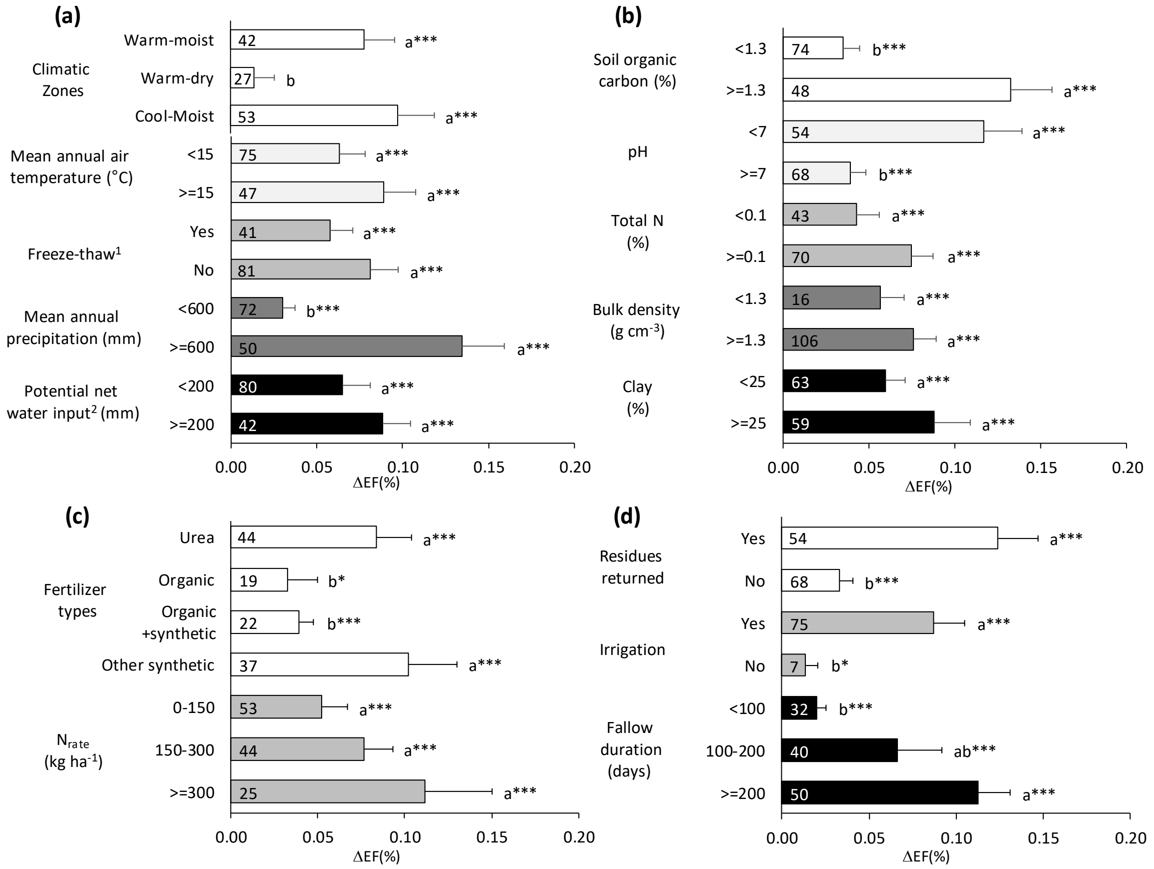
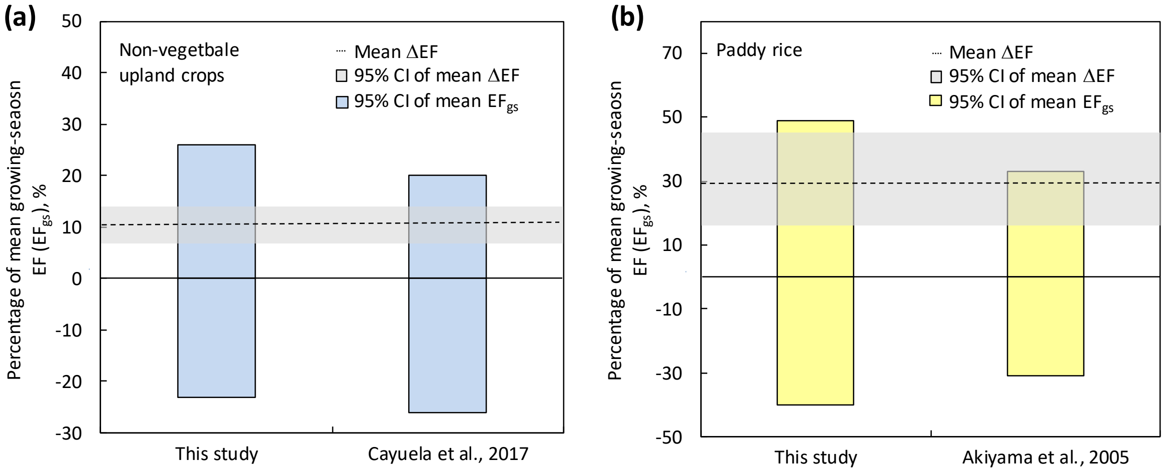

(a)
Climatic Zones
Warm-moist
42
a***
Warm-dry
27
b
Cool-Moist
53
a***
Mean annual air temperature (°C)
<15
75
a***
>=15
47
a***
Freeze-thaw¹
Yes
41
a***
No
81
a***
Mean annual precipitation (mm)
<600
72
b***
>=600
50
a***
Potential net water input² (mm)
<200
80
a***
>=200
42
a***
0.00
0.05
0.10
0.15
0.20
ΔEF(%)
(b)
Soil organic carbon (%)
<1.3
74
b***
>=1.3
48
a***
pH
<7
54
a***
>=7
68
b***
Total N (%)
<0.1
43
a***
>=0.1
70
a***
Bulk density (g cm-3)
<1.3
16
a***
>=1.3
106
a***
Clay (%)
<25
63
a***
>=25
59
a***
0.00
0.05
0.10
0.15
0.20
ΔEF(%)
(c)
Fertilizer types
Urea
44
a***
Organic
19
b*
Organic +synthetic
22
b***
Other synthetic
37
a***
Nrate (kg ha-1)
0-150
53
a***
150-300
44
a***
>=300
25
a***
0.00
0.05
0.10
0.15
0.20
ΔEF(%)
(d)
Residues returned
Yes
54
a***
No
68
b***
Irrigation
Yes
75
a***
No
7
b*
Fallow duration (days)
<100
32
b***
100-200
40
ab***
>=200
50
a***
0.00
0.05
0.10
0.15
0.20
ΔEF(%)

Fig.3


(a)
Percentage of mean growing-seaosn EF (EF_{gs}), %
50
40
30
20
10
0
-10
-20
-30
Non-vegetbale upland crops
Mean ΔEF
95% CI of mean ΔEF
95% CI of mean EF_{gs}
This study
Cayuela et al., 2017
(b)
70
50
30
10
-10
-30
-50
Paddy rice
Mean ΔEF
95% CI of mean ΔEF
95% CI of mean EF_{gs}
This study
Akiyama et al., 2005

637

638 **Fig.4**