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A global meta-analysis of nitrous oxide emission from drip-irrigated cropping system

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Abstract

Drip irrigation is a useful practice to enhance water and fertilizer nitrogen (N) use efficiency. However, the use of drip irrigation to mitigate nitrous oxide (N_2O) emissions in agricultural systems globally is uncertain. Here, we performed a global meta-analysis of 485 field measurements of N_2O emissions from 74 peer-reviewed publications prior to March 2021, to quantify the fertilizer-induced N_2O emission factor (EF) of drip irrigation and examine the influencing factors of climate, crop, soil properties, and source and rate of fertilizer N application. The results showed that drip irrigation reduced ($p < 0.05$) N_2O emissions by 32% and 46% compared to furrow and sprinkler irrigation systems, respectively. The overall average EF with drip irrigation was 0.35%, being two-thirds lower than the IPCC Tier I default value of 1% (kg N_2O-N/kg added fertilizer N). The EF was not significantly affected by climate, crop, soil texture, soil organic carbon content, and pH. The EF was also not significantly ($p > 0.05$) affected by synthetic N fertilizer source despite a lower numerical value with enhanced efficiency than conventional fertilizers. The EF increased significantly ($p < 0.001$) with N addition rate in a binomial distribution. Using the IPCC default EF overestimated N_2O emissions inventories for drip-irrigated cropping systems by 7614 and 13,091 Mg per year for China and the globe, respectively. These results indicate that drip irrigation should be recommended as an essential N_2O mitigation strategy for irrigated crop production.

KEYWORDS

drip irrigation, emission factor, fertilizer response, meta-analysis, nitrous oxide, soil texture

1 | INTRODUCTION

One fifth of cropland in the world receives irrigation and contributes to over 40% of the world's food production (FAO, 2014). In semi-arid and arid regions where soil moisture limits crop growth, irrigation water can alleviate crop moisture stress to enhance yields. However, traditional delivery practices such as flooding of furrows within fields and more recent application by sprinkler of water to soil and crop canopy surfaces are wasteful of water (Sánchez-Martín et al., 2008). More recently, development of drip irrigation by delivering low volume of water to the rooting zone of crops using plastic tubing has improved use efficiency of irrigation water, and has been adopted widely in semiarid and arid regions (Vázquez et al., 2005, 2006). According to the International Commission on Irrigation and Drainage (ICID), the global drip-irrigated agricultural area has reached 14.4 million ha, about 5% of irrigated area (ICID, 2020).

A consequence of importance to the environment because of the application of nitrogen (N) to crops is the resulting emission of the gas, nitrous oxide (N_2O), to the atmosphere. According to the Intergovernmental Panel on Climate Change (IPCC), more than 80% of N_2O emissions of anthropogenic origins are from croplands because of the addition of N fertilizers and livestock manures (IPCC, 2013). With a warming potential that is 298 times greater than carbon dioxide (Myhre et al., 2013), N_2O accounts for 6% of annual emissions (in carbon dioxide equivalents) of climate warming gases from human activities (IPCC, 2014). Further, N_2O is the most important stratospheric ozone-depleting gas emitted by human activities (Ravishankara et al., 2009). Reducing N_2O emissions is a key step toward achieving the goals of the Paris Agreement (Tian et al., 2020). Consequently, there is considerable interest in management practices to mitigate N_2O emissions from crop production (Akiyama et al., 2010; Wang et al., 2018; Zhou et al., 2017).

Fertigation is often used in drip irrigation systems to deliver dissolved fertilizer N to the root zone in multiple applications during crop growth. The delivery of N to crops with fertigation increases the N use efficiency of fertilizers compared to the application of granular fertilizers to soil followed by irrigation (Ma et al., 2018; Maris et al., 2015; Sánchez-Martín et al., 2008). The improved N use efficiency of fertilizers for crop production means the emissions of N_2O per amount of crop produced can be lower for drip-irrigated compared to other irrigation systems.

The emissions of N_2O for cropland under drip irrigation have shown to be lower than those for furrow and sprinkler irrigation (Bronson et al., 2018; Guardia, Cangani, Sanz-Cobena, et al., 2017; Li et al., 2020; Sanchez-Martín et al., 2010). However, a globally systematic analysis of N_2O emissions and applied N-scaled emission factor (EF) of different irrigation practices can be used to improve the accuracy of global inventories and databases of N_2O emissions. The analysis may also promote the adoption of drip irrigation to reduce N_2O emissions from agriculture. Further, understanding how climate, soil properties, and fertilizer N application rates relate to the emissions from drip-irrigated systems would further improve regional and global inventories.

Nitrous oxide is an intermediate product of the nitrification and denitrification processes produced depending on soil temperature, moisture, and the availability of mineral N and organic carbon (C). Under drip irrigation, the localized distribution of soil water and inorganic N substrates for N cycling processes occurs in vertical and lateral distances from drip emitters, corresponding to the spatial variability in N_2O emissions within fields (Sánchez-Martín et al., 2008; Guardia, Cangani, Andreu, et al., 2017). Previous studies have attributed to the lower N_2O emissions from drip than furrow irrigation to a better match of fertilizer N delivery with crop needs (Kennedy et al., 2013; Sanchez-Martín et al., 2010). In contrast, the findings of other studies have shown an increase in the frequency of wetting–drying cycles under drip irrigation enhanced the N_2O emissions (Fentabil et al., 2016; Smart et al., 2011).

The EF is the percentage of applied fertilizer N emitted as N_2O. It is often used to estimate N_2O emissions from agricultural lands by applying EF with shipments and applications of N fertilizers at regional or global scales. For example, the IPCC Tier I protocol uses an EF of 1%, indicating that 1% of the applied fertilizer N would emit as N_2O-N. Some recent studies have reported N_2O emissions to differ from a 1% EF depending on the rate of fertilizer N applied to soil, the source of N fertilizer (product type), crop type, and water management (Cayuela et al., 2017; Gerber et al., 2016). Based on a global meta-analysis, Shcherbak et al. (2014) found EF increased exponentially with N rates when N addition exceeds crop needs. Individual studies have reported EF to increase linearly or exponentially with N addition rate (Hoben et al., 2011; Ma et al., 2010; McSwiney & Robertson, 2005; Signor et al., 2013). It remains to be determined what a global meta-analysis of N_2O emissions from drip-irrigated cropping systems will indicate for a relation of EF to fertilizer N rate. Results of such analysis would provide implication for estimating N_2O inventories at global scale.

Fertilizer N products vary in their capacity to be transformed to N_2O. For drip-irrigated cotton in the province of Xinjiang, China, we recently reported that the inclusion of inhibitors of nitrification and urea hydrolysis with urea applied by drip fertigation but not granular polymer-coated urea applied pre-plant reduced the EF of N_2O emissions compared to conventional granular urea (Ma et al., 2018). A recent global meta-analysis based on dryland agricultural systems by Li et al. (2018) reported that the enhanced efficiency fertilizers (EEFs) including polymer-coated urea and stabilized urea with nitrification or urease inhibitors decreased N_2O emissions by 31–58% compared to conventional urea. Also using a global meta-analysis, Zhou et al. (2017) reported livestock manure to have an EF of 1.83% compared to 1.38% for conventional synthetic fertilizers. These studies highlight that N_2O emissions may vary not only with the type of irrigation practice but also with the type of fertilizer N used.

Climate, soil properties, and crop species can also exert significant influence on N_2O emission and EF of N fertilizers in agricultural systems. Based on 1008 N_2O emissions measurements from the agriculture field, Stehfest and Bouwman (2006) reported the N_2O emissions from subtropical climates were higher than other climates. In addition, soil pH and soil texture were found to have a significant influence on N_2O emissions, and N_2O emissions continuously increased with SOC content (Stehfest & Bouwman, 2006). Aguilera et al. (2013) reported that crop species affected the EF of N fertilizers due to differences in N demand by the plants. How climate, crop species, N fertilizer product type, and soil properties affect N_2O emissions and EF of N fertilizers with drip irrigation has not been examined. Meta-analysis provides a means to determine the role of the environmental and management factors on N_2O emissions.

In this study, a meta-analysis based on 485 measures of accumulative N_2O emissions from 74 peer-reviewed published studies was conducted to (1) quantify the direct N_2O emissions under drip irrigation compared to other irrigation systems such as furrow and sprinkler; and (2) determine the importance of climate, soil properties, N fertilizer product type, and rate of fertilizer N to the EF of fertilizers under drip irrigation.

2 | MATERIALS AND METHODS

2.1 | Data collection

In this study, data of N_2O emissions from drip-irrigated agricultural systems were obtained from peer-reviewed journal articles published between 1990 and March 2021. The publication databases, Web of Science (Thomson Reuters), Google Scholar (Google), and the Chinese National Knowledge Infrastructure (CNKI), were searched using the Boolean string of ("nitrous oxide" OR N_2O OR "greenhouse gas") AND (drip OR irrigat*). Screening of the publications had followed the PRISMA approach (Liberati et al., 2009), resulting in a total of 74 publications (Figure S1). Publications were retained for use in a meta-analysis if: (a) the study was field based and N_2O emissions accumulated at least a crop season (paddy field, greenhouse and laboratory incubation experiments excluded), (b) the study was of replicated plot design with at least three replicates per treatment, (c) the study included a control treatment condition of no added fertilizer N, or (d) N_2O emissions were reported for treatment of drip irrigation and at least one other irrigation system, or (e) treatments of N product type or rate of fertilizer addition in a drip-irrigated system.

Based on the criteria, a total of 485 cumulative N_2O emission observations from nine countries were included in this study (Figure 1). These observations were further grouped into three categories of (1) Irrigation System Emissions (drip, furrow, and sprinkler systems, 171 observations, Appendix S1), (2) Drip irrigation Emission Factors (for climatic zone, crop, soil properties, and N sources and rates, 222 observations, Appendix S2), and (3) Drip irrigation N Rate Emissions (the relationship between N_2O emission and N rate, 364 observations, Appendix S3). Some studies had contributed to multiple observations in the three groups of analyses, whereas others were included in one group but not in the other. For example, one paper (Ye et al., 2020) reported the N_2O emissions from drip and furrow irrigation fields, as affected by fertilizer management practices but without reporting the N application rate, so it is included in the first group but not in the third.

From each publication, the seasonal or annual cumulative N_2O emissions (kg N_2O-N ha^{-1}, N_2O multiplied by 28/44 is converted to N_2O-N) and N addition rates (kg N ha^{-1}), as well as the measure of variance and the number of replicates, were extracted for each treatment from data tables, figures, and text included in the publications. Data presented only as figures were extracted using the Engauge Digitizer (version 4.1) computer software program (Li et al., 2015). If the study reported only seasonal variation of N_2O flux, the cumulative emissions were estimated by the summation of daily N_2O flux rates obtained using the linear interpolation method. Additional information including geographic location, climate data, soil texture class, pH, SOC, irrigation type, amount of irrigation water, crop species, duration of the experimental period, and fertilizer products used were also extracted (Appendices S1–S3). Seven studies did not report the complete soil properties, so information on soil texture class (four studies in Appendix S2), pH (three studies in Appendix S2), and SOC (three studies in Appendix S2) were obtained from the Harmonized World Soil Database v1.2 (FAO, 2012) using the latitude and longitude of each study (Wang et al., 2018; Zhou et al., 2017).

The irrigation systems used in the studies were assigned to furrow, sprinkler, or drip irrigation. In addition, four categorical (climate zone, crop type, soil texture, and fertilizer product) and three continuous

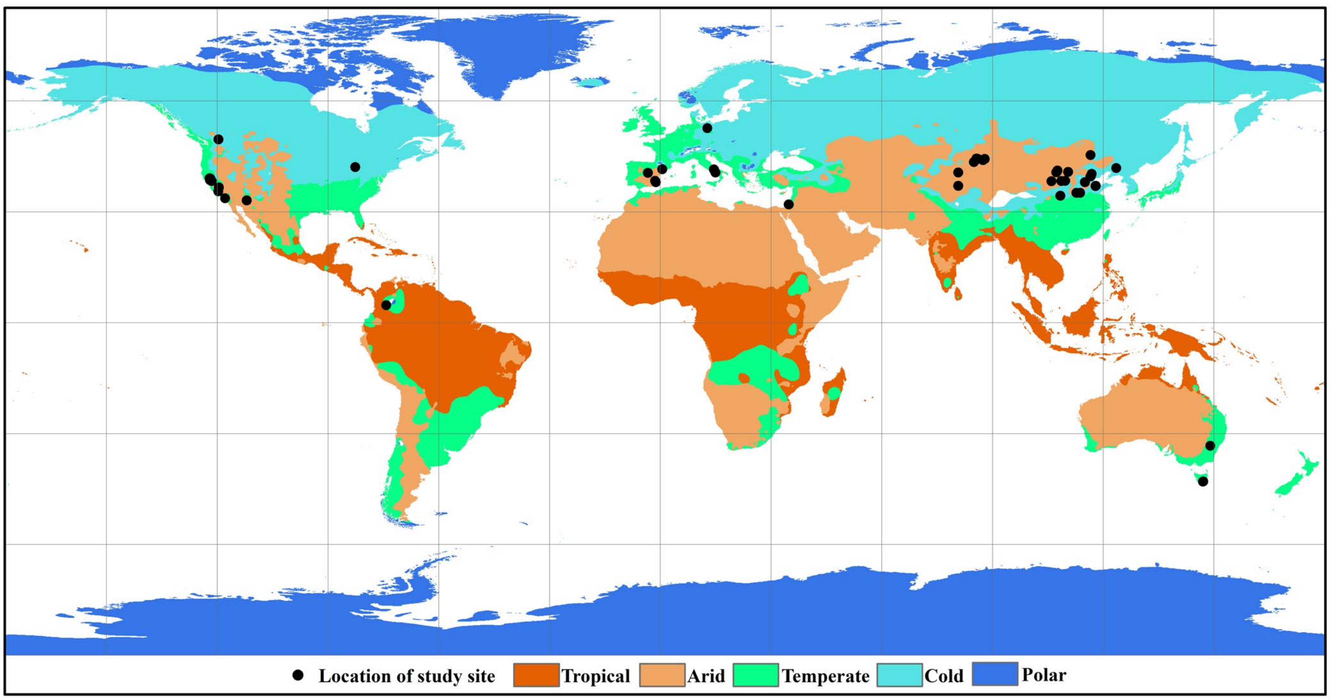

FIGURE 1 Köppen-Geiger climate type map and location of the study sites included in this meta-analysis (*n* = 74) [Colour figure can be viewed at wileyonlinelibrary.com]

(SOC, soil pH, N application rate) factors were included in the analysis of EF. The climate zone of each study was placed to the Köppen-Geiger climate designations of Arid, Temperate, or Cold (Peel et al., 2007). The crop species used in the studies were designated to three crop types, namely Cotton for Fiber, Grain (maize, wheat), and Horticultural (grape, potato, melon, olive, lettuce, and broccoli). The study soils were designated to three texture groups, namely Sand (sand, sandy loam, sandy clay loam, loamy sand textures), Loam (loam, silt loam), and Clay (clay, clay loam), with soil texture being classed according to USDA (1999). Fertilizer N product was grouped into Conventional synthetic fertilizers (urea, compound NPK fertilizers, and various forms of nitrate and ammonium fertilizers), EEFs (polymer-coated urea and stabilized urea incorporated with nitrification or urease inhibitors), or Organic addition (livestock or green manures).

2.2 | Data analysis

The effect of drip irrigation on N_2O emission relative to furrow or sprinkler irrigation was assessed using the natural logarithm of the response ratio (ln *RR*) as effect size shown in Equation (1; Lipsey & Wilson, 2001).

$$\text{Effect size} = \ln \text{RR}_i = \ln\left(\frac{\overline{X}_{it}}{\overline{X}_{ic}}\right) = \ln\left(\overline{X}_{it}\right) - \ln\left(\overline{X}_{ic}\right) \quad (1)$$

For each study *i*, $\overline{X}_{it}$ is the mean of cumulative N_2O emissions (kg N_2O-N ha^{-1}) for furrow or sprinkler irrigation and is that for drip irrigation.

The EF was used for the effect size of climate, soil properties, and N fertilizer products and rates on N_2O emissions under drip irrigation (Cayuela et al., 2017). The EF was calculated as the percentage of fertilizer-induced N_2O emissions (emitted N_2O corrected for emissions from an unfertilized Control) relative to the rate of applied N product (Equation 2).

$$\text{EF}_i = \frac{\overline{X}_{it} - \overline{X}_{ic}}{\text{applied N}} \times 100, \quad (2)$$

where $\overline{X}_{it}$ and $\overline{X}_{ic}$ are the means of cumulative N_2O emissions (kg N_2O-N ha^{-1}) for the fertilized treatment and the unfertilized Control for each study *i*, respectively. Applied N is the rate of N application (kg N ha^{-1}). According to the definition of emission factor, EF_i is recorded as 0 when $\overline{X}_{it}$ is lower than $\overline{X}_{ic}$.

The variance of effect size and EF for each study is estimated by Equation (3; Hedges et al., 1999).

$$v_i = \frac{\text{SD}_{it}^2}{\overline{X}_{it}^2 \times n_{it}} + \frac{\text{SD}_{ic}^2}{\overline{X}_{ic}^2 \times n_{ic}}, \quad (3)$$

where SD_{it} and SD_{ic} are the standard deviations of $\overline{X}_{it}$ and $\overline{X}_{ic}$, respectively, n_{it} and n_{ic} are the numbers of replicates per treatment for $\overline{X}_{it}$ and $\overline{X}_{ic}$, separately. For studies in which standard deviation or standard error was not reported, the SD_{it} and SD_{ic} were estimated by "Bracken, 1992" approach using the *metagear* package for R (Bracken, 1992; Lajeunesse, 2016).

The total variance (v_i^*) for each individual study *i* was considered as the summation of within-study variance (v_i) and between-study variance (τ^2; Equation 4). The restricted maximum likelihood (REML) was used to estimate τ^2 (Veroniki et al., 2016).

$$v_i^* = v_i + \tau^2. \quad (4)$$

A nonparametric weighting function was used to weigh each individual study (Hedges et al., 1999). For each study, the weighting factor w_i was calculated as the inverse of the pooled variance ($1/v_i^*$). When multiple observations were extracted from the same study, we adjusted the weights by the total number of observations per study. The final weight (w_i^*) used in the analyses was decided by Equation (5):

$$w_i^* = w_i/n_i = 1/n_i\left(v_i + \tau^2\right) \quad (5)$$

where n_i is the number of $\ln \text{RR}_i$ or EF_i in study *i*.

The weighted effect size ln RR* (Equation 6) and weighted EF* (Equation 7), and mean effect size $\overline{\ln \text{RR}^*}$ (Equation 8) and mean emission factor $\overline{\text{EF}^*}$ (Equation 9) were then calculated using the following equations.

$$\ln \text{RR}_i^* = w_i^* \times \ln \text{RR}_i, \quad (6)$$

$$\text{EF}_i^* = w_i^* \times \text{EF}_i. \quad (7)$$

$$\text{Mean effect size} = \overline{\ln \text{RR}^*} = \frac{\sum_i \ln \text{RR}_i^*}{\sum_i w_i^*}, \quad (8)$$

$$\text{Mean EF} = \overline{\text{EF}^*} = \frac{\sum_i \text{EF}_i^*}{\sum_i w_i^*}, \quad (9)$$

where $\ln \text{RR}_i^*$, EF_i^*, and w_i^* are ln RR, EF, and *w* of the *i*th observation, respectively.

The meta-analysis was performed using the package *metafor* version 2.4.0 (Viechtbauer, 2010) and *metaforest* (Van Lissa, 2020) in R version 4.0.3 (R Core Team, 2020). A random-effects model was used to assess the significant effects of mean effect size and mean EF with 95% confidence intervals (CIs). The effects were considered significant if the 95% CI value of the mean effect size did not overlap with 0. This model was also used to assess the residual heterogeneity. There was a significant residual heterogeneity in the random-effects meta-analysis for the Irrigation System Emissions ($Q_T = 1998.7$, $p < 0.0001$) and the Drip irrigation Emission Factors dataset ($Q_T = 6487.8$, $p < 0.0001$). A mixed-effects meta-analysis model was used to assess the variations in effect size or EF according to several categorical and continuous moderators. In this model, the total heterogeneity (Q_T) of each variable in the categorical group was partitioned into the explained heterogeneity by the moderator (Q_M) and the unexplained (unknown factors) residual heterogeneity (Q_E). The significance of Q_M represented the mean effect sizes that were significantly different between various levels of the categorical group (Viechtbauer, 2007). For the continuous moderators, the statistical results were reported as the Q_E, the Q_M, the intercept distance, the slope, and the p values. The relationships were considered significant at $p < 0.05$. The mean effect size $\overline{\ln RR'}$ was transformed as a percentage to express the magnitude of reductions of N_2O emission with drip irrigation relative to furrow or sprinkler irrigation systems by Equation (10).

$$1 - \frac{1}{e^{\overline{\ln RR^*}}} \times 100\%. \tag{10}$$

Publication bias was assessed using the Funnel plots and Egger's regression test (Egger et al., 1997; Sterne & Egger, 2001). In cases where the Funnel plots and Egger's regression test showed publication bias, the trim and fill method was applied to estimate the missing studies and their effect on the mean effect size or EF (Duval & Tweedie, 2000; Gurevitch et al., 2018).

Drip irrigation N Rate Emissions database was used to determine the relationship between cumulative N_2O emission and N addition rate under drip irrigation. For studies where only one calculative N_2O emission value at a certain fertilizer application was reported, a weight value was set as 1. If a study had multiple (n) calculative N_2O emission values with same N application rate, the weight of each value was $1/n$. An exploratory moderator analysis based on machine learning was followed with a mixed-effects meta-regression model to determine the relationship between cumulative N_2O emission and N addition rate under drip irrigation (Van Lissa, 2020).

The area and N application rate were used to estimate the fertilizer-induced N_2O-N emission changes by drip irrigation in China and the globe. Here, the drip-irrigated area and average N application rate in each individual country were obtained from the International Commission on Irrigation and Drainage (ICID) and the Food and Agriculture Organization of the United Nations (FAO), respectively (FAO, 2020; ICID, 2020). The EF for the drip-irrigated cropland in each country was assessed based on the model from this meta-analysis. The annual N_2O emissions from each country was then calculated by combining the area of drip-irrigated cropland, the average N rate, and EF. The global N_2O emissions from drip-irrigated cropland system were then calculated as the summation of that in each country (Table S1).

3 | RESULTS

3.1 | Irrigation system

Drip irrigation significantly reduced N_2O emissions by 32% (95% CI: 20%–42%) and 46% (95% CI: 30%–58%), compared to furrow and sprinkler irrigation system, respectively (Figure 2). There was no significant (p = 0.1443) difference between furrow and sprinkler systems. In addition, the Funnel plots and Egger's regression test showed a publication bias for mean effect size, with the mean N_2O emission reduction margin of drip irrigation being 44% (95% CI: 36%–52%) after applying the trim and fill method (Figure S2).

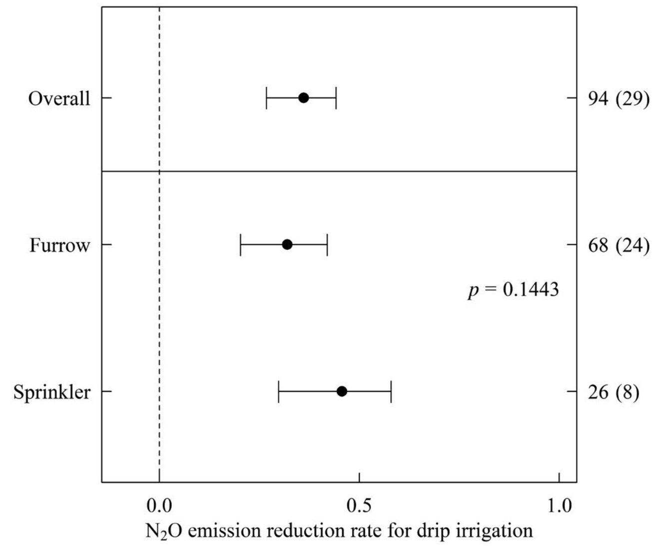

FIGURE 2 N_2O emission reduction rate (1-1/exp (effect size)) for drip relative to furrow and sprinkler irrigation systems. Numbers of the observations (studies) for each category are given on the right axis. The p values for the differences between furrow and sprinkler systems are shown in the panel

3.2 | Effects of climate and crop type on EF in drip irrigation

The mean EF in drip irrigation system was 0.35% (95% CI: 0.28%–0.41%; Figure 3). There was no publication bias for EF based on the Funnel plots and Egger's regression test (Figure S3). Drip irrigation with a Temperate climate had the lowest EF of 0.28% (95% CI: 0.10%–0.46%), which was lower than that with a Cold climate of EF 0.37% (95% CI: 0.24%–0.50%) and Arid climate with EF of 0.35% (95% CI: 0.27%–0.43%). Among the test crops, Horticultural had higher EF of 0.36% (95% CI: 0.21%–0.51%) than Cotton for Fiber of 0.35% (95% CI: 0.25%–0.44%) and Grain of 0.34% (95% CI: 0.24%–0.44%). The differences in EF between climates and crops were, however, not statistically significant. [Correction added on 3 June 2021, after first online publication: the word “lower” has been replaced with “higher”.]

3.3 | Effect of soil properties on EF in drip irrigation

The EF of soil texture, soil organic carbon content, and pH groups did not significantly differ in drip irrigation (Figure 4a; Table 1). Still, the mixed-effects meta-analysis model showed a significantly ($p < 0.05$) positive correlation between EF and clay content of soil (Figure 5a; Table 1).

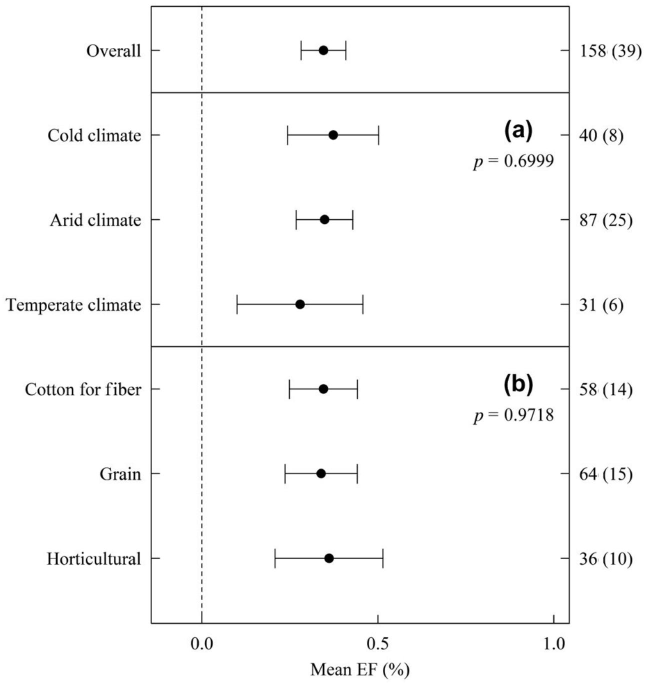

FIGURE 3 Effects of climate (a) and crop (b) on N_2O emission factor (EF) in drip irrigation system. Numbers of the observations (studies) for each category are given on the right axis. Error bars represent 95% confidence intervals (CIs). The *p* values for the differences between subcategories are shown in the panel

3.4 | Effects of fertilizer N source and application rate on EF in drip irrigation agriculture

The EEFs had significantly (p = 0.01) lower EF (0.21%; 95% CI: 0.05%–0.36%) than Organic addition (EF: 0.49%; 95% CI: 0.34%–0.65%; Figure 4b). The Conventional synthetic fertilizers had an intermediate EF of 0.35% (95% CI: 0.27%–0.42%), which was not significantly different from that of EEFs or Organic addition. Analyzed by mixed-effects meta-analysis model, EF was positively (p < 0.05) related to N application rate (Figure 5b; Table 1).

Across all observations of cumulative N_2O emission under drip irrigation, based on the machine learning with a mixed-effects meta-regression model, the best-fit response curve for N_2O emissions as a function of N rate was the quadratic function:

$$N_2O = 0.6696 + 0.001\,N(1.119003 + 0.009362\,N),$$

where N_2O is the total N_2O emissions (kg N_2O-N ha^{-1}) and N is the N addition rate (kg N ha^{-1}). The coefficient of determinant (R^2) was relatively low at 0.31 in spite of being significant (Figure 6). Based on the data of drip-irrigated area (ICID, 2020) N application rate (FAO, 2020), fertilizer-induced N_2O-N emissions from drip-irrigated agriculture are 7614 and 13,091 Mg per year overestimated by IPCC (2006) for China and the globe, separately (Table 2).

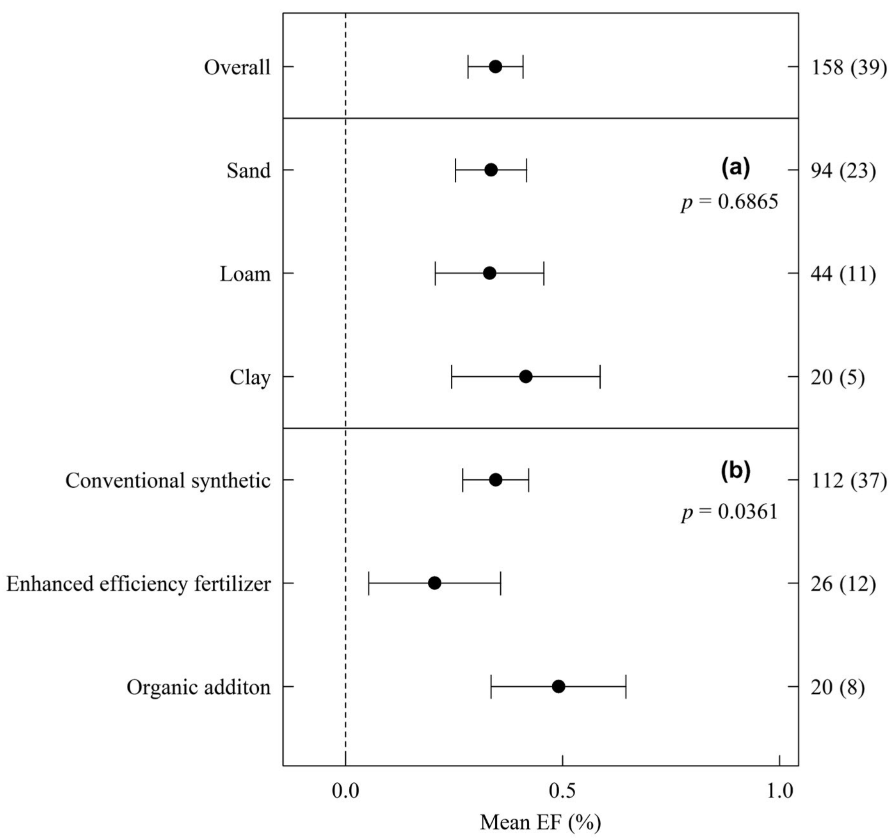

FIGURE 4 Effects of soil texture (a) and type of N addition (b) on N_2O emission factor (EF) in drip-irrigated cropland. Numbers of the observations (studies) for each category are given on the right axis. Error bars represent 95% confidence intervals (CIs). The *p* values for the differences between subcategories are shown in the panel

	Q_E	Q_M	Intercept distance	Slop	*p*	*n*
N application rate	6478.3	4.2	0.2052	0.0006	0.0399	158 (39)
Clay content	560.2	7.6	0.1135	0.0076	0.006	95 (22)
pH	6443.0	0.4	0.033	0.0392	0.5073	158 (39)
SOC	6156.4	2.1	0.2753	0.0075	0.1514	158 (39)
Mean air temperature	2908.4	0.7	0.4651	−0.009	0.3978	127 (31)
Mean annual precipitation	6459.2	0.2	0.3205	0.0001	0.6186	152 (38)
Experiment duration	6446.4	0.4	0.3107	0.0002	0.5198	158 (39)

TABLE 1 Relationship of N_2O emission factor (EF) under drip irrigation with N application rate, soil clay content, pH, soil organic carbon (SOC), mean air temperature, mean annual precipitation, and experimental duration. Statistical results were reported as the difference among groups' EF (Q_M) and the residual error (Q_E) from the mixed-effects model. The relationship is significant at $p < 0.05$. Numbers of the observations (studies) are given as *n*

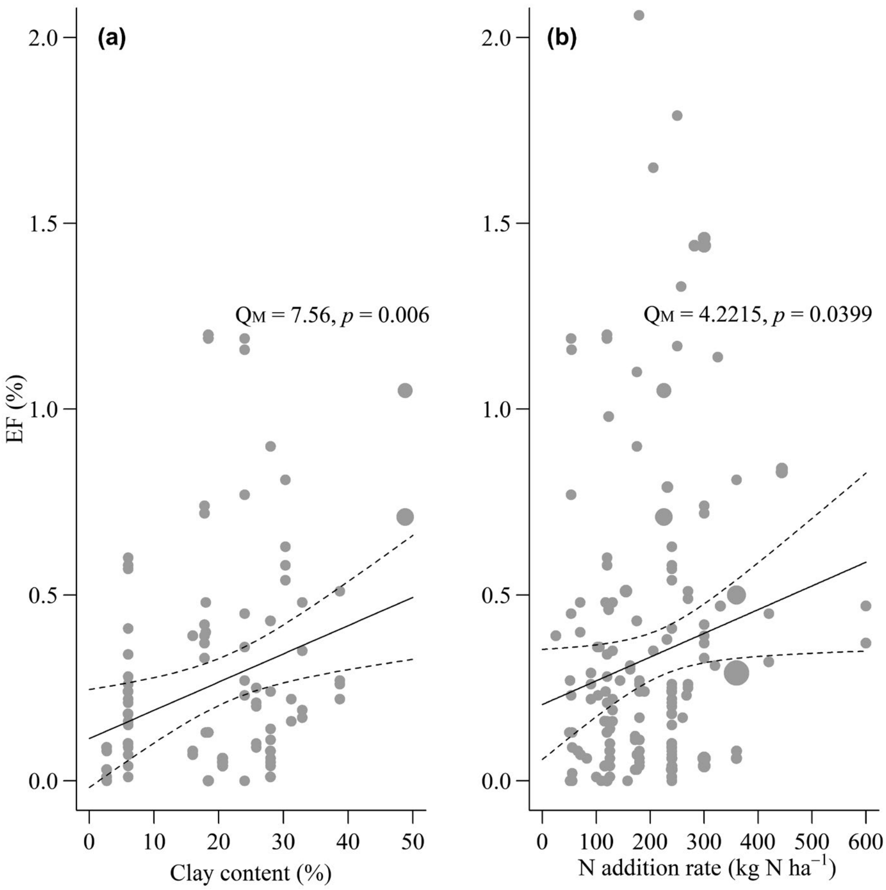

FIGURE 5 Effects of soil clay content (a) and N addition rate (b) on N_2O emission factor (EF) in drip-irrigated cropland. Solid and dashed lines represent the regression line and 95% confidential interval, respectively. [Correction added on 3 June 2021, after first online publication: Figure caption 5 has been modified.]

4 | DISCUSSION

4.1 | Drip irrigation has lower N_2O emissions compared to conventional irrigation systems

Drip irrigation generally had lower N_2O emission from agricultural croplands compared to furrow and sprinkler irrigation systems in some studies (Guardia, Cangani, Sanz-Cobena, et al., 2017; Kennedy et al.,2013; Sanchez-Martín et al., 2010), whereas in others the opposite was observed (Fentabil et al., 2016; Guo et al., 2016; Smart et al., 2011). This global meta-analysis showed that drip irrigation significantly decreased N_2O emissions by one third relative to furrow and sprinkler irrigation systems (Figure 2). Lower N_2O emissions under drip than conventional irrigation systems are likely associated with several factors. First, the spatial distribution of water under drip irrigation could have resulted in simultaneously a wet area near the dripper and a dry area between drip lines. Guardia, Cangani, Andreu, et al. (2017) had proposed that NH_4^+ tends to accumulate in wet areas with soil moisture suitable for the reduction of N_2O to N_2, whereas NO_3^- accumulates in dry areas where nitrification is limited. Other studies confirmed lower soil moisture content under drip than furrow irrigation reduced the activity of N_2O-producing bacteria and thus the production and emission of N_2O (Jha et al., 1996). Sánchez-Martín et al. (2008) also reported that the first N_2O

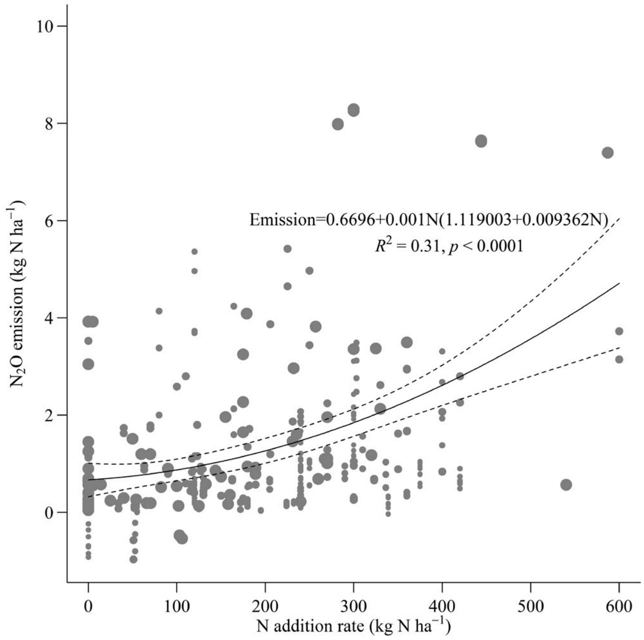

FIGURE 6 Changes in N_2O emission with N addition rate in drip-irrigated cropland. Solid and dashed lines represent the regression line and 95% confidential interval, respectively. Size of data points depended on the weight of data. Results obtained with mixed-effects meta-regressions follow with the exploratory moderator analysis (Figure S4)

TABLE 2 Estimation of N_2O emissions in China and the globe based on the emission factor from this study and IPCC

	China	Globe	References
Drip-irrigated area (10^6 ha)	5.27	14.41	ICID (2020)
N_2O emission factor (%)	1	1	IPCC (2006)
	0.35	0.35	This study
*N_2O emissionss induced by N application in drip-irrigated filed (Mg N_2O-N year^{-1})	10,990	17,832	IPCC (2006)
	3375	4740	This study
	7614	13,091	Overestimated by IPCC (2006)

*Calculations are based on drip irrigation area (ICID, 2020) and N application rate for agricultural land (FAO, 2020) in each country. Details on country-based estimation are provided in Table S1.

pulse in drip irrigation was five times smaller than that for furrow irrigation, due to lower soil moisture in the former. In the current study, the average amount of irrigated water was 33% less in drip than furrow and sprinkler irrigation systems. Second, N supply with drip irrigation can better synthesize water delivery and crop needs and thus reduce its losses to the environment (Kennedy et al., 2013; Ma et al., 2018). The current meta-analysis confirms the benefits of drip irrigation in a reduction of N_2O emissions and suggests that drip irrigation should be recommended as an essential mitigation strategy for irrigated crop production.

4.2 | Factors influencing EF in drip irrigation systems

Based on the current meta-analysis, the derived EF of N_2O emissions across drip irrigation studies was 0.35%, which is considerably lower than the IPCC Tier I default value of 1% (IPCC, 2006). In addition, the EF determined here is also lower than previously reported of drip irrigation in Mediterranean climates (Aguilera et al., 2013; Cayuela et al., 2017). These results suggest that the use of the IPCC default can considerably overestimate N_2O emissions at the regional or global scale. Across all the studies included in the current meta-analysis, EF ranged from 0 in an olive orchard in Spain (Vilarrasa-Nogué et al., 2019) to 2.06% in a maize crop in China (Tian et al., 2017), suggesting a high variation of EF as affected by environmental, crop, and management factors. Vilarrasa-Nogué et al. (2019) found in their study that soils acted as a net sink of N_2O with or without N fertilization, and attributed the negative EF to the enhanced N_2O consumption at higher N rates. The current study has thoroughly investigated the effects of climate type, crop type, soil properties including texture, SOC, and pH, and product and rate of fertilizer application on N_2O emissions from drip-irrigated agricultural soils.

4.2.1 | Climate condition

Our meta-analysis showed that there was no significant effect of climate on EF, although the value of Cold (EF: 0.37%) being higher than Arid (EF: 0.35%) and Temperate (EF: 0.28%) climates specially. The differences in the application rate of N fertilizer are likely the dominant factors attributing to the variation of N_2O emissions among climate zones. The lower EF for Temperate than other climates is attributed to the generally lower application rate of N fertilizers. For example, the average N application rate was only 105 kg N ha^{-1} for Temperate climate, compared to 206 and 271 kg N ha^{-1} for Arid and Cold climate, respectively. This is confirmed by a recent meta-analysis which showed that the average fertilizer N application rate for drip irrigation in Mediterranean environments was 295 kg N ha^{-1} resulting in an average N_2O EF of 0.51% (Cayuela et al., 2017).

4.2.2 | Crop type

Our meta-analysis revealed the EF of N_2O did not significantly differ among crop types, ranging between 0.33% and 0.35%, which are considerably lower than the IPCC Tier I default value of 1% (IPCC, 2006). This result presented here provides further evidence for the generally low N_2O emission under drip irrigation system.

4.2.3 | Soil texture

In spite of the fact that N_2O EF was not significantly different between the three categories (sand, loam, and clay) of soil texture, results of the mixed-effects analysis showed a clearly trend of increasing EF with soil clay content. Similarly, Rochette et al. (2018) summarized soil N_2O studies in Canada and found that soil N_2O EF increased with soil clay content, confirming the role of soil texture on N_2O emissions. The greater EF of soils with high clay content could be associated with the increased denitrification due to low levels of O_2 and high C availability (Rochette et al., 2004). Under drip irrigation, the fine-textured soil with better water-holding capacity can help to create anaerobic conditions for denitrification and improve the microbial activity (Kim et al., 2014). In contrast, sandy soils with lower water-holding capacity were frequently reported with low N_2O emission factors (Kuang et al., 2018).

4.2.4 | Soil organic carbon

Similar to previous meta-analysis studies (Buckingham et al., 2014; Cayuela et al., 2017) which investigated N_2O emissions and EF from various ecosystems, SOC did not affect N_2O EF under drip irrigation in this study. These results contradict with some individual studies which reported greater N_2O emissions from soils with higher SOC (Lemke et al., 1998; Pelster et al., 2012). The absence of SOC effect on N_2O EF in the current analysis could be associated with the interactions with other variables under drip irrigation. For example, increasing SOC may increase the denitrification process under the anaerobic conditions with drip irrigation through providing the electron donor, resulting in the further reduction of N_2O to N_2 and decrease N_2O emissions (Weier et al., 1993). Besides, SOC may also interact with the climatic and soil texture factors and thus complex its influence on N_2O EF (Rochette et al., 2018).

4.2.5 | Soil pH

The absence of soil pH on N_2O EF in our analysis contradicts the results by Wang et al. (2018) who reported a decreasing EF of N_2O emission with increasing soil pH based on 1104 field measurements globally (Wang et al., 2018). The reduction of EF at high soil pH was attributed to the decreasing ratio of $N_2O/(N_2O + N_2)$ due to increased enzyme activities of N_2O reductase and thus complete denitrification of N_2O to N_2 (Bakken et al., 2012). In the current study, the absence of pH effect on EF of N_2O emissions under drip irrigation was most likely associated with the limited number of observations at acidic soils (pH < 6.0). The fact that only three observations existed for acidic soils could significantly hinder the soil pH effect on EF and bias the results. The limited number of studies with acidic soils also suggests that most arid regions where irrigations are needed had neutral to basic soils.

4.2.6 | Type of fertilizer

Results of this meta-analysis showed that N_2O EF was not significantly different between the EEFs and the conventional synthetic fertilizers. In contrast, other meta-analysis revealed that EEFs such as polymer-coated urea and the use of inhibitors could reduce EF by 50% compared with conventional fertilizers (Li et al., 2018). The ineffectiveness of EEFs compared to synthetic fertilizer under drip irrigation might be associated with several factors. First, fertilizer N is generally dissolved in the irrigation water and applied directly into the root zone through multiple in-season applications over the crop growing period, hindering the effectiveness of EEF products. Second, under drip irrigation, the only area near the drip lines receives water, whereas other areas are still relatively dry, limiting the efficacy of urease and nitrification inhibitors to slow N transformation. Despite being statistically insignificant, EF of the EEFs in the current meta-analysis was only two thirds of that of conventional fertilizers. In an individual field experiment with cotton grown under drip irrigation, we recently also observed that the use of double inhibitors significantly reduced N_2O EF (Ma et al., 2018).

In the current meta-analysis, organic additions such as animal or green manure resulted in numerically but not statistically higher EF than synthetic fertilizers, suggesting the variability of manure addition on N_2O emissions which are highly associated with environmental conditions. Both positive and negative effects of manure addition on N_2O emissions from drip irrigation have been reported. For example, Tao et al. (2018) reported that manure addition reduced N_2O emission from a drip-irrigated cotton field compared with chemical fertilizer, due to a reduced ratio of $N_2O/(N_2O + N_2)$ through complete denitrification. In contrast, in the same region with less rainfall and on a desert soil with less organic C, Kuang et al. (2018) reported manure application increased N_2O emission and EF than urea in drip-irrigated cotton field due to the increased organic C supply. The inconsistent results highlight the importance of soil properties, especially soil C availability, in determining the effect of manure addition on N_2O emissions. The absence of fertilizer type effect in the meta-analysis could also be associated with the generally low N_2O emissions under drip irrigation, which hindered the differences associated with fertilizer treatments. Further studies are needed to determine under what conditions manure application can increase soil C storage and crop productivity without increasing N_2O emissions.

4.2.7 | Rate of fertilizer

Our analysis revealed that N_2O EF of drip irrigation increased with fertilizer N rate, suggesting a potential for reducing emissions by improving fertilizer N use efficiency. Previous studies reported both linear (constant EF) or nonlinear increase in N_2O emissions in response to fertilizer N rate in individual field experiments (Hoben et al., 2011; Ma et al., 2010; McSwiney & Robertson, 2005; Signor et al., 2013), or global-scale meta-analysis (Gerber et al., 2016; Shcherbak et al., 2014; Wang et al., 2018). It is proposed that linear relationship is mostly observed at N rates less than or equal to crop needs and the nonlinear relationship occurs at N rates greater than crop needs where excess N can stimulate N_2O production (Snyder et al., 2009; Van Groenigen et al., 2010). In the current study, we confirmed a nonlinear increase in N_2O emissions in response to N addition rate under drip-irrigated conditions. Such a relationship suggests that N supply under drip irrigation is likely greater than crop needs and highlights the potential opportunities of reducing fertilizer N rate while maintaining or improving crop productivity in irrigated agriculture.

In the current study, we observed a binomial increase in N_2O emissions in response to fertilizer N rate, based on 364 observations in 73 field studies under drip-irrigated condition (Figure 6). Cayuela et al. (2017) reported a mean EF of 0.51% for drip-irrigated cropland in Mediterranean climates with a mean fertilizer N rate of 295 kg N ha^{-1}. With our model, a similar EF value of 0.39% was predicted for the same application, implying that our model is suitable for estimating N_2O emission in drip irrigation agriculture. However, the low coefficient of determination (R^2 = 0.31) in our model suggests that multiple factors comprehensively regulated EF.

We have compared our model with the IPCC default and that by Shcherbak et al. (2014; Figure 7). Results showed that the EF in drip irrigation is still lower than the IPCC default of 1% even at high N application rate about 600 kg N ha^{-1}. Further, the increasing rate of N_2O emission with the N application rate was also lower in our regression compared to the model for upland grain crops in Shcherbak et al. (2014). The lower increasing rates of EF under drip irrigation might be associated with several factors. First, N_2O emissions were 36% lower under drip irrigation compared to conventional irrigation, resulting in the lower increasing rates of EF in our than Shcherbak et al.'s model. Second, multiple fertigations in crop growing season were widely used in drip irrigation, which could have increased crop N uptake and reduced the response of EF to N addition. Finally, the low water-filled pore sapce (WFPS) could have also attributed to the lower response of EF to N addition in drip irrigation.

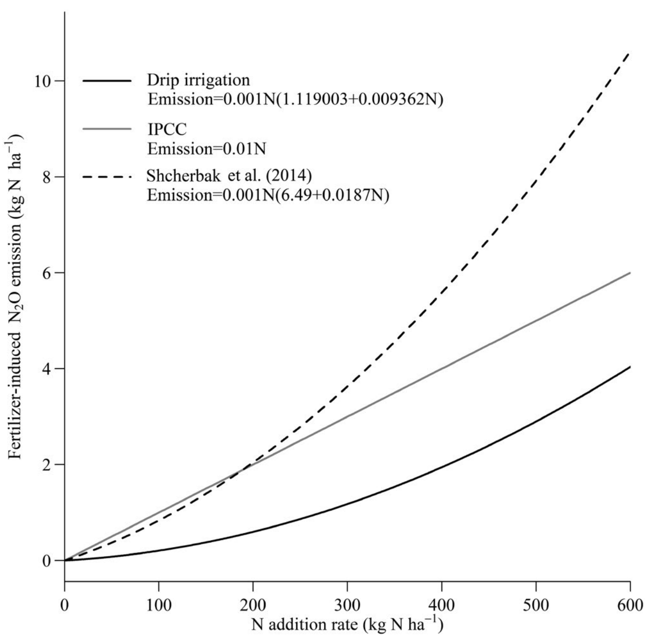

FIGURE 7 The linear and nonlinear increase in fertilizer-induced N_2O emission in response to fertilizer N addition rate for drip irrigation in the present study, IPCC Tier I, and Shcherbak et al. (2014)

Based on the widely spread of drip irrigation in arid and subarid climate zone, using our model would help to estimate N_2O emissions from drip-irrigated croplands at both regional and global scales. Combined with the reported data from ICID (2020) and FAO (2020), this meta-analysis estimates that the fertilizer-induced N_2O emissions from drip-irrigated agriculture are 3375 Mg year^{-1} for China and 4740 Mg year^{-1} for the globe. Use of the IPCC Tier I approach would result in an overestimation of double emissions for China or nearly triple emissions globally. Although the FAO data on the average N rate for each country were based on the general agricultural use, rather than the drip irrigation system only, this is the best approach with current data availability. Likely the N_2O emission inventory for the drip irrigation system is even lower than the assessment in this study, because generally less N fertilizers are used in the drip irrigation than other crop production systems. It should also be noticed that most studies used for the meta-analysis did not consider emissions from the nongrowing season, which could account for nearly 30% for some temperate regions where N_2O flux at the spring-thaw represents a significant source (Wagner-Riddle et al., 2017), although this study did not find a significant association of EF with experimental duration.

5 | CONCLUSION

Drip irrigation is an effective strategy to mitigate N_2O emissions from croplands, which significantly reduces N_2O emissions by 36% compared with furrow and sprinkler irrigation systems. Globally, the mean N_2O emission factor for drip irrigation agricultural systems was 0.35%. Emission factor was not affected by climate condition, crop type, soil organic carbon content, and pH. Compared to the conventional synthetic fertilizers, use of EEFs did not significantly affect EF while there was a decreasing trend of EF with the use nitrification inhibitors. Being consistent with other studies, we observed a binomial increase in N_2O emissions in response to fertilizer N rate under drip irrigation while emissions and EFs were generally lower than other models (e.g., IPCC default EF of 1%; Shcherbak et al., 2014), confirming the benefit of drip irrigation in reducing N loss pathway as N_2O emissions. The nonlinear equation also suggests that the EF is not constant at high fertilizer N rates, highlighting the importance to avoid applying fertilizer N to exceed crop needs. Using the IPCC Tier I default EF value overestimated the fertilizer-induced N_2O emissions from drip-irrigated agriculture by 7614 and 13,091 Mg year^{-1} for China and the globe, respectively.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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