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Tea-planted soils as global hotspots for N_2O emissions from croplands

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Supplementary material for this article is available online

Abstract

Tea-planted soils generally receiving high nitrogen (N) fertilizer doses are more vulnerable to acidification, and turn into significant sources of the potent greenhouse gas nitrous oxide (N_2O). However, little is known about the magnitude of soil N_2O emissions from global tea plantations. Based on a global meta-analysis of field experimental data collected from major tea growing countries, we quantify annual N_2O emissions, calculate direct emission factors (EF_d) and identify key environmental controls of emissions from tea plantations. However, most data are from China and Japan, which is to be expected given that tea plantations in these countries represent >60% of the global area and the vital environmental research community in both countries. Results suggest that annual N_2O emissions from soils of global tea plantations are on average 17.1 kg N ha^{-1} (or 8008 kg CO_2-eq ha^{-1}), being substantially greater than those reported for cereal croplands (662–3757 kg CO_2-eq ha^{-1}). The global mean EF_d for N applications to tea plantations equals 2.31% (with a 95% confidence interval of 1.91%–2.71%), being two times higher than the Intergovernmental Panel on Climate Change default value of 1%. Across tea plantations worldwide, total N_2O emissions are estimated to be 57–84 Gg N yr^{-1}, or 1.5%–12.7% of total direct cropland N_2O emissions. Given that tea plantations account for only 0.3% of total cropland area, our finding highlights that tea-planted soils are global hotspots for N_2O emissions and that these systems might be prime targets for climate change mitigation in the agricultural sector. Considering that tea is a high price commodity for which consumers may be willing to apply pressure for more climate-smart production, possible mitigation efforts include use of controlled-release fertilizers or nitrification inhibitors, and application of biochar and/or lime for increasing soil pH; i.e. measures that increase N use efficiency while reducing the climate footprint of tea production.

1. Introduction

Nitrous oxide (N_2O) is a potent greenhouse gas (GHG) contributing *ca.* 6% to observed global warming, and is also the most important contributor to stratospheric ozone layer destruction in the twenty-first century (IPCC 2013). Agricultural land uses comprise about 40% of total land area (Foley *et al* 2011), and N_2O emissions from agricultural soils are the dominating source (*ca.* 60%) of total anthropogenic N_2O emissions (Ciais *et al* 2013). Emissions of N_2O from agricultural soils are driven by the application of synthetic nitrogen (N) fertilizers and manure, and these emissions are projected to increase by approximately 50% from 2000 to 2050 (Davidson 2009, Syakila and Kroeze 2011). To limit warming in 2100 °C to 2 °C above pre-industrial levels, it will be required that GHG emissions from all related sectors, especially the agricultural sector, will be strongly reduced (Wollenberg *et al* 2016), putting N_2O emissions from agricultural soils and fertilizer use in the focus.

Tea (*Camellia sinensis* L.) is the most widely consumed beverage in the world. It is planted over a wide range of climatic (tropical, subtropical and temperate) conditions ranging from 45°N to 34°S latitude in as many as 62 countries across the globe. Total tea planting area was *ca.* 4.9 million hectares in 2018 (FAO 2018) and is expanding rapidly because of the economic and social importance of tea production. The main tea growing countries are China (61%), India (13%), Kenya (5%), Sri Lanka (5%), Indonesia (2%) and Japan (1%), accounting for *ca.* 87% of the world total tea planting area (FAO 2018). Due to varied agro-climatic conditions, the cultivation management practices (e.g. fertilizer type and rate) for tea plantations are variable from country to country. However, common features across tea planting are high rainfall and the use of high doses of inorganic and/or organic N fertilizers to obtain high free amino acid contents in the tea leaves for high quality of the product (Tokuda and Hayatsu 2004, Mishima *et al* 2012). For example, average N application rates used in tea fields have been reported to be >800 kg N ha^{-1} yr^{-1}, and in some cases even above 2000 kg N ha^{-1} yr^{-1} in Japan (Wang *et al* 2001, Tokuda and Hayatsu 2004). Current levels of N inputs in Chinese tea plantations range from 450 to 900 kg N ha^{-1} yr^{-1}, with an average of 553 kg N ha^{-1} yr^{-1} (Han *et al* 2013, Yao *et al* 2015). Even for Kenya where fertilizer applications are the second most expensive agronomic inputs in tea plantations, but where international tea companies pay farmers in dependence of tea quality, local farmers do apply up to 800 kg N ha^{-1} yr^{-1}, with a common rate of 200–350 kg N ha^{-1} yr^{-1} (Kamau *et al* 2000, Owuor *et al* 2010). Thus, N fertilizer inputs to tea plantations are much higher as compared to cereal cropping systems, which are on a global average in a range of 81–117 kg N ha^{-1} yr^{-1} (Gerber *et al* 2016).

Furthermore, as a result of specific environmental conditions, tea is usually planted on well-drained, acidic soils (Ruan *et al* 2013). Soil organic C content tends to increase with the duration of tea growing, due to the large quantity of litter falls and pruning materials from tea plants as well as the amendment of organic fertilizers by tea farmers (Yao *et al* 2018, Chiti *et al* 2018). The combination of relatively high soil C contents, high fertilizer N use, acidic soils and high rainfall are known to promote N_2O formation in soils via nitrification, denitrification and chemo-denitrification (Zhu *et al* 2014, Yao *et al* 2015), and high N_2O emissions from tea-planted soils have been increasingly noted in many studies. Akiyama *et al* (2006) reviewed data on N_2O emissions from Japanese agricultural fields, and found the highest N_2O emissions from tea plantations as compared to other crops. Jumadi *et al* (2005) reported that soil-emitted N_2O in tea garden was greater relative to pine and potato soils in Indonesia. Also, in China Han *et al* (2013) and Yao *et al* (2018) observed that annual N_2O emissions from tea plantations were much higher as compared to other upland fields or rice paddy fields. However, while studies consistently show that soil N_2O emissions from tea plantations are high, and major differences with regard to the magnitude of N_2O emissions from different tea-planted soils under various agro-climatic conditions have been noted (Akiyama *et al* 2006, Yao *et al* 2018), the reason for which so far remain unexplored.

Previous studies have suggested that to improve estimates of current and future agricultural N_2O emissions and establish effective N_2O mitigation efforts, it is essential for policy makers to acquire information on region-specific and crop-specific N_2O emissions and direct emission factors (EF_d, which is defined as the difference in annual N_2O emissions from the fertilized and unfertilized treatments per unit of N inputs), as the use of IPCC default value 1% (IPCC 2006) for EF_d might lead to strongly biased N_2O emission estimates (e.g. Yan *et al* 2003, Wang *et al* 2018). Despite the cultural and economic importance of tea plantations, previous reviews and meta-analyses of N_2O emissions from agricultural soils did not include data from tea-planted soils (e.g. Bouwman *et al* 2002, Kim *et al* 2013, Shcherbak *et al* 2014). Moreover, even the few studies available addressing N_2O emissions from tea plantations only focused on emissions at site to regional scale (e.g. Akiyama *et al* 2006, Mishima *et al* 2012, Yao *et al* 2015), while an overall synthesis and estimation of soil N_2O emissions and EF_ds across tea plantations worldwide is still lacking.

Therefore, we conducted a comprehensive and quantitative synthesis of published data concerning N_2O emissions from global tea-planted soils. The primary objective was to assess if a robust tea-specific N_2O EF_d can be identified on basis of published datasets. Furthermore, we aimed at quantifying total global N_2O emissions from tea-planted soils in dependence of environmental factors (e.g. climate, stand age, managements and soil properties) to evaluate the importance of this source in relation to other agricultural N_2O sources.

2. Methods

2.1. Literature search and data extraction

We conducted an exhaustive search of peer-reviewed articles published in the Web of Science as well as in the China Knowledge Integrated Database prior to August of 2019. Based on a combination of searching terms (i.e. 'nitrous oxide' AND 'N_2O' AND 'tea'), we extracted results from field studies on soil N_2O

emissions from tea plantations only, while rejecting results from laboratory incubation experiments and/or modeling studies. To be included in our datasets, soil N_2O emissions were measured using chamber-based techniques with sampling frequencies varying from daily to biweekly, and these studies must have covered an observational period of at least an entire year. Furthermore, inclusion of a field study required that detailed information on the use of inorganic and organic N fertilizers, i.e. with synthetic N fertilizer alone or with a full or partial substitution of synthetic N fertilizer by manure and information on soil properties is provided, with treatments reflecting most common management practices. To estimate the direct N_2O EF_d, soil N_2O emissions from unfertilized treatments were compared to those with conventional N treatments at the same experimental site. For sites where background N_2O emissions from unfertilized treatments were not reported, we estimated those based on data from studies in the same region because they had similar climate and soil conditions. Experimental studies with alternative fertilization practices such as controlled-release fertilizers, biochar, liming materials and nitrification inhibitors were collected as a separate group (when assessing the effect of the fertilization type), but were not included to estimate the mean annual N_2O emissions and EF_d for global tea plantations because of their specific mechanisms on inhibiting soil N_2O emissions (e.g. Wang *et al* 2018, Yue *et al* 2019). All studies report that fertilizer application to tea plantations, either as synthetic and/or organic N fertilizers, is done by banding and split applications across the year. Thus, the effect of fertilization mode was not evaluated in this study.

Based on our selection criteria 25 studies were identified (figure S1 (available online at stacks.iop.org/ERL/15/104018/mmedia)), reporting on 139 observational datasets on soil N_2O emissions from common fertilization managements ($n = 83$) and alternative fertilization practices ($n = 20$) as well as unfertilized treatments ($n = 36$) (table S1). Additionally, key characteristics (e.g. location, climate, soil properties, management practices, etc.) were extracted from the articles or, if missing, via communication with the authors of the field study. There are some more studies (e.g. Huang *et al* 2015, Liao *et al* 2019), but that those were not included as a result of the incubation experiments and modeling studies. It should be noted here that only one report each is available on N_2O emissions from tea plantations in India (measurements only cover 5 months: Gogoi and Baruah 2011) and Indonesia (laboratory combined with field study by Jumadi *et al* 2005). For Kenya two reports have been published. Most of the studies are from China and Japan, which, however, are key countries of tea production, e.g. China alone contributing about 61% of the total global tea planting area (FAO 2018).

2.2. Data and statistical analyses

As suggested by previous studies (e.g. Wang *et al* 2018), we performed a pair-wise meta-analysis using EF_d as effect sizes. In brief, the EF_d was calculated as the difference in annual N_2O emissions (in kg N ha^{-1} yr^{-1}) from the fertilized (E_F) and unfertilized (E_0) treatment divided by the applied N fertilizer rate, i.e. EF_d (%) = ($E_F - E_0$)/N × 100. Both standard deviations and standard errors of EF_d were rarely provided in most studies, and thus, our analysis was performed on effect sizes weighted by replication to avoid extreme weights occurring (van Groenigen *et al* 2011), using the following equation:

$$w = (N_{fertilization} \times N_{unfertilization}) / (N_{fertilization} + N_{unfertilization}) \quad (1)$$

where w is the weight given to each case, $N_{fertilization}$ and $N_{unfertilization}$ are the number of replicates for the fertilized and unfertilized treatment, respectively.

The non-parametric Kolmogorov–Smirnov test showed that the response ratio (RR, RR = ln (E_F/E_0)) data were normal distributed (figure S2), indicating the suitability of the database for meta-analysis (Wang *et al* 2018). In our meta-analysis, several categorical variables were used to examine their influences on annual EF_ds according to sub-groups/levels, including climate, stand age, soil properties and management-related parameters (table S2). Mean effect sizes and the 95% confidence intervals (CIs) of each category generated by bootstrapping (999 iterations) were calculated with a categorical random-effect model by MetaWin 2.1 (Rosenberg *et al* 2000). Means of effect size between different sub-group/levels were considered to be statistically significant at $\alpha = 0.05$ when 95% CIs were nonoverlapping, and they were also considered significantly different from the IPCC default value (1%) if the 95% CI did not overlap with 1%. The between-group heterogeneity (Q_b) test was used to further estimate the significance of each subgrouping category. Furthermore, non-linear, linear and stepwise multiple regression analysis were performed to explore the relationships between environmental and management-related variables and annual N_2O emissions as well as annual EF_ds.

3. Results

3.1. Annual N_2O emissions

Mean annual soil N_2O emissions from fertilized and unfertilized tea plantations were 17.1 kg N ha^{-1} yr^{-1} (CI: 13.1–21.3 kg N ha^{-1} yr^{-1}) and 2.8 kg N ha^{-1} yr^{-1} (CI: 1.4–5.2 kg N ha^{-1} yr^{-1}), respectively (figure 1). For fertilized soils of tea plantations, annual N_2O emissions were on average higher at sites with precipitation ≥1500 mm (24.0 kg N ha^{-1} yr^{-1}) as compared to those with <1500 mm (10.0 kg N ha^{-1} yr^{-1}) (table 1). Mean

Table 1. Observation numbers (n), mean of nitrogen (N) application rate and the corresponding mean annual nitrous oxide (N_2O) emissions and their 95% confidence intervals (CIs) as affected by precipitation, stand age, fertilizer type soil pH and C/N ratio.

	N application rate (kg N ha^{-1} yr^{-1})			Annual N_2O emissions (kg N ha^{-1} yr^{-1})	
	n	Mean	SD	Mean	CIs
Precipitation (mm)					
<1500	41	413	192	10.0b	7.8–12.6
≥1500	42	575	322	24.0a	17.1–31.2
Stand age (years old)					
<15	49	410	175	11.4b	8.0–15.6
≥15	34	618	346	25.2a	17.9–33.6
Fertilizer type					
Synthetic	17	346	277	11.1ab	4.1–20.9
Manure	12	264	155	13.0ab	6.8–20.6
Synthetic-manure mixture	54	593	249	19.8a	14.5–25.6
Alternative[a]	20	474	224	7.6b	5.5–10.2
pH					
<3.5	13	692	244	33.3a	18.7–47.4
3.5–4.2	32	501	255	14.6ab	10.1–19.3
4.2–6.1	38	422	278	13.6b	9.1–18.4
C/N ratio					
<10	13	311	157	14.1a	7.36–21.0
10–15	59	521	272	18.8a	13.5–24.1
>15	11	574	338	11.3a	4.02–21.5

[a] Alternative fertilizations refer to treatments with controlled-release fertilizers, biochar, liming materials and nitrification inhibitors.
The mean of annual N_2O emissions followed by different letters within a column are significantly different at $P < 0.05$.

annual N_2O emissions increased with stand age and were more than two times higher for sites ≥15 years old as compared to sites with a plantation age <15 years old (25.2 vs. 11.4 kg N ha^{-1} yr^{-1}). Application of a mix of synthetic and organic fertilizers showed in average highest N_2O emissions (19.8 kg N ha^{-1} yr^{-1}), which was also the group with the highest mean N application rate (593 kg N ha^{-1} yr^{-1}). In studies that included alternative fertilization practices as treatments, N application rates were on average higher than in treatments receiving synthetic fertilizers or manure only. For this group, however, mean annual N_2O emission with 7.6 kg N ha^{-1} yr^{-1} was lowest (table 1). Our analysis further revealed that mean N_2O emissions increased with decreasing soil pH values, with emissions from soils with a pH < 3.5 (33.3 kg N ha^{-1} yr^{-1}) being more than twice as much as emissions with a soil pH at 4.2–6.1 (13.6 kg N ha^{-1} yr^{-1}). Besides, it should be noted that the group with a C/N ratio ≥15 showed significantly lower mean N_2O emissions as the groups with a C/N ratio of 10–15 or <10 (11.3 vs. 14.1 or 18.8 kg N ha^{-1} yr^{-1}), though N application rates were highest rate as compared to that of 10–15 or <10 (table 1).

Using the entire dataset (n = 119), stepwise multiple regression analysis showed that N application rate was the most important factor controlling N_2O emissions (figure 2(a)), while other factors such as C/N ratio, precipitation and pH were of lesser importance or did not contribute at all to explain the observed variability in annual N_2O emissions across sites (table S3; figure S3).

3.2. Direct emission factors of N_2O

The global mean EF_ds for tea plantations were calculated to be 2.31%, with a 95% CI of 1.91%–2.71% (figure 1). The EF_ds correlated linearly with N application rates (figure 2(b)). Likewise, the response ratio of N_2O emissions (i.e. RR) was strongly positively correlated with N application rates (figure S4).

To identify the effect of environmental and management-related variables on annual N_2O EF_ds, we were running analyses for individual variables broken down into different categories (figure 3). There was no significant difference in EF_ds across most of the categorical variables except for N application rate ($P < 0.01$) and fertilization type ($P = 0.04$) (table S4). Among others, our analyses revealed that with increasing mean annual precipitation and stand age EF_ds in tendency, though not statistically significant, increased (precipitation: 2.61% for ≥1500 mm soils, n = 42 versus 2.02% for <1500 mm soils, n = 41; stand age: 2.57% for ≥15 years old plantations, n = 34 versus 2.14% for <15 years old plantations, n = 49), with the overall effect size (EF_ds) being in all cases significantly greater than the IPCC default value of 1% (figure 3(a)). Similar results, i.e. significantly greater EF_ds than the IPCC 1% estimate, were obtained if the dataset was analyzed for the effect of fertilizer type and rate (except N application rates <250 kg N ha^{-1} yr^{-1} for which the EF_ds were 1.36%, n = 17) (figure 3(b)). For the fertilizer types, the mean EF_ds did not significantly differ among soils managed with synthetic N fertilizers (1.75%, n = 17), manure (2.61%, n = 12) and combinations of both (2.42%,

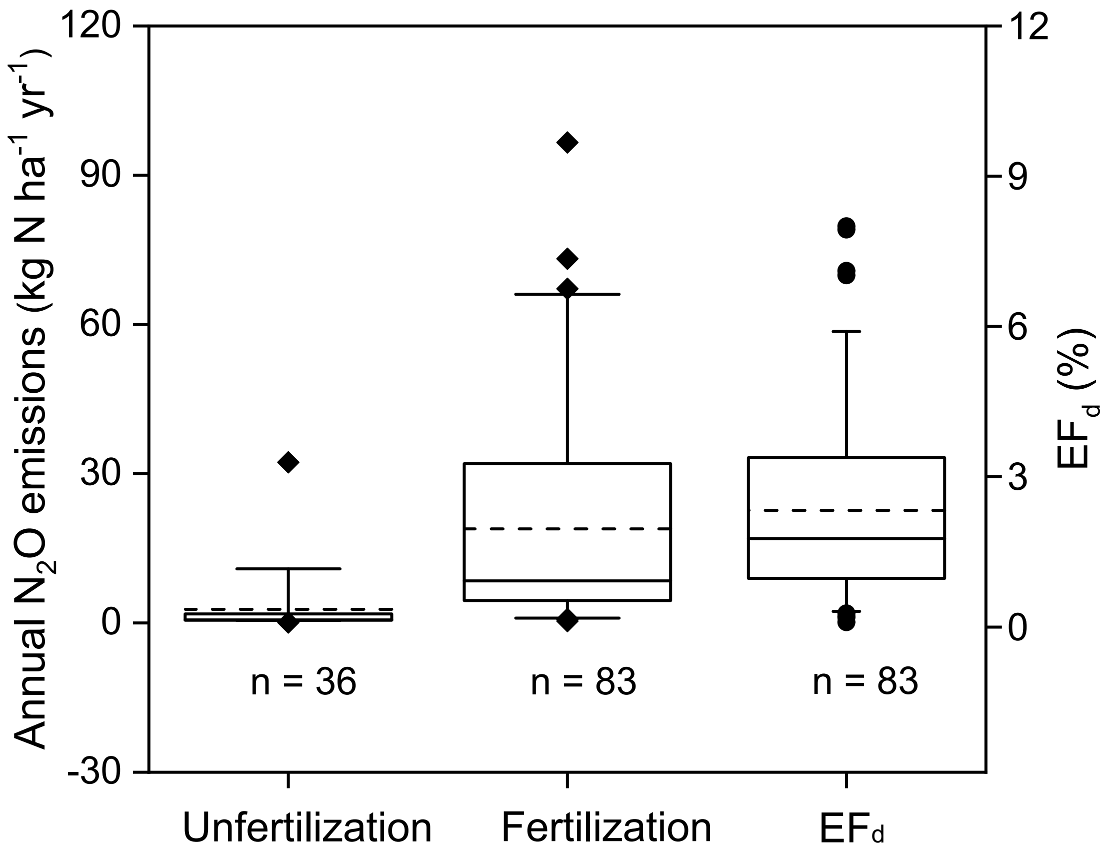

Figure 1. Box-plots representation of annual nitrous oxide (N_2O) emissions in the unfertilized and fertilized tea plantations as well as the direct N_2O emission factors (EF_d). Dotted and black solid lines inside the boxes represent means and medians, respectively. Box boundaries represent 75th and 25th percentiles, whisker caps represent 95th and 5th percentiles, as well as rhombus and circles represent outliers. Numbers under the boxes indicate sample sizes.

$n = 54$). However, for studies including alternative fertilization practices, a reduced EF_d of 1.20% ($n = 20$) was calculated, which was not statistically different from the IPCC default value of 1%.

Soil pH, texture, organic C, total N or C/N ratio did not significantly affect the EF_ds. However, the overall EF_ds calculated on the basis of soil properties were significantly higher relative to the IPCC default value of 1%, except for sites with soil C/N ratios >15 (1.48%, $n = 11$) (figures 3(c)–(d)). For the soil pH and C/N ratio, the average EF_ds tended to decrease with increasing these factors values, with highest EF_ds occurring for soils with pH < 3.5 (2.69%, $n = 13$) and a C/N ratio <10 (2.88%, $n = 13$), respectively. The results for different textural classes suggested that medium (2.65%, $n = 45$) and fine (2.53%, $n = 5$) textured soils were more prone to high EF_ds than coarse textured soils (1.83%, $n = 33$). Also, soil organic C and total N contents were related to the EF_ds. The average EF_ds for soils with SOC $\geq$ 20 g C kg^{-1} (2.53%, $n = 46$) and TN $\geq$ 2 g N kg^{-1} (2.60%, $n = 44$) were generally higher than those for soils with <20 g C kg^{-1} (2.04%, $n = 37$) and <2 g N kg^{-1} (1.99%, $n = 39$), respectively (figure 3(d)).

4. Discussion

4.1. Annual N_2O emissions and EF_ds and their controlling factors

The GHG balance of tea plantations is almost entirely driven by soil N_2O fluxes, while changes in soil C stocks or CH_4 fluxes are of minor importance (e.g. Yao *et al* 2018, Chiti *et al* 2018). However, the magnitude of soil N_2O emissions from tea plantations worldwide varies widely (table S1) most likely due to differences in climate (e.g. precipitation) and soil properties (e.g. soil texture, soil organic C and pH) as well as management practices (e.g. fertilizer type and N application rate) (Bouwman *et al* 2002, Fu *et al* 2015). Based on a thorough analysis of soil N_2O emissions from tea plantations, we found a surprisingly high mean value of 17.1 kg N ha^{-1} yr^{-1} (figure 1). In terms of the specific global warming potential of 298 for N_2O relative to CO_2 for a 100 year timescale, including climate carbon feedbacks (IPCC 2013), the estimated mean N_2O emission equals to 8008 kg CO_2-eq ha^{-1} for tea. Linquist *et al* (2012) conducted a meta-analysis of GHG (CH_4 and/or N_2O) emissions from major cereal cropping systems worldwide, and estimated that for rice, wheat

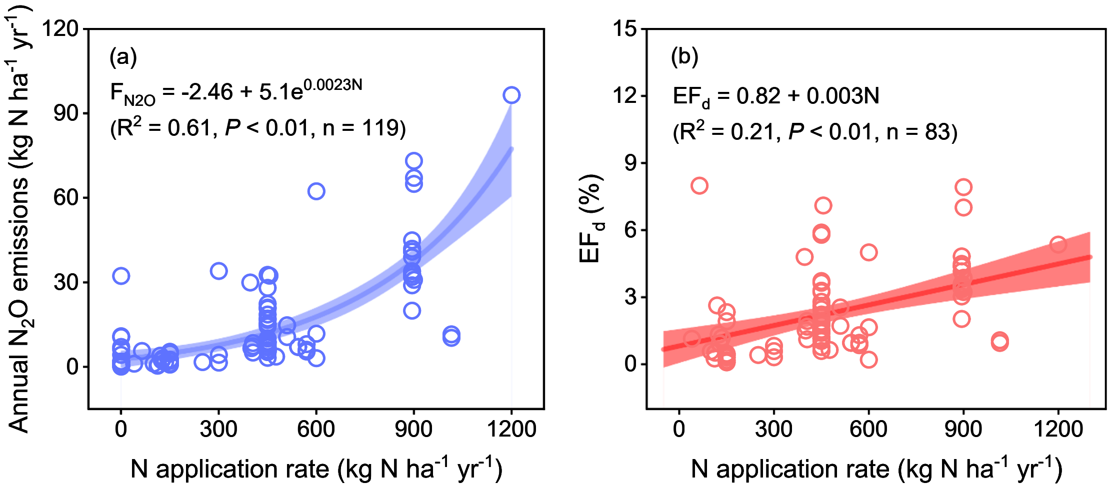

Figure 2. Relationships between nitrogen (N) application rate and (a) annual nitrous oxide (N_2O) emissions as well as (b) direct N_2O emission factor (EF_d) across tea plantations worldwide. The shaded areas represent 95% confidence bands.

and maize annual GHG emissions in CO_2 equivalents are on an average of 3757, 662 and 1399 kg CO_2-eq ha^{-1}, respectively. That is, even if compared to rice, which is known to be a crop with a high GHG footprint due to high emissions of CH_4 from flooded paddy fields, tea plantations result in a more than double as high GHG footprint, which is solely driven by soil N_2O emissions. Based on the global mean tea production of 1.5 Mg ha^{-1} yr^{-1} in 2018 (FAO 2018), yield-scaled annual N_2O emissions for tea might be estimated at 11.4 g N kg^{-1} tea production (or 5338 kg CO_2-eq Mg^{-1} tea production). These yield-scaled GHG emissions for tea are approximately one order of magnitude higher than estimates of Linquist *et al* (2012) for cereal crops (i.e. 657, 166 and 185 kg CO_2-eq Mg^{-1} for rice, wheat and maize, respectively), indicating that tea production has a significant climate footprint.

The high emissions of N_2O from soils of tea plantations are mainly driven by high inputs of N fertilizers. Our analysis shows that against the assumption of IPCC (2013), soil N_2O emissions positively exponentially increase with N application rates, becoming obvious once N fertilization rates are higher than approximately 250 kg N ha^{-1} yr^{-1}. Average rates of N fertilization across sites (83 observations) in our study are around 500 kg N ha^{-1} yr^{-1} (40–1200 kg N ha^{-1} yr^{-1}) (table S1). Such high N fertilization rates for tea, which are 5–6 times higher than global mean N fertilization rates for cereal crops (Gerber *et al* 2016), by far exceed the nitrogen demand of the tea crop which is estimated at 200 kg N ha^{-1} yr^{-1} (Wang *et al* 2001). One may argue that our synthesis is biased towards high N fertilization rates as most datasets were derived from studies in China and Japan. However, we also included the few additional studies available for Kenya, India and Indonesia to broaden the picture. Moreover, it should be noted that China and Japan contribute already approximately 62% to the world total tea planting area (FAO 2018). Finally, the common N application rates for tea plantations in other key tea producing regions are high too, with reported application rates ranging from 200 to 750 kg N ha^{-1} yr^{-1} (figure S1). That N_2O emissions increase exponentially once N fertilization rates exceed crop demands has been also reported by several researches (e.g. Philibert *et al* 2012, Kim *et al* 2013, Shcherbak *et al* 2014, Song *et al* 2018). However, those earlier regression analyses did not include tea plantations and the developed regression lines were only valid for N fertilization rates <300–500 kg N ha^{-1} yr^{-1}, while fertilization rates for tea plantations usually exceed 300 kg N ha^{-1} yr^{-1} (table S1; figure S5).

Nevertheless, the high magnitude of soil N_2O emissions remains stunning, specifically even for unfertilized soils of tea plantations a mean N_2O emission of 2.8 kg N ha^{-1} yr^{-1} was calculated (figure 1), which is a factor of two higher than the estimate of 1.4 kg N ha^{-1} yr^{-1} for cereal crops in China (Gu *et al* 2007), or the suggested 1 kg N ha^{-1} yr^{-1} for global croplands used by the IPCC (IPCC 2006). Such high 'background' emissions can probably be explained by the legacy of high inputs of synthetic and organic N fertilizers. As reported by previous studies, long-term tea planting results in high soil concentrations of residual N, mostly in the form of NO_3^-, in soil profiles (Han *et al* 2012, Chen and Lin 2016, Qiao *et al* 2018), which provide the substrate for denitrifiers. Under high soil NO_3^- concentrations the end product of denitrification is predominantly N_2O (Firestone *et al* 1979, Kim and Hernandez-Ramirez 2010, Butterbach-Bahl *et al* 2013). Another factor likely being responsible for high soil N_2O emissions is the low soil pH, as at low soil pH values N_2O reduction by the N_2O reductase is reduced, either due to direct pH effect on the assembly of the N_2O reductase (Russenes *et al*

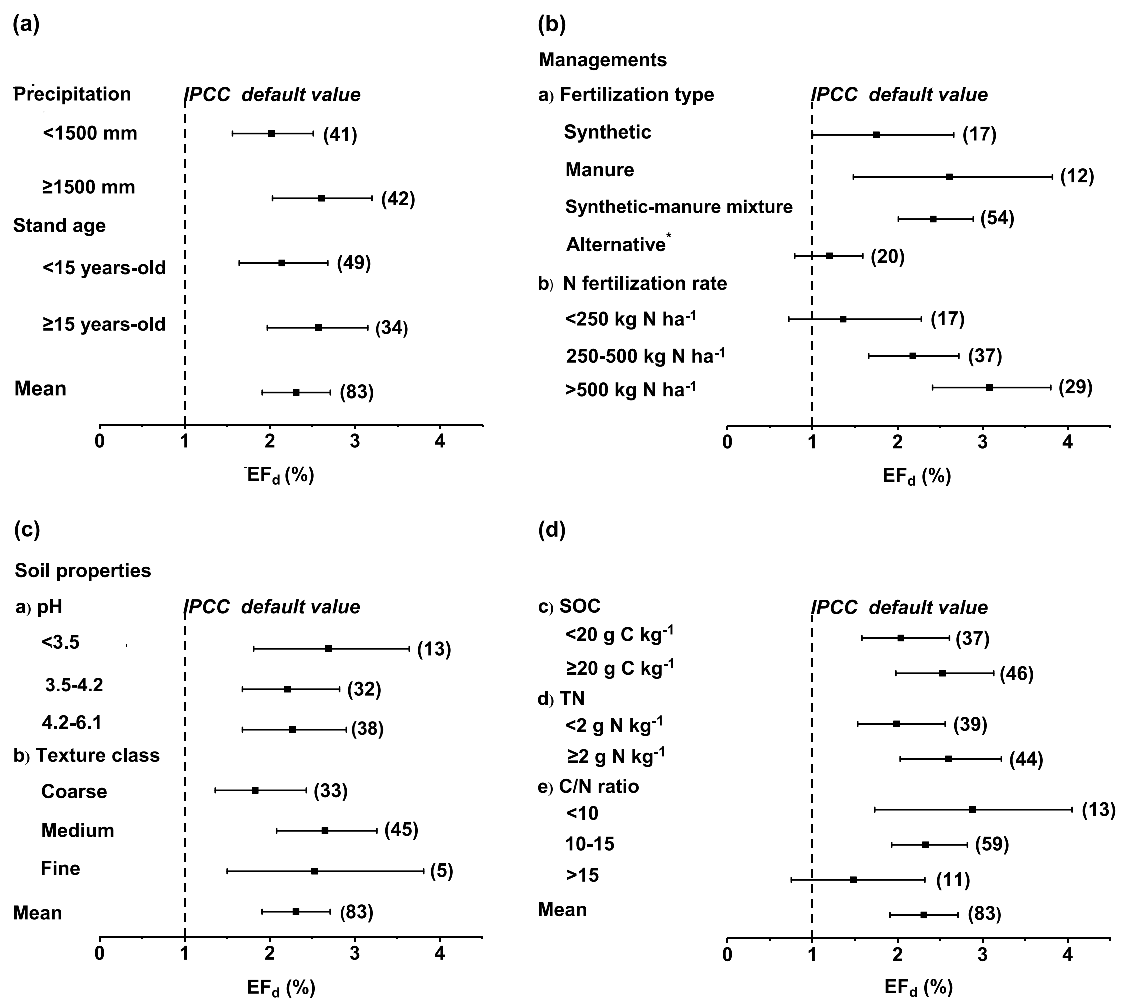

Figure 3. Effects of (a) precipitation and stand age, (b) managements and (c–d) soil properties on annual direct emission factors (EF_d) of nitrous oxide (N_2O) across tea plantations worldwide. Symbols represent means of effect size (EF_d (%)) with 95% confidence intervals (CIs). The EF_d (%) between different sub-group/levels were considered to be statistically significant at $\alpha = 0.05$ when 95% CIs were nonoverlapping, and they were also considered significantly different from the IPCC default value (1%) if the 95% CIs did not overlap with 1%. The numbers shown in parentheses correspond to the observation numbers in each sub-group/levels upon which the statistical analysis was based. * Alternative fertilizations refer to treatments with controlled-release fertilizers, biochar, liming materials and nitrification inhibitors. Studies include in this figure are shown in table S1 in Supporting information.

2016) or due to shifts in the soil denitrifier community towards denitrifiers lacking the gene for N_2O reductase (Cûhel *et al* 2010). Moreover, at soil pH values <3.5 which showed the significantly higher soil N_2O emissions in our analysis, chemo-denitrification might be an additional pathway of N_2O production (Kesik *et al* 2006).

Based on our meta-analysis, a global mean EF_d for tea is 2.31%, comparable to the global emission factor of 2.3% for the change in total soil N_2O emissions relative to the change in total N-input, including N-fertilizer, manure, biological nitrogen fixation, and NO_x deposition from non-agricultural sources (Thompson *et al* 2019). However, our calculated EF_d is more than twice as high as the estimate for croplands in East, Southeast and South Asia (0.93%; Yan *et al* 2003), or the IPCC default value of 1% for global croplands (IPCC 2006). The EF_d for tea is also significantly higher than EF_ds reported for other horticulture crops, cereal crops, fiber crops and oil crops (table 2). This shows that tea-planted soils are hotspots of N_2O emissions within the agricultural sector. Consistent with previous studies (e.g. Kim *et al* 2013, Shcherbak *et al* 2014), increasing N application rates resulted in increased N_2O EF_ds (figure 2(b)).

Besides, results of our meta-analysis indicate that stand age, precipitation as well as soil properties affect EF_ds. For example, N_2O emissions were generally higher in regions with high precipitation (i.e. $\geq$1500 mm). This is most likely that differences in precipitation lead to the changes in soil hydrological conditions, such as soil water content or the ratio of soil water content to field capacity, both show a positive or quadratic correlation with soil N_2O fluxes (e.g. Castellano *et al* 2010, Zhou *et al* 2020). Higher precipitation and its consequent effect on the increased soil water contents limit the availability of oxygen and provide more favorable conditions for denitrification

Table 2. Comparison of the direct N_2O emission factor (EF_d), nitrogen (N) application rate and evaluation method for various crop types.

Crop	Region	EF_d (%)	N application rate (kg N ha^{-1})	Evaluation method	Reference
Vegetable	Global	0.94	232	Meta-analysis	Razaei Rashti *et al* 2015
Fruit	Global	1.15	206	Review	Gu *et al* 2019
Horticulture	Mediterranean	0.67	100	Meta-analysis	Aguilera *et al* 2013
Wheat	Global	0.82	81	Nonlinear model	Gerber *et al* 2016
Maize	Global	0.91	101	Nonlinear model	Gerber *et al* 2016
Cotton	Global	0.85	99	Nonlinear model	Gerber *et al* 2016
Rapeseed	Global	0.87	108	Nonlinear model	Gerber *et al* 2016
Rice	Global	0.68	193	Meta-analysis	Linquist *et al* 2012
Wheat	Global	1.21	101	Meta-analysis	Linquist *et al* 2012
Maize	Global	1.06	119	Meta-analysis	Linquist *et al* 2012
Rice	Global	0.31	–	Review	Akiyama *et al* 2005
Rice	Global	0.46–0.53	–	Meta-analysis	Wang *et al* 2019
Upland crops	Global	1.05	–	Meta-analysis	Wang *et al* 2019
Crops	Asia	0.93	–	Meta-analysis	Yan *et al* 2003
Crops	Global	1.00	–	Linear model	IPCC 2006
Tea	Global	2.31	500	Meta-analysis	This study

as soils tend to be over extended time periods to be predominantly anaerobic, and thus improving soil N_2O fluxes (Tokuda and Hayatsu 2004, Charles *et al* 2017). The EF_ds for fine- (2.53%) and medium-textured soils (2.65%) are in tendency greater than for coarse-textured soils (1.83%), which agrees well with findings by Bollmann and Conrad (1998) and Stehfest and Bouwman (2006). Likely this is due to differences in pore size distribution, with smaller pores being more common in fine- and medium-textured soils as compared to coarse-textured soils, which on the one hand supports water retention, but on the other hand reduces soil aeration and thus, promotes anoxic conditions in soils and N_2O production through denitrification. Likewise, our results demonstrate an increase of EF_ds with increasing concentrations of soil organic C and total N. This corroborates previous studies stating that at high soil organic C contents, the N_2O-related nitrification and denitrification rates are stimulated (Li *et al* 2005, Owen *et al* 2015). This explanation also provides reasoning why with increasing stand age of the tea bushes N_2O emissions tend to increase, as in our study the mean soil organic C and total N contents in tea plantations with stand age ≥15 were significantly higher than those of tea fields with stand age <15 (i.e. SOC: 57.2 vs. 20.8 g C kg^{-1}; TN: 4.80 vs. 1.68 g N kg^{-1}, table S1). Moreover, the soil C/N ratio was negatively related to the EF_ds for soils of tea plantations, which is consistent with findings on the relationship between soil C/N ratio and N_2O emission reported by Klemedtsson *et al* (2005) for forest soils. Nevertheless, the investigated environmental factors (i.e. stand age, precipitation, soil properties and fertilization) are all related, exerting complex interactive effects on soil N_2O emissions, so that remains difficult to single out one specific factor. Thus, targeted experiments as greater sample sizes are needed to test the robustness of the above mentioned relationships for N_2O emissions from tea soils.

4.2. Total N_2O emissions from global tea plantations and mitigation efforts

Globally, tea was planted on 4.9×10^6 ha in 2018, equaling *ca.* 0.3% of the total global cropland area (FAO 2018). Considering regional differences in the optimized productivity and profitability of tea plantations, recommended global N fertilization rates are in the range of 400–600 kg N ha^{-1} yr^{-1} for mature tea fields (Hajiboland 2017), with an estimated mean value of 500 kg N ha^{-1} yr^{-1} (personal communication with advisors of Tea Research Institute, Chinese Academy of Agricultural Sciences). Multiplying the area with the recommended global fertilization rate and the N_2O EF_ds obtained in this study, the global N_2O emission from tea-planted soils were estimated to be approx. 57 Gg N yr^{-1}. An alternative way to estimate global N_2O emissions is to multiply the mean area-based N_2O emissions (i.e. 17.1 kg N ha^{-1} yr^{-1}) with the total tea planting area, which results in an estimate of 84 Gg N yr^{-1}. These estimates can be compared to estimates for soil N_2O emissions from global croplands, which range from 0.66 to 3.8 Tg N yr^{-1} (Del Grosso *et al* 2008, Syakila and Kroeze 2011, Ciais *et al* 2013, Gerber *et al* 2016, Tian *et al* 2018, Wang *et al* 2020), and which do not include emissions from tea plantations. Hence, total N_2O emissions from global tea-planted soils as estimated by EF_ds approach are approximately 1.5%–8.6% (mean: 3.1%) of total soil N_2O emissions from croplands worldwide. Similarly, total tea N_2O emissions upscaled by area-based emission account for 2.2%–12.7% (mean: 5%) of the reported total direct cropland N_2O emissions. These percentages are a significant fraction of global N_2O emissions for a crop that is planted on only 0.3% of the global cropland, highlighting the importance of tea-planted soils as significant contributors to climate change and stratospheric ozone depletion. However, we do note as well that approach inherits significant uncertainties due to the limited number of studies available and the overrepresentation of studies on N_2O emissions from tea plantations from China and Japan. Despite the uncertainties in the emission estimates, it is to be expected that N_2O emissions from tea plantations will further increase in the future as the demand for high quality tea is further increasing and as this demand can be expected to be covered by ensuing increases in N application rate and planting area (Tokuda and Hayatsu 2004, Li *et al* 2016, He *et al* 2019). On the other hand, our study also shows that N_2O emissions from N-rich and highly acidic tea-planted soils can be mitigated through alternative fertilization managements. For example, our results show that on average the application of controlled-release fertilizers or the addition of biochar, liming materials and nitrification inhibitors reduced soil N_2O emissions and EF_ds by 48% and 47%, respectively (table 1; figure 3). Thus, there is significant potential to reduce soil N_2O emissions from a globally important source—a goal which can possibly be achieved, considering that tea is a high price commodity for which consumers may be willing to apply pressure for more climate-smart production.

5. Conclusion

This work is the first quantitative synthesis investigating annual N_2O emissions and EF_ds from global tea-planted soils. In comparison to cereal cropping systems, tea plantations exerted a higher N_2O emission due to heavy fertilizer N inputs and high soil residual N as well as particular acidic soil conditions. The global mean EF_d for tea (2.31%) is more than double than estimates for other crops such as vegetable, fruit and cereal, or the default value of 1% used by the IPCC. If the available information on soil N_2O emissions are representative for global tea plantations, our study implies that soil N_2O emission from tea plantations worldwide contribute approx. 1.5%–12.7% to total global N_2O emissions from croplands, although the area planted with tea is only 0.3% of the global cropland area. Mitigating emissions from such a key source, with mitigation potentials around 48% if tested alternative management practices are applied, are significant in the frame of discussion around mitigating GHG emissions from the agricultural sector. Considering that tea has substantial economic benefits and high consumption levels worldwide, the consumers may be willing to apply pressure for developing more climate-smart management practices to reduce GHG emissions while ensuring tea production. It should be mentioned, however, that reports on N_2O emissions from tea plantations outside of China and Japan are scarce or missing and that due to the limited geographical representation of current studies the total N_2O emissions budget from global tea plantations is currently uncertain.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

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