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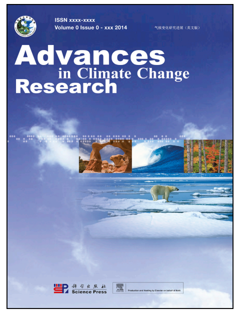

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Direct emission factors for inventorying NO_x emissions from managed soils as part of the IPCC methodology framework

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Abstract

The current inventory framework of the Intergovernmental Panel on Climate Change (IPCC) relies on a single generalized default direct emission factor (EF), which inadequately captures the substantial heterogeneity in nitric oxide (NO) emissions from managed soils and may therefore lead to systematic biases in nitrogen oxides (NO_x) inventories across vegetation types and environmental conditions. To address this limitation, and given that soil-emitted NO_x is predominantly released as NO, we synthesized global field observations of direct EFs for NO to develop an updated methodological framework for Tier 1- and Tier 2-based inventories of national and global direct NO_x emissions from managed soils. For Tier 1, our synthesis yielded 0.49% (95% confidence interval: 0.41%–0.58%), 1.66% (1.17%–2.15%), 0.10% (0.05%–0.17%), and 0.11% (0.06%–0.18%) as aggregated EFs for managed soils (I) growing upland vegetation types other than tea plantations ($EF_{1,O(NOx)}$), (II) utilized for tea plantations ($EF_{1,Tea(NOx)}$), (III) cultivated with flooded rice ($EF_{1,FR(NOx)}$), and (IV) receiving urine and dung deposition by grazing animals ($EF_{3(NOx)}$), respectively. Significant differences in direct EFs were observed among major cropping systems, with the highest, intermediate and lowest values occurring in types II, I and III, respectively ($p = 0.001$). For type I, soil organic carbon (SOC) content was identified as the most robust factor regulating direct EFs of NO ($p = 0.001$). Accordingly, for one Tier 2 option, this type was further disaggregated into two SOC-based subcategories, with direct EFs of 0.31% (0.25%–0.37%) for SOC ≤ 1% ($EF_{1,O,SOC \leq 1\%(NOx)}$), and 0.62% (0.49%–0.75%) for SOC > 1% ($EF_{1,O,SOC>1\%(NOx)}$). These newly developed direct EFs would enable more accurate inventories of NO_x emissions from managed soils and better support targeted mitigation strategies.

Keywords: Nitrogen oxides (NO_x) emissions, Nitric oxide (NO) emissions, Emission factor for direct emissions, Managed soils, Tier 1 or 2 methodology

1 Introduction

Anthropogenic perturbations of the global nitrogen (N) cycle have substantially increased the mobilization and transfer of reactive N to the atmosphere, with managed soils now recognized as a major source for emissions of gaseous N species (Canadell *et al*., 2021; Tian *et al*., 2023; Yan *et al*., 2025). Among these gases, nitrogen oxides (NO_x) are particularly important due to their roles in tropospheric ozone formation, atmospheric oxidation processes, secondary aerosol formation, and broader air quality deterioration (Almaraz *et al*., 2018; Gong *et al*., 2024). Nitric oxide (NO) and nitrogen dioxide (NO_2) are collectively referred to as NO_x in the field of atmospheric chemistry and environmental science. However, direct field measurements of soil NO_2 emissions remain scarce because soil-derived NO_x is produced and emitted predominantly as NO rather than NO_2 (e.g., Liu *et al.*, 2024). Once emitted into the atmosphere, NO can be rapidly oxidized to NO_2 over a short timescale (e.g., Shah *et al.*, 2020). Therefore, direct soil NO_x emissions are commonly characterized through measurements or estimates of NO emissions.

In managed land systems, direct NO emissions from soils are closely associated with anthropogenic N inputs through a) amendments of synthetic N fertilizers and organic manure and/or wastes, b) retention or incorporation of crop residues, c) decomposition of soil organic matter following land use changes and/or drainage and cultivation of organic soils, and d) direct deposition of excreta by grazing animals (IPCC, 2019; Wang *et al*., 2022). Soil NO emissions result from complex interactions among multiple N transformation pathways, which are influenced by both biotic and abiotic factors (Butterbach-Bahl *et al*., 2013; Hall & Matson, 1999; Song *et al*., 2021). The dominant biological pathways for NO production are microbial nitrification and denitrification. Abiotic production can also occur through chemically mediated processes, such as chemodenitrification, particularly under conditions that favor nitrite (NO_2^-) accumulation, including acidic soils and rapidly changing redox conditions (Medinets *et al*., 2015). The rates of nitrification and denitrification are primarily governed by availability of substrates, soil moisture, soil pH, and ecosystem type (Lan *et al*., 2013; Wankmüller *et al*., 2024; Zhao *et al*., 2025). These factors are further influenced by management practices, which can enhance or reduce NO emission. This complexity results in substantial spatial and temporal variability in NO fluxes at the soil–atmosphere interface, often leading to the presence of hotspots and the occurrence of episodic emission spikes (Huber *et al*., 2024; Lado-Monserrat *et al*., 2014; Wang *et al*., 2024). Consequently, accurate quantification of direct NO emissions from managed soils remains challenging, particularly when upscaling emissions to national, regional and/or global scales and deriving direct emission factors (EFs) from bottom-up approach, such as national fertilizer consumption statistics (Hergoualc'h *et al.,* 2021; Lin *et al*., 2024).

Following the IPCC methodological framework for estimating direct nitrous oxide (N_2O) emissions from managed soils (IPCC, 2006, 2019), Tier 1 and Tier 2 approaches for NO_x addressed in this study are EF-based approaches, whereas the Tier 3 method, which is beyond the scope of this study, relies on process-oriented modelling. For both Tier 1 and Tier 2, the direct EF is defined as the fraction of applied N lost as NO_x emissions during the year of application, analogous to the direct EFs for N_2O. To ensure consistency and facilitate comparisons across reporting frameworks, direct EFs of NO_x in this study are expressed on N mass basis (NO_x–N), representing only the N component regardless of molecular form or subsequent atmospheric reactions (Mathivanan *et al*., 2026). The Tier 1 approach applies default EFs and provides a simple, transparent, and comparable method for countries lacking country-specific EFs or detailed spatial information (Goglio *et al*., 2024; Xia *et al*., 2024; Zhang *et al*., 2024). In contrast, the Tier 2 approach uses country- or condition-specific EFs supported by more detailed activity data or environmental information, thereby allowing emissions to be differentiated according to key natural and management regulators (Goglio *et al*., 2024; Obi-Njoku *et al*., 2024; Liang *et al*., 2020). Therefore, Tier 2 provides an intermediate and inventory-compatible approach between the simple default assumptions of Tier 1 and the process-based modelling of Tier 3, provided that the stratification variables are scientifically relevant, statistically supported, and practically applicable at the inventory scale.

In the IPCC (2006) guidelines for N_2O inventories from managed soils, a value of 0.7% derived from Bouwman *et al*. (2002) was used as the default fraction of synthetic fertilizer- and manure-derived N lost through emissions of ammonia (NH_3) and NO_x. This value was subsequently updated to an average of 1.1% (adapted from IPCC, 2019). Despite this update, accumulating evidence indicates that direct NO_x emissions cannot be adequately represented by a single default EF value applied universally across all managed soils (e.g., Wang *et al*., 2022). This limitation highlights the need to develop Tier 2 direct EFs within an EF-based framework, thereby improving inventory estimates by incorporating spatial variations in soil conditions and management practices at national, regional, and global scales (Liang *et al*., 2020; Xia *et al*., 2024). Recent syntheses further support this transition by showing consistent variations in direct NO_x emissions across cropping systems, environmental conditions, and management practices (Wang *et al*., 2022, 2024). For example, crop-specific EFs have been shown to improve estimates of fertilizer-induced NO_x emissions compared with the use of a single aggregated EF (Wang *et al*., 2022). Moreover, meta-analytical evidence suggests that the response of soil NO_x emissions to fertilizer N inputs is nonlinear, implying that fixed EFs may bias estimates in both low- and high-input systems (Wang *et al*., 2024). Data-driven global mapping studies also indicate that incorporating variables such as ecosystem types and environmental conditions can substantially improve the spatial representation of soil NO_x emissions, further highlighting the need for a more differentiated inventory framework (Tian *et al*., 2023). These findings highlight the need to develop a more differentiated Tier 1 and Tier 2 EFs framework for direct NO_x emissions from managed soils.

This study aims to provide updated EFs for estimating direct NO_x emissions from managed soils. The specific objectives are to a) compile a global dataset of field experiments/observations on NO_x emissions from managed soils reported in peer-reviewed literature, b) derive aggregated direct EFs for managed soils of the global scale as default vales for the Tier 1 approach, as well as disaggregated direct EFs across different managed lands systems and/or N input regimes to support the Tier 2 method, and c) identify key sources of uncertainty that should be addressed in future field measurements and subsequent methodology refinement.

2 Materials and methods

2.1 Literature search and data extraction

Collection of peer-reviewed publications (before May 2026) was performed using Web of Science (https://apps.webofknowledge.com/), Google Scholar (https://scholar.google.com/), and the China National Knowledge Infrastructure (https://kns. cnki.net/), with search topics focusing on soil NO emissions (Fig. 1). Specific search terms for the published articles were combined with respect to 'nitric oxide' OR 'NO', AND 'emission', AND 'soil'. The dataset compiled by Wang *et al*. (2022), which covered studies published before May 2021 and was provided as online supplementary material, served as the starting point for database updating. Additional studies were identified by screening newly retrieved publications and snowballing from references cited in Wang *et al*. (2022) and other included studies to ensure comprehensive coverage of direct soil NO emissions in the present synthesis. To minimize potential confounding factors in literature screening, only field experimental data were included while studies based on laboratory incubation, pot experiments or modeling were excluded. Studies that did not cover the full cropping season were also excluded. A field study had to report the N application rates for each treatment, including the N input from synthetic fertilizers and/or organic manure, as well as the N from urine and dung deposited by grazing animals. Moreover, measurements for N treatments and the control group had to be conducted during the same experimental period on sites with similar cultivation histories. For each treatment, cumulative NO emissions were extracted or calculated and expressed as kg N/hm^2 per season for flooded rice growing seasons in rice–upland crop rotations with double or triple annual cropping, or as N/hm^2 per year for other cropping systems and managed land uses. Unit conversions were performed where necessary. Studies involving enhanced-efficiency N fertilizers (EENFs), such as nitrification/urease inhibitors, biochar amendments and slow-release fertilizers, were excluded due to their inhibitory effects on soil NO emissions could bias the synthesized direct EFs. The raw data used in this synthesis was either obtained directly from tables and texts or extracted indirectly by digitizing graphs using GetData Graph Digitizer (http://www.getdata-graph-digitizer.com/). Based on our criteria for quantitative synthesis, the literature search and selection yielded 93 publications reporting field-based soil NO emissions across different major types of N sources for NO_x emissions from managed soils (Table A1). This extensive collection also incorporated additional relevant data, such as geographical location, land use type, soil properties (e.g., soil organic carbon (SOC) contents), and management practices (e.g., N type) to provide a comprehensive overview of global NO emission dynamics. The extracted NO emission data were grouped into four types of major N sources including those inputs in the soils a) cultivated with flooded rice, b) utilized for tea plantations, c) growing vegetation types other than flooded rice and tea, and d) receiving urine and dung deposited by grazing animals or applied with slurry. Fig. 2 shows the spatial distribution of field measurement sites for each major N source category.

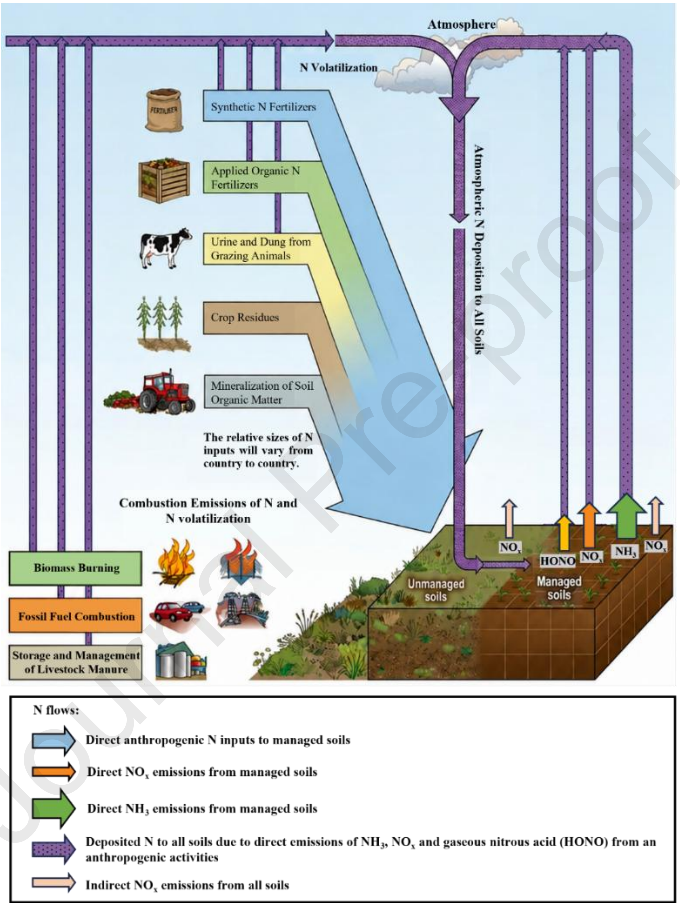

Fig. 1 Schematic diagram illustrating the sources and pathways of nitrogen (N) that result in nitrogen oxides (NO_x) emissions from soils. Sources of N applied to managed soils are represented with the blue arrows on the graphic. Sources of N deposited to managed and/or unmanaged soils are represented with the purple arrows filled with dots. Anthropogenic emission pathways are also shown with arrows filled with dots, which include the various pathways of (a) direct emissions of ammonia (NH_3), NO_x and nitrous acid (HONO) from managed soils and other sources, (b) atmospheric deposition of these gases and their products (mainly NH_4^+ and NO_3^-) to all soils, and, (c) consequent indirect emissions of NO_x. Applied Organic N Fertilizers include animal manure, all compost, sewage sludge, etc. Crop Residues include above- and below-ground residues for all crops and from perennial forage crops and pastures following renewal. On the lower right-hand side is a cut-away view of a representative section of managed soils (with brown mosaics) and unmanaged lands.

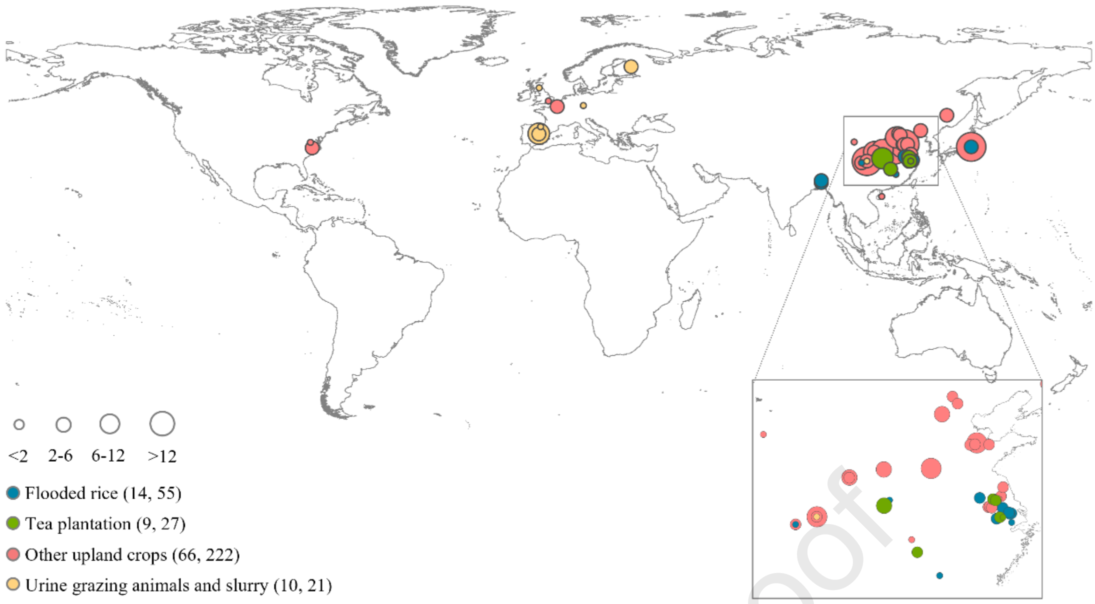

Fig. 2 Locations of field sites for available direct emission factors (EFs) of nitric oxide emissions observed in managed soils of the globe. For the legends, the size of each empty cycle with a range of numbers indicates the sample size of studies; the former figure for each of the four major types of nitrogen sources is count number of studies and the latter is the total cases of available observed direct EFs.

2.2 Data assembly and analyses

We performed a pair-wise meta-analysis using the direct EFs of NO as an effect size, in agreement with preceding studies (e.g., Wang *et al*., 2022, 2025). When EF values were unavailable in the collected original publications, we calculated them using the seasonally/year-roundly cumulative NO emission data from both N-unfertilized and N-fertilized treatments, alongside the total N application rates at the seasonal/annual scale. The equation used was:

$$\mathrm{EF} = (E_N - E_0) / N, \qquad (1)$$

where EF denotes the seasonal (for the flooded rice season in a rice-upland crop rotation) or annual (for the other managed lands or cropping systems) direct emission factor of NO (in kg NO_x-N/(kg N)), E_N and E_0 the seasonally/annually cumulative emission of NO (in kg N/hm^2 per season or per year) from the N-fertilized and unfertilized treatments, respectively and, N the seasonal/annual N application rate (kg N/hm^2 per season or per year).

To classify the factors influencing direct EF, potentially relevant independent variables were grouped into specific categories and subcategories. Cropping systems were divided into flood rice, tea plantations, and others. The other type included non-tea upland cropping systems, such as upland rotation regimes of upland cereal crops, upland cereal-fallow regimes, vegetables, and orchards. Based on soil property criteria provided by USDA (http://www.nrcs.usda.gov/), soils were classified as acid or non-acid using a pH threshold of 6.5, and soil texture was classified as coarse, medium, or fine. Following the principle of maximizing within-group homogeneity outlined by Zhao *et al*. (2022), mean annual precipitation (MAP), mean annual air temperature (MAT), SOC content, total nitrogen (TN) content, and the SOC-to-TN ratio (C/N) were segmented into two levels. Specifically, the subgroups were < 600 and ≥ 600 mm for MAP, < 15 and ≥ 15 °C for MAT, ≤ 10 and > 10 g C/kg for SOC, ≤ 1 and > 1 g N/kg for TN, and ≤ 11 and > 11 for C/N ratio. For N managements, N application rates were classified as <300 and ≥300 kg N/hm^2, and types of N fertilizers were classified as synthetic, organic, and combined synthetic and organic fertilizers.

The mean EF, i.e., $\overline{\mathrm{EF}}$, for each group (aggregated category or disaggregated subcategory) was calculated by MetaWin 2.1 (Rosenberg *et al.*, 2000) as:

$$\overline{\mathrm{EF}} = \frac{\sum_{i=1}^{n}(w_i \mathrm{EF}_i)}{\sum_{i=1}^{n} w_i}, \quad (2)$$

wherein n is the number of cases for observed EF data involved in a category/subcategory, EF_i the direct emission factor of NO for the i^{th} case, and w_i the weight of EF_i in determining $\overline{\mathrm{EF}}$.

The weight w_i was defined by the reciprocal of the variance v_i in the observations resulting in EF_i (Eq. 3). The variance v_i for $\mathrm{EF_i}$ was expressed by $v_i = k_i\mathrm{SD}_i^2$ or $v_i = k_i^2\mathrm{SE}_i^2$, with k_i denoting the number of experimental replicates for obtaining EF_i and, SD_i and SE_i the standard deviation and standard error, respectively, with $\mathrm{SD}_i = k_i^{1/2}\mathrm{SE}$.

For the i^{th} case that is occasionally lacking of reported SD or SE, our analysis estimated w_i using the numbers of replicates to minimize extreme weight issues (van Groenigen *et al*., 2011; Xia *et al*., 2017), following Eq. 3:

$$w_i = \frac{1}{v_i} \approx n_i^{\mathrm{t}} n_i^{\mathrm{c}} / (n_i^{\mathrm{t}} + n_i^{\mathrm{c}}) \quad (3)$$

wherein n_i^{t} and n_i^{c} represent the number of spatial replicates for the treatment (N-fertilized) and control (N-unfertilized), respectively, in the i^{th} case to observe their annually/seasonally cumulated NO emissions and thus to estimate annually/seasonally EF_i.

Using MetaWin 2.1 (Rosenberg *et al.*, 2000), the uncertainty range for each category/subcategory was estimated as the bootstrap confidence interval (CI) of 95%, which was given by the 2.5$^{\mathrm{th}}$ and 97.5$^{\mathrm{th}}$ percentiles of the array with 1000n elements, following a random categorical model approach (Wang *et al.*, 2025). This array was generated through including the data of the n observed EFs and those generated by randomly re-sampling the n cases for 999 times (Dixon, 1993).

Differences in the means of direct EFs between two categories/sub-categories were considered statistically significant when their 95% CIs did not overlap with each other. Between-group heterogeneity tests were also performed to evaluate whether direct EFs differed significantly among categories/subcategories.

Potential publication bias was assessed using Rosenthal's fail-safe number (N_{fs}) (Rosenberg, 2005). A result was considered robust when N_{fs} exceeded $5n + 10$, where n is the number of studies included in the analysis (Koricheva *et al.*, 2013). The calculated N_{fs} was 15,141.5, exceeding the threshold value of 1605, indicating no substantial publication bias.

The IPCC guidelines for direct NO_x emissions from managed soils require a methodology consistent with that used for direct N_2O emissions from managed soils (https://www.ipcc-nggip.iges.or.jp/home/2027slcf.html). To achieve this, we extracted and analyzed direct EF data of NO from the dataset established in this study to derive $EF_{1(NOx)}$, $EF_{2(NOx)}$ and $EF_{3(NOx)}$. These three variables of NO_x correspond to the EF_1, EF_2 and EF_3 for direct EFs of N_2O, from managed soils, respectively, as defined in the IPCC Guidelines for Greenhouse Gas Inventories (IPCC, 2006, 2019). Specifically, EF_1 applies to other anthropogenic N inputs to managed soils, EF_2 applies to mineralized N in drained and/or cultivated organic soils, and EF_3 applies to urine- and dung-N deposited by grazing animals. To determine and refine these EFs for NO_x, we first analyzed all collected NO_x EFs data from managed soils, excluding observations related to urine and dung deposition by grazing animals. Statistical significance analyses were used to identify the major environmental and management factors contributing to EF variability. The results supported the derivation of aggregated $EF_{1(NOx)}$ values for Tier 1 and disaggregated $EF_{1(NOx)}$ values for Tier 2. $EF_{3(NOx)}$ was evaluated independently using observations of urine and dung deposition, while observations from managed organic soils were evaluated separately to derive $EF_{2(NOx)}$.

Unless otherwise specified, uncertainty ranges reported hereafter are given as 95% CIs.

3 Results and discussion

3.1 Data availability for stratification of direct NO_x emission factors

To develop direct NO_x EFs for managed soils, we first evaluated whether organic soils in peatlands should be treated separately from mineral upland soils. Among the annual cumulative NO emission data compiled in this synthesis (Fig. A1, Table A1), only limited observations were available for organic soils in peatlands ($n = 7$) (e.g., Bhattarai *et al*., 2022; Liu *et al.*, 2024; Regina *et al.*, 1998). These organic soils showed a mean annual NO emission of 1.19 (uncertainty range: 0.24–2.63) kg N/hm^2 per year, which did not differ significantly from the mean of 3.02 (uncertainty range: 2.45–3.67) kg N/hm^2 per year observed for mineral upland soils ($n = 264$), suggesting that current evidence is insufficient to support a significant difference in direct NO_x EFs between managed organic and mineral soils.

The resulting database contained 340 entries of direct EFs for N inputs to managed soils. Based on these data, cropping system was identified as the primary regulatory factor for Tier 1 $EF_{1(NOx)}$, with significant differences in direct EFs among flooded rice, tea plantations, and non-tea upland cropping systems ($p = 0.001$) (Fig. 3). We then assessed whether each Tier 1 category had sufficient data to support further stratification for Tier 2 EFs. The non-tea upland cropping systems had the largest sample size ($n = 237$), allowing further analysis of environmental and management regulators (Table 1, Fig. 3). In contrast, the relatively small sample sizes available for flooded rice ($n = 55$), tea plantations ($n = 27$), and urine and dung deposition by grazing animals ($n = 21$) were insufficient to identify key regulatory factors for further stratification (Table 1). For non-tea upland cropping systems, several environmental and management variables significantly affected direct NO EFs, including MAP ($p = 0.014$), SOC ($p = 0.001$), TN ($p = 0.001$), C/N ($p = 0.002$), soil texture ($p = 0.004$), N fertilization rate ($p = 0.003$), and N fertilizer type (p = 0.006) (Fig. 3, Table A2). Among these variables, SOC was identified as the most robust stratification factor for Tier 2 $EF_{1(NOx)}$, because its significant effect was supported by the most comparable and sufficiently large sample sizes between subgroups (n = 103 for ≤1% versus n = 131 for >1%). The TN showed the same level of statistical significance, but with less balanced subgroup sample sizes (with n = 86 for ≤1 g N/kg versus n = 147 for >1 g N/kg) (Table A2).

3.2 Direct emission factors of NO_x for Tier 1

3.2.1 Aggregated categorization of direct emission factors for NO_x from managed soils

Following the IPCC methodology grouping for N_2O emissions from managed soils (IPCC, 2006, 2019), the direct N_2O EF_1 applies to N inputs from synthetic fertilizers, organic manures, crop or pasture residues, and SOC mineralization to/in cropping systems. EF_2 applies to N inputs in drained and/or managed organic soils, whereas EF_3 applies to urine- and dung-N deposited by grazing animals on pastures, ranges, and paddocks. Correspondingly, this study defines $EF_{1(NOx)}$, $EF_{2(NOx)}$ and $EF_{3(NOx)}$ for direct NO emissions from managed soils. However, $EF_{2(NOx)}$ for drained and/or managed organic soils was omitted in determining default EFs for Tier 1, given the aforementioned insignificant differences in NO emissions between organic and mineral managed soils (Fig. A1). Considering the similar fundamental processes governing NO production and emission from soils, and the lack of observations from N-fertilized land uses other than croplands, we assumed that Tier 1 $EF_{1(NOx)}$ could be applied not only to managed cropland soils, including conventional crops such as cereals, root crops, vegetables, tea, and orchards, as well as unconventional crops such as herbs used for medicinal, beverage, or recreational purposes, but also to managed forest land, grassland, and wetland. These include, for example, N-fertilized forests for timber or bamboo-shoot production, N-fertilized grasslands for hay production, lawns, or swards, and N-fertilized flooded soils cultivated with cash hydrophytes.

The database established in this synthesis includes 319 and 21 field-observation entries for N source categories corresponding to $EF_{1(NOx)}$ and $EF_{3(NOx)}$, respectively (Table A1). Given that field-observed direct EFs of NO differed significantly among the three major cropping-system categories (Fig. 3), the N sources represented by $EF_{1(NOx)}$ were further divided into three aggregate categories, i.e., flooded rice, represented by $EF_{1,FR(NOx)}$, tea plantations, represented by $EF_{1,Tea(NOx)}$, and other systems, more specifically non-tea upland cropping systems, represented by $EF_{1,O(NOx)}$ (Table 1).

In the following sub-sections, the estimated values of $EF_{1,FR(NOx)}$, $EF_{1,Tea(NOx)}$ and $EF_{1,O(NOx)}$, as well as $EF_{3(NOx)}$, for Tier 1 are described and discussed.

Table 1 Direct emission factors (EF, in kg NO_x-N/(kg N)) for NO emissions from managed soils

Aggregated parameter	**Mean**[b]	**Uncertainty**[b]	**Disaggregated parameter**	**Mean**[b]	**Uncertainty**[b]
$EF_{1,O(NOx)}$[a, c]	0.0049 (*n* = 237)	0.0041–0.0058	$EF_{1,O,SOC\leq1\%(NOx)}$[a, b]	0.0031 (*n* = 103)	0.0025–0.0037
			$EF_{1,O,SOC>1\%(NOx)}$[a, e]	0.0063 (*n* = 131)	0.0049–0.0075
$EF_{1,FR(NOx)}$[a, f]	0.0010 (*n* = 55)	0.0005–0.0017	–	–	–
$EF_{1,Tea(NOx)}$[a, g]	0.0166 (*n* = 27)	0.0117–0.0215	–	–	–
$EF_{3(NOx)}$[a, h]	0.0011 (*n* = 21)	0.0006–0.0018	–	–	–

[a] The raw data to derive the direct EF values as well as their uncertainty ranges are found in Table A1, with *n* denotes sample size of worldwide field observations on direct EFs of nitric oxide (NO) for managed soils of aggregated categories or disaggregated subcategories.

[b] Detailed description of the methods used in determining the mean values and uncertainty ranges are found in the text of Section 2.2.

[c] $EF_{1,O(NOx)}$ denotes the annual direct EFs of NO for the nitrogen (N) inputs in the managed soils other than those growing flooded rice and/or utilized for tea plantations, i.e., the N-fertilized soils for growing non-tea upland crops (including perennial upland crops, annual upland crops, seasonal upland crops in rotational regimes of flooded rice and upland crops, and orchards) and non-crop upland vegetation (including N-fertilized forests, forage grass, sward and/or lawn).

[b] $EF_{1,O,SOC\leq1\%(NOx)}$, as one subcategory of $EF_{1,O(NOx)}$, denotes the annual direct EFs of NO for managed soils with soil organic carbon (SOC) contents of no more than 1% (i.e., 10 g C/kg).

[e] $EF_{1,O,SOC>1\%(NOx)}$, as another subcategory of $EF_{1,O(NOx)}$, denotes the annual direct EFs of NO for managed soils with SOC contents higher than 1%.

[f] $EF_{1,FR(NOx)}$ denotes the annual/seasonal direct EFs of NO for the N inputs in the managed soils cultivated with flooded rice or other hydrophyte crops (e.g., lotus).

[g] $EF_{1,Tea(NOx)}$ denotes the annual direct EFs of NO for the N inputs in the managed soils growing tea plantations.

[h] $EF_{3(NOx)}$ denotes the annual direct EFs of NO for the urine- and dung-N deposited on pastures, ranges, and paddocks by grazing animals.

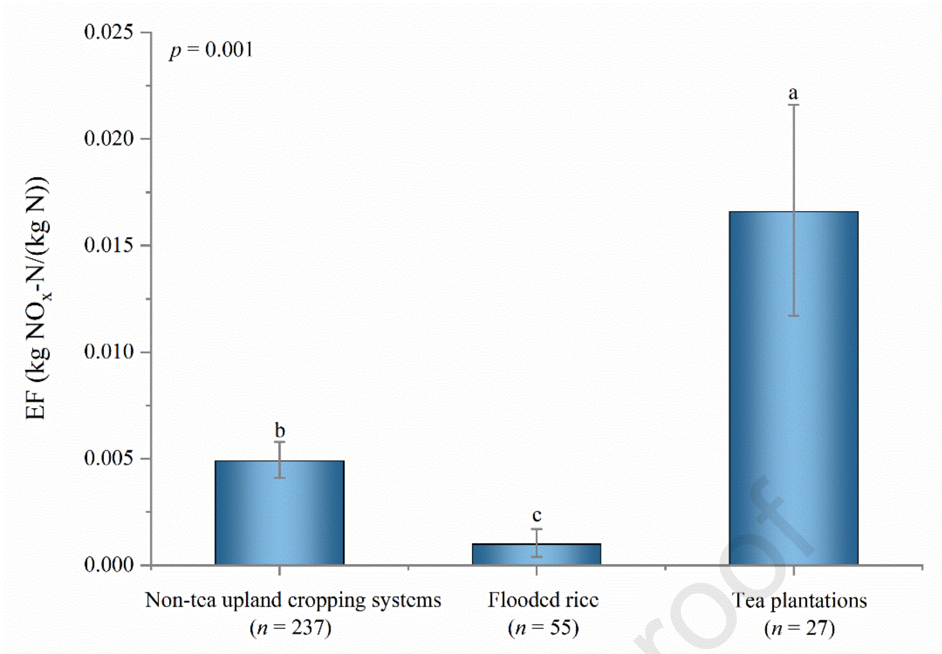

Fig. 3 Effect of major cropping systems on direct emission factors (EFs) of nitric oxide (NO) from soils with nitrogen (N) fertilizer application. The height of each column represents the mean value of direct EFs for the soils growing specific major cropping type, with its error bar indicating the uncertainty range at the 95% confidence interval (CI, i.e., 2.5th to 97.5th percentiles). The differences in direct EFs between any pair of the three major cropping types are considered statistically significant when their uncertainty ranges at the 95% CI do not overlap with each other and are shown by different lower-case alphabets above the columns. *n* indicates the sample size of observations within each subgroup. The non-tea upland cropping systems include rotations of upland cereal crops, upland cereal-fallow systems, vegetables and orchards.

3.2.2 Direct emission factors of NO_x for soils cultivated with flooded rice

The N source category represented by $EF_{1,FR(NOx)}$ for Tier 1- and Tier 2-based NO_x inventory compilation refers to anthropogenic N inputs to flooded soils. The database established in this study included 55 entries for annual/seasonal NO EFs from soils cultivated with flooded rice (Table A1). Based on these observations, the mean Tier 1 $EF_{1,FR(NOx)}$ was estimated at 0.0010 kg NO_x-N/(kg N), with an uncertainty range of 0.0005–0.0017 kg NO_x-N/(kg N), corresponding to 0.10% and 0.05%–0.17%, respectively (Table 1). The direct NO EFs for flooded rice systems were significantly lower than those for the other managed-soil categories ($p < 0.05$) (Fig. 3). The low value of $EF_{1,FR(NOx)}$ confirms that paddy rice fields are marginal sources of NO emissions at the global scale (Liu *et al*., 2017; Wang *et al*., 2022). The exceptionally low direct EFs of NO for flooded soils cultivated with rice are primarily governed by the prevailing strong soil redox conditions. Soil NO is produced mainly as a byproduct of aerobic nitrification (Abada *et al*., 2023; Zhao *et al*., 2025). In waterlogged paddies or other flooded soils, prolonged anaerobic conditions during the growing season, especially shortly after N fertilization, inhibit this aerobic pathway and consequently constrain NO production at its source microsites. Additionally, the anaerobic matrix of flooded soils often functions as a biological sink for NO_x, leading to low net emissions. Although denitrification and chemodenitrification can also produce NO, however, the NO is highly susceptible to further reduction during denitrification when overlying floodwater and water-filled soil pores restrict its transport, diffusion, and eventual emission from saturated/flooded soils surfaces (Medinets *et al*., 2015). Small amounts of NO produced in aerobic microsites, such as the soil surface or rhizosphere, are therefore largely intercepted within the surrounding anaerobic environment and reduced to N_2O or N_2 through consumptive denitrification before they can escape to the atmosphere (Gaihre *et al*., 2019; Qian *et al*., 2023).

3.2.3 Direct emission factors of NO_x for soils utilized for tea plantations

The N source category represented by $EF_{1,Tea(NOx)}$ for Tier 1- and Tier 2-based NO_x inventory compilation refers to anthropogenic N inputs to upland soils utilized for tea plantations. The database compiled in this synthesis included 27 entries of direct NO EFs from tea plantations (Table A1). Tea plantations were identified as primary hotspots of NO emissions among managed soils, with direct NO EFs 3 to 6 times higher than those of other managed upland soils (Table A1). The database established in this synthesis yielded a mean of 0.0166 and an uncertainty range of 0.0117–0.0215 kg NO_x-N/(kg N) (i.e., 1.66% and 1.17%–2.15%, respectively) for $EF_{1,Tea(NOx)}$ of Tier 1 (Table 1).

Tea cultivation is intrinsically associated with a relatively narrow range of extreme soil conditions, particularly strong soil acidity, which distinguishes this upland cropping system from broader land use categories. The disproportionately high direct EFs of NO observed in tea plantations (Tables 1 and A1, Fig. 3) are driven by specific management practices and biogeochemical conditions, especially their substantially lower soil pH compared with other cropland soils. Such low pH is mainly caused by aluminum-mediated interactions between tea plants and soils, together with periodic pruning practices in tea plantations (e.g., Zhang *et al*., 2020). Soil pH in tea plantations can often decline to below 4.5 after several years of continuous tea cultivation (e.g., Zhang *et al.*, 2020). Moreover, as a perennial cash crop, tea usually requires heavy N fertilization, with an average rate of approximately averaged 500 kg N/hm^2 per year, to maximize yield and quality (Chen *et al*., 2025; Wang *et al*., 2020), thereby providing abundant substrates for NO and N_2O production. Long-term application of ammonium (NH_4^+)-based fertilizers, such as urea and/or organic manure, combined with the physiological preference of tea plants for NH_4^+ uptake, further promotes soil acidification (Wang *et al*., 2020, 2023). Under strongly acidic conditions, NO and N_2O productions can be enhanced through coupled biotic and abiotic pathways. In particular, soil pH below 4.5 can directly trigger chemodenitrification, an abiotic chemical decomposition of NO_2 into NO and N_2O (Wang *et al*., 2022; Zhang *et al.*, 2020). Meanwhile, specialized acid-tolerant nitrifying communities may remain active despite strong acidity, maintaining high turnover rates of N (Li *et al*., 2018; Takahashi *et al*., 2025). The interaction between high substrate availability and acid-driven chemical reactions explains why tea plantations exhibit an order-of-magnitude higher NO and N_2O emissions compared to other cropping systems, making them critical targets for improved N management (Wang *et al*., 2020).

3.2.4 Direct emission factors of NO_x for upland soils growing non-tea vegetation

The N source category represented by $EF_{1,O(NOx)}$ for Tier 1- and Tier 2-based NO_x inventory compilation includes anthropogenic N inputs to managed upland soils and/or N released from soil organic matter due to land use change or managed organic soils. The database compiled in this synthesis contained 237 entries of direct EFs for this category (Table A1). Based on these observations, the aggregate $EF_{1,O(NOx)}$ was estimated to be 0.0049 (uncertainty range: 0.0041–0.0058) kg NO_x-N/(kg N) (i.e., 0.49%, 0.41%–0.58%) (Table 1). Statistically, these direct EFs were at an intermediate level, being significantly higher than those for lowland soils cultivated with flooded rice ($p < 0.05$) but significantly lower than those for upland soils utilized for tea plantations ($p < 0.05$). Because managed vegetation types, which broadly reflect differences in soil water conditions and/or acidity, were considered in the aggregate categorization, our Tier 1 estimates of $EF_{1,O(NOx)}$ together with those of $EF_{1,FR(NOx)}$ and $EF_{1,OTea(NOx)}$, are expected to better represent NO emissions from managed soils than the single default values of 0.7% recommended by Bouwman *et al*. (2002) and 1.1% adapted from IPCC (2019) for all managed soils These updated Tier 1 defaults can support NO_x inventory compilation based on national or global datasets on cropping systems, managed vegetation, and soils.

3.2.5 Direct emission factors of NO_x for soils with nitrogen deposition by grazing animals

The N source category represented by $EF_{3(NOx)}$ for Tier 1- and Tier 2-based NO_x inventory compilation corresponds to urine- and dung-N deposited by grazing animals on pastures, ranges and paddocks. The database established in this synthesis includes 21 entries of direct NO EFs for this category (Table A1). In fact, only one study, Maljanen *et al*. 2007, directly reported field measurements for grazing excreta, providing merely four observations from a single site. To broaden the empirical basis, these data were combined with direct NO EFs from studies on slurry application (Table A1). This combination is a practical approach, as both grazing excreta and slurry represent concentrated, labile N inputs at the soil surface, exhibiting similar microbial transformation kinetics and substrate-driven emission pulses (Cai & Akiyama, 2016; van der Weerden *et al*., 2021). Based on these data, the Tier1 $EF_{3(NOx)}$ was estimated with a mean value of 0.0011 kg NO_x-N/(kg N) and an uncertainty range of 0.0006–0.0018 kg NO_x-N/(kg N), i.e., 0.11% and 0.06%–0.18%, respectively (Table 1). The mean value of $EF_{3(NOx)}$ for livestock excreta deposition was comparably low, similar to $EF_{1,FR(NOx)}$ for lowland soils cultivated with flooded rice, yet remains significantly lower than $EF_{1,Tea(NOx)}$ and $EF_{1,O(NOx)}$ for other managed upland soils ($p < 0.05$). This disparity likely arises from extreme localized pH and/or elevated ionic strength within excreta patches, which can transiently inhibit NO-producing nitrifiers or shift N partitioning toward NH_3 volatilization (Giltrap *et al*., 2020).

3.3 Direct emission factors of NO_x for Tier 2

Using the identified factor of SOC content, which showed the most significant difference in direct EFs between the two subgroups ($p = 0.001$) while maintaining comparable sample sizes of 103 and 131, respectively (Table A2, Fig. 4), managed soils cultivated with non-tea upland cropping systems represented by $EF_{1,O(NOx)}$ were further disaggregated into two subcategories. The two subcategories were defined as managed upland soils with SOC ≤ 1% (i.e., 10 g C/kg), represented by $EF_{1,O,SOC\leq1\%(NOx)}$, and

SOC > 1%, represented by $EF_{1,O,SOC>1\%(NOx)}$. The observed direct NO EFs yielded mean values of 0.0031 and 0.0063 kg NO_x-N/(kg N), equivalent to 0.31% and 0.63%, respectively. Their uncertainty ranges were 0.0025–0.0037 and 0.0049–0.0077 kg NO_x-N/(kg N), equivalent to 0.25%–0.37% and 0.49%–0.77%, respectively, for $EF_{1,O,SOC\leq1\%(NOx)}$ and $EF_{1,O,SOC>1\%(NOx)}$ (Table 1). These values can serve as Tier 2 options when country-specific EFs are unavailable. Higher SOC concentrations promote the development of soil micro- and macropores, thereby improving aeration and facilitating NO_x diffusion from production sites to the atmosphere (Liu *et al*., 2020). SOC-rich soils also provide more substrates for microbial processes, including nitrification and denitrification, that contribute to NO_x production (Wang *et al*., 2022). Together, these physical and biochemical mechanisms help explain the higher direct EFs observed in soils with elevated SOC.

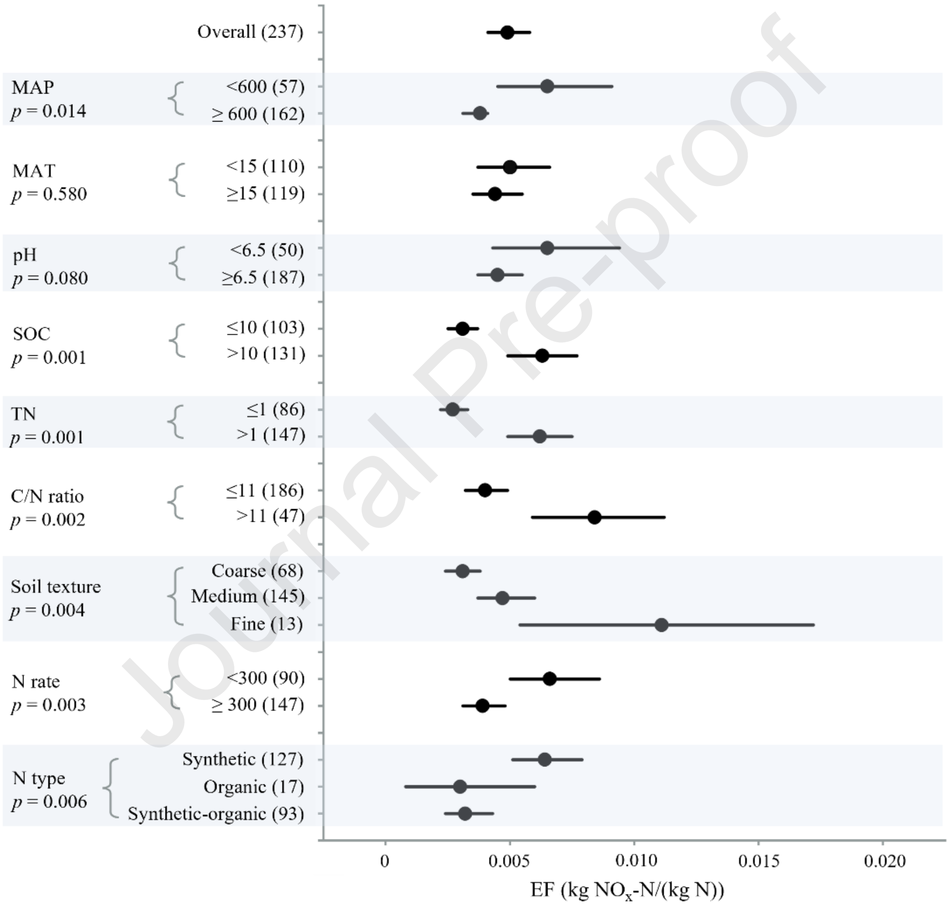

Fig. 4 Effects of environmental factors/variables on direct emission factors (EFs) of nitric oxide (NO) for managed soils with non-tea upland cropping systems. MAP, mean annual total precipitation (mm). MAT, mean annual temperature (°C). SOC, soil organic carbon (g C/kg). TN, total nitrogen (g N/kg). C/N ratio, SOC to TN ratio. N rate, N fertilization rate (kg N/hm^2). Their detailed values are found in Table A1. Each solid dot represents the mean direct EF value for all cases or for those specific to a subgroup of a factor/variable, with its horizontal bar indicating the uncertainty range at the 95% confidence interval (CI). A statistically significant difference in direct EFs across different subgroups of a factor/variable is identified when their uncertainty ranges (95% CI) do not overlap with each other. The significance of between-group heterogeneity indicates significant differences at $p < 0.05$. The number in parentheses indicates the sample size of observations within each subgroup of a factor/variable.

Considering that the EF values for both disaggregated subcategories of $EF_{1,O,SOC\leq1\%(NOx)}$ and $EF_{1,O,SOC>1\%(NOx)}$, were derived from up-to-date, globally distributed field observations with relatively large sample sizes (Table A1), they provide a robust empirical basis for Tier 2 NO_x inventories, even though their spatial coverage is not yet uniform (Fig. 2). For other anthropogenic N sources of managed soils cultivated with flooded rice, utilized for tea plantations, and/or with deposition of urine and dung by grazing animals, the limited number of available field observations (21–55 entries) (Table A1) remains insufficient to support further disaggregation across management or environmental gradients without introducing substantial categorical uncertainty. Therefore, no further stratification is recommended for the Tier 2 values of $EF_{1,FR(NOx)}$, $EF_{1,Tea(NOx)}$ and $EF_{3(NOx)}$. This limitation does not preclude Tier 2-based inventory development, as countries can still apply the Tier 2 approach when country-specific EFs are available.

3.4 Variability and uncertainty

Variability and uncertainty in this study arise primarily from the inherent complexities of soil N dynamics, simplifications in lower-tier methodologies, and limitations in the current empirical data. First, uncertainty is introduced by the generalized approaches used in Tier 1 methods. For example, the lack of disaggregation between managed mineral and organic soils suggests that specific emission dynamics, such as peat decomposition, are not accounted for, partly because of the limited studies. Similarly, treating animal excretion on pasture, range, and paddock as a single generalized N input fails to capture the distinct emission potentials of urine and dung, as NO_x is produced more rapidly from urine than from dung (Sitters and Olde Venterink, 2021). The use of aggregated values can therefore lead to substantial uncertainty depending on the dominant livestock systems and animal types, such as dairy versus beef cattle, in a given country. Second, NO_x emissions are highly sensitive to the physicochemical properties of the applied N. For organic N sources, the C/N strongly influences emission rates, resulting in substantially different NO_x emission patterns from high-C amendments, such as straw-rich manure, compared to liquid slurries (Huang *et al*., 2004; Yang *et al*., 2022). Moreover, in grazing systems, emissions often exhibit non-linear responses due to the formation of spatial 'hotspots' in urine patches (Charteris *et al*., 2021). This introduces considerable variability when precise activity data, such as stocking density, are unavailable. Finally, spatial bias in field observations remains a significant constraint. The uneven geographical distribution of studies (Fig. 2), combined with variations in experimental duration and measurement techniques, limits the universality of the derived direct EFs (Table 1).

Overall inventory uncertainty can be gradually reduced as expanding observational networks improve the spatial and temporal density of field data, thereby supporting the broader adoption of Tier 2 methodologies. However, a more fundamental reduction in uncertainty requires a transition toward Tier 3 approaches. By integrating process-based biogeochemical models with high-resolution environmental datasets, Tier 3 methods can mechanistically capture the nonlinear interactions among soil, climate, and management factors (e.g., Zhang *et al*., 2020), including complex dynamics that remain inherently simplified within the empirical framework of lower-tier methodologies.

4 Conclusions

This study synthesized global field observations to derive direct emission factors (EFs) of nitric oxide (NO) emissions from managed soils, providing potential default values for Tier 1 and Tier 2 nitrogen oxide (NO_x) inventories within the Intergovernmental Panel on Climate Change (IPCC) framework, analogous to the methodology for direct nitrous oxide (N_2O) emissions. The results indicate substantial differences in direct EFs among four major N source categories, defined by their management (I) growing upland vegetation types other than tea plantations, (II) utilized for tea plantations, (III) cultivated with flooded rice, and (IV) receiving urine and dung deposition by grazing animals. The type II soils exhibit the highest direct EFs, approximately four times higher than the type I and fifteen times higher than the types III and IV. Within the type I soils, soil organic carbon (SOC) content is the most influential factor. Accordingly, the type I can be further disaggregated into two subcategories, with the higher-SOC subgroup exhibiting nearly twice the direct EFs of the lower-SOC subgroup. The mean direct EFs for each type or sub-category can therefore serve as default values for the Tier 1 and Tier 2 inventory approach. Given that the single generalized default value of direct EF provided up to date by the IPCC cannot adequately capture the inherent heterogeneity of NO_x emissions across global/national managed soils, the aggregated and disaggregated direct EFs quantified in this study for specific types of N sources defined by managed vegetation and/or soil conditions strengthens the scientific basis for NO_x accounting and enables more accurate national emission inventories. The methodology proposed here also provides a foundation for future updates to IPCC guidelines and supports the development of targeted mitigation strategies for NO_x emissions from terrestrial ecosystems with managed soils.

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Author Contributions

Xunhua ZHENG and Yan WANG designed the study. Yan WANG and Xunhua ZHENG performed the research. Yan WANG analyzed the data and wrote the initial draft of the paper. Siqi Li, Zhisheng Yao, Niveta JAIN, Marta ALFARO, Martial BERNOUX, Julia DREWER, Changke WANG, Alberto SANZ-COBENA, Sylvia S. NYAWIRA, Wanli LIAN, Guangxuan YAN, Weiwei CHEN, Yanjiang CAI and Xunhua ZHENG reviewed and revised the paper. All authors contributed to the discussion and interpretation of the results.

Competing interests

The authors declare no conflict of interest.

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Declaration of interests

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

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Table 1 Direct emission factors (EF, in kg NO_x-N/(kg N)) for NO emissions from managed soils

Aggregated parameter	Mean[b]	Uncertainty[b]	Disaggregated parameter	Mean[b]	Uncertainty[b]
$EF_{1,O(NOx)}$[a, c]	0.0049 (*n* = 237)	0.0041–0.0058	$EF_{1,O,SOC\leq1\%(NOx)}$[a, d]	0.0031 (*n* = 103)	0.0025–0.0037
			$EF_{1,O,SOC>1\%(NOx)}$[a, e]	0.0063 (*n* = 131)	0.0049–0.0075
$EF_{1,FR(NOx)}$[a, f]	0.0010 (*n* = 55)	0.0005–0.0017	–	–	–
$EF_{1,Tea(NOx)}$[a, g]	0.0166 (*n* = 27)	0.0117–0.0215	–	–	–
$EF_{3(NOx)}$[a, h]	0.0011 (*n* = 21)	0.0006–0.0018	–	–	–

[a] The raw data to derive the direct EF values as well as their uncertainty ranges are found in Table A1, with *n* denotes sample size of worldwide field observations on direct EFs of nitric oxide (NO) for managed soils of aggregated categories or disaggregated subcategories.

[b] Detailed description of the methods used in determining the mean values and uncertainty ranges are found in the text of Section 2.2.

[c] $EF_{1,O(NOx)}$ denotes the annual direct EFs of NO for the nitrogen (N) inputs in the managed soils other than those growing flooded rice and/or utilized for tea plantations, i.e., the N-fertilized soils for growing non-tea upland crops (including perennial upland crops, annual upland crops, seasonal upland crops in rotational regimes of flooded rice and upland crops, and orchards) and non-crop upland vegetation (including N-fertilized forests, forage grass, sward and/or lawn).

[d] $EF_{1,O,SOC\leq1\%(NOx)}$, as one subcategory of $EF_{1,O(NOx)}$, denotes the annual direct EFs of NO for managed soils with soil organic carbon (SOC) contents of no more than 1% (i.e., 10 g C/kg).

[e] $EF_{1,O,SOC>1\%(NOx)}$, as another subcategory of $EF_{1,O(NOx)}$, denotes the annual direct EFs of NO for managed soils with SOC contents higher than 1%.

[f] $EF_{1,FR(NOx)}$ denotes the annual/seasonal direct EFs of NO for the N inputs in the managed soils cultivated with flooded rice or other hydrophyte crops (e.g., lotus).

[g] $EF_{1,Tea(NOx)}$ denotes the annual direct EFs of NO for the N inputs in the managed soils growing tea plantations.

[h] $EF_{3(NOx)}$ denotes the annual direct EFs of NO for the urine- and dung-N deposited on pastures, ranges, and paddocks by grazing animals.