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An inventory of N_2O emissions from agriculture in China using precipitation-rectified emission factor and background emission

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Abstract

Fertilized agricultural soils are a major anthropogenic source of atmospheric N_2O. A credible national inventory of agricultural N_2O emission would benefit its global strength estimate. We compiled a worldwide database of N_2O emissions from fertilized fields that were consecutively measured for more than or close to one year. Both nitrogen input (N) and precipitation (P) were found to be largely responsible for temporal and spatial variabilities in annual N_2O fluxes (N_2O–N). Thus, we established an empirical model ($N_2O\text{–}N = 1.49\ P + 0.0186\ P \cdot N$), in which both emission factor and background emission for N_2O were rectified by precipitation. In this model, annual N_2O emission consists of a background emission of 1.49 P and a fertilizer-induced emission of $0.0186\ P \cdot N$. We used this model to develop a spatial inventory at the 10×10 km scale of direct N_2O emissions from agriculture in China. N_2O emissions from rice paddies were separately quantified using a cropping-specific emission factor. Annual fertilizer-induced N_2O emissions amounted to 198.89 Gg N_2O–N in 1997, consisting of 18.50 Gg N_2O–N from rice paddies and 180.39 Gg N_2O–N from fertilized uplands. Annual background emissions and total emissions of N_2O from agriculture were estimated to be 92.78 Gg N_2O–N and 291.67 Gg N_2O–N, respectively. The annual direct N_2O emission accounted for 0.92% of the applied N with an uncertainty of 29%. The highest N_2O fluxes occurred in East China as compared with the least fluxes in West China.

Keywords: Emission factor; Background emission; IPCC methodology; Nitrous oxide; Precipitation; Uncertainty

1. Introduction

Nitrous oxide (N_2O), an important atmospheric trace gas, contributes greatly to the global warming and stratosphere ozone depletion. Although the N_2O budget remains poorly understood at present, fertilized agricultural soils where N_2O is naturally produced through the processes of nitrification and denitrification have been believed to be a major source of annual global N_2O emission (Mosier et al., 1998). Reliable regional or global estimate of N_2O emissions from agricultural soils depends on an examination of methodologies to reduce the current high uncertainty in the estimates (IPCC, 2000). One potential way to do this is to develop predictive flux models, such as a simple empirical model (e.g. the IPCC methodology, IPCC, 2000) and a process-oriented model (e.g. the DNDC model, Li et al., 1992, 2001).

The relationship between nitrogen input and N_2O emission established by Eichner (1990) and Bouwman (1996) motivated the concept of emission factor (EF). The emission factor is defined as a fraction of the nitrogen input released in the form of N_2O within the current seasonal or annual period. Based on results obtained by Bouwman (1996), the default emission factor of N_2O for synthetic nitrogen averages 1.25%, ranging from 0.25% to 2.25% and N_2O background emission is assumed to be $1\ \text{kg}\ N_2O\text{–N}\ \text{ha}^{-1}\ \text{yr}^{-1}$ in the IPCC methodology (IPCC, 2000). Although some

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other agriculture practices and environmental factors are also believed to be important to N_2O emission (Clayton et al., 1997; Henault et al., 1998; Bouwman et al., 2002; Dobbie and Smith, 2003), the current IPCC methodology does not consider their effects. As a consequence, the IPCC methodology often fails to represent large spatial and temporal variabilities in fertilizer-induced N_2O emissions that were frequently observed in previous studies (e.g. Kaiser and Ruser, 2000; Dobbie and Smith, 2003; Zou et al., 2005a).

Another general approach for estimating direct N_2O emissions from agroecosystem is based on the process-oriented model such as the DNDC model (Li et al., 2001). Some process-oriented models are expected to be effective tools to minimizing the uncertainty in N_2O emission estimates; however, available data are often too limited to satisfy the input requirements of these complex models. In order to minimize uncertainty in estimates by the simple empirical model and to reduce data input requirements of the process-oriented model, indeed, the summary model has been suggested as a potential solution (IPCC, 2000). Some key parameters such as precipitation, temperature and soil physiochemical parameters are believed to be responsible for the variability in N_2O fluxes by the process-oriented model (e.g. Li et al., 2001). Incorporation of these key parameters into the IPCC methodology could be an effective approach to minimizing the uncertainty in N_2O estimates.

China is one of large agricultural countries in the world. It contains 12% of world's total crop harvest area where 25% of the global synthetic nitrogen was consumed in 2003 (FAO, http://apps.fao.org). Recently, some studies have attempted to establish an account of agricultural N_2O emissions in China. For example, Xing (1998) used the IPCC default emission factor to estimate N_2O emission in China's agriculture. Li et al. (2001) estimated N_2O emission using a process-oriented model. In Zheng et al.'s (2004) study, agricultural N_2O estimate was based on the up-scaling average of site-scale EFs. To our knowledge, no study has developed an empirical model in which both emission factor and background emission are rectified by key parameters to estimate agricultural N_2O emission in China, although this approach could potentially minimize its uncertainty.

Here, we compiled and statistically analyzed the available measurements of N_2O from fertilized fields worldwide. The objective of this study was to establish an empirical model in which the emission factor and background emission for N_2O in the IPCC methodology were rectified by key environmental parameters. Based on this model, we further developed a spatial inventory of direct N_2O emissions from fertilized fields in China.

2. Materials and methods

2.1. Data source

We collected direct N_2O measurements that were published in peer-reviewed English and Chinese journals between 1982 and 2003. Data published in Chinese were gathered from the Chinese Journal Net (CJN) full-text database and those in English from the Science Citation Index (SCI) database. The dataset included croplands and grasslands where fertilizer N was applied (e.g. Velthof et al., 1996; Clayton et al., 1997). Data extraction complied with the following criteria: (1) We only considered field studies that were carried out for more than or close to one year; (2) N_2O flux data from paddy fields were excluded since N_2O emission pattern from paddies is distinctly different from uplands; (3) Measurements that were taken from unplanted soils or organic soils were excluded; (4) N_2O emissions from N-fixing legume fields and fields with additional organic N or nitrification inhibitors input were rejected as well.

In the end, the employed dataset comprised 206 measurements from 42 sites. Of these, 46 measurements were taken from China and 160 from other countries. Data originated mostly from Western Europe, East Asia and North America. For each data point, we recorded the annual total N_2O emission, the synthetic nitrogen application rate, the precipitation and mean temperature, the location of measurement and the soil physiochemical parameters including soil total N content, soil organic carbon content, and pH (Table 1). Due to data scarcity and inconsistent report in the literature, the timing and method of fertilizer application, the type of crop residue and tillage conditions were not taken into account in this study. Soil parameters were directly compiled from the original literature. We only gathered a total sample of 118 for each soil parameter due to limited available data in the literature. Climate information was derived from an online database of WDC (World Data Center for Meteorology, website at: "http://www.ncdc.noaa.gov/oa/wmo/wdcamet.html") except that it was available in the original literature. This online database consists of data on monthly precipitation and mean temperature during the period 1900–2003 at the global scale. Based on the geographic co-ordinates and sites of the measurement retrieved from the original research papers, we calculated annual precipitation and mean temperature for the experimental year.

2.2. Statistical analysis

We conducted a pairwise correlation for each pair of variables including field measurement data of annual N_2O emission, N fertilizer application rate, soil total N content, organic carbon content, and pH, annual precipitation and mean temperature. To identify some key factors controlling N_2O emission, we further conducted a partial correlation analysis that represents the correlation of each pair of variables after adjusting for all the other variables. Comparing results of both analyses allow us to identify some possible spurious correlations between variables and N_2O emissions. In partial correlation analyses, factors with statistically significant levels ($P < 0.05$) were regarded to be responsible for temporal and spatial variabilities in N_2O emission.

Table 1
Annual N_2O emissions dependent on nitrogen inputs and their relevant environmental data in agricultural fields

Site	Latitude	Longitude	*n*	N_2O emission (kg N ha^{-1} yr^{-1})	N input (kg N ha^{-1} yr^{-1})	Precipitation (mm)	Temperature (°C)	STN (g kg^{-1})	pH	SOC (g kg^{-1})	Reference
Berkshire, UK	51°30′N	1°20′W	2	3.50–8.00	250–500	714	9.4	2.3	6.3	35.0	Eggington and Smith (1986)
Boghall Farm, UK	55°50′N	3°14′W	8	0.30–4.70	120–200	403–731	8.8–11.2		5.7–7.0	26.7–31.3	Smith et al. (1998), Dobbie et al. (1999)
Cambridgeshire, UK	52°20′N	0°05′E	1	1.20	190	550	12		7.7	29.0	Dobbie and Smith (2003)
Hampshire, UK	51°05′N	1°15′W	1	1.70	387	768	12		7.8	29.0	Dobbie and Smith (2003)
Suffolk, UK	52°15′N	0°43′E	1	0.70	132	590	12		7.7	11.6	Dobbie and Smith (2003)
Bush Estate, UK	55°50′N	3°14′W	1	3.79	172	675	13		5.8	31.9	Skiba et al. (1998)
Gloucestershire, UK	51°53′N	2°14′W	1	3.00	260	780	12		7.1	29.0	Dobbie and Smith (2003)
Crichton, UK	55°04′N	3°37′W	1	5.10	208	1097	10.5		5.6	60.3	Smith et al. (1998)
Cumbria, UK	54°30′N	3°0′W	1	4.70	130	1220	12		6.6	34.8	Dobbie and Smith (2003)
Nottinghamshire, UK	53°00′N	1°0′W	1	2.40	165	600	12		5.7	11.6	Dobbie and Smith (2003)
Penicuik, UK	55°53′N	3°26′W	9	1.50–13.40	279–700	685–946	7.6–8.8	2.7	5.5	31.9	Clayton et al. (1997), Ryden (1983)
Midlothian, UK	55°53′N	3°26′W	6	1.00–9.40	60–360	661–946	7.9–12	0.8–1.3	4.2–5.7	29.0–31.9	Smith et al. (1998), Dobbie et al. (1999), Dobbie and Smith (2003), Skiba et al. (1998)
Wamphray farm, UK	55°58′N	2°47′W	1	7.70	462.5	558	9.4				Dobbie et al. (1999)
Leicestershire, UK	52°46′N	0°53′W	1	5.30	298	600	12		5.6	23.2	Dobbie and Smith (2003)
Auchincruive, UK	55°24′N	4°26′W	2	3.80–4.50	310–320	897–982	8.8				Dobbie et al. (1999)
Oxfordshire, UK	51°39′N	1°10′W	2	5.00–7.00	400	670–730	9.7		6.7	23.0–40.0	Webster and Dowdell (1982)
Braunschweig, Germany	52°17′N	10°27′E	21	0.97–5.90	60–350	508–611	7.7–9.3	1.1	7.4	9.4	Heinemeyer (1998), Kaiser and Ruser (2000), Kaiser and Heinemeyer (1996)
Gottingen, Germany	51°03′N	9°06′E	13	0.53–2.3	55–195	581–640	8.7	1.8	7.5	16.0	Flessa and Beese (1995), Kaiser and Ruser (2000)
Kiel, Germany	59°09′N	35°08′E	1	1.50	91.7	697	8.1	1.5	5.4	18.0	Mogge et al. (1999)
Potsdam, Germany	52°24′N	13°04′E	11	0.55–3.89	150	397–569	10.1–11.3	1.4	6.3	9.0	Hellebrand et al. (2003)
Scheyern, Germany	48°30′N	11°21′E	26	1.30–9.60	40–275	873–1046	7.4	1.4–1.8	5.8–6.3	15.0–20.3	Ruser et al. (2001), Dörsch (2000), Flessa et al. (1995, 2002), Flessa and Beese (1995)
Siggen, Germany	47°45′N	9°57′E	1	2.96	200	792	7.5	4.6	7.0	47.2	Stephan and Karl (2001)
Timmerlah, Germany	52°17′N	10°27′E	14	1.09–3.5	45–210	372–677	7.7–9.7	1.1	7.4	9.4	Kaiser and Ruser (2000), Kaiser et al. (1998)
Heino, Netherlands	52°26′N	6°14′E	4	3.10–13.20	313–743	868–995	9.5–10.5				Velthof and Oenema (1995), Velthof et al. (1996)
Lelystad, Netherlands	52°31′N	5°29′E	3	5.00–16.10	277–731	931–993	9.5–10.5				Velthof and Oenema (1995), Velthof et al. (1996)
Zegveld, Netherlands	52°06′N	5°07′E	2	11.90–17.30	521–713	820–894	9.5–10.5				Velthof and Oenema (1995), Velthof et al. (1996)
Hokkaido, Japan	43°14′N	141°50′E	5	3.50–9.90	270–322	642–928	13.7–15.4	2.7	5.5	29.0	Kanako et al. (2002)
Ithaca, USA	42°26′N	76°30′W	6	1.60–3.80	130	756–926	7.6–7.9				Duxbury et al. (1982)
Madison, USA	43°04′N	89°24′W	2	3.60–5.20	181–237	584	7.3		6.7	12.0	Cates and Keeney (1987)
Isabela, Puerto Rico	18°28′N	67°02′W	1	11.39	300	1100	24	2.6	6	28.0	Choudhary et al. (2001)
Mayaguez, Puerto Rico	18°12′N	67°08′W	1	3.83	300	1100	26	3.8	6.8	37.0	Choudhary et al. (2001)
Lajas, Puerto Rico	18°03′N	67°04′W	1	4.01	300	1100	23	2.4	6.4	21.0	Choudhary et al. (2001)
Manawatu, New Zealand	40°21′S	175°39′E	2	2.37–3.42	153–307	600	12.1	2.8	5.6	33.0	Mosier and Delgado (1997)
New Delhi, India	28°40′N	77°12′E	2	1.09–1.64	120	750	20	0.3	8.1	4.5	Pathak et al. (2002)
Shenyang, China	41°32′N	122°23′E	6	1.21–4.52	35–350	774–893	9–15.5	0.8	6.3	9.4	Huang et al. (1995, 1998)

(*continued on next page*)

Table 1 (*continued*)

Site	Latitude	Longitude	*n*	N_2O emission (kg N ha^{-1} yr^{-1})	N input (kg N ha^{-1} yr^{-1})	Precipitation (mm)	Temperature (°C)	STN (g kg^{-1})	pH	SOC (g kg^{-1})	Reference
Shijiazhuang, China	37°53′N	114°41′E	4	1.75–2.11	158–308	546–699	12.7	0.8	8.5	7.4	Song et al. (1997), Su et al. (1992)
Yucheng, China	36°57′N	116°36′E	2	2.90–3.40	420–480	610	13.1	0.5	7.9	4.5	Dong et al. (2001)
Fengqiu, China	35°00′N	114°24′E	13	1.46–5.82	150–480	401–749	14.7–25.2	5.8	8.6	4.5	Ding et al. (2001a,b, 2003), Xing and Zhu (1997), Xing (1998), Xu et al. (2000a,b)
Nanjing[a], China	31°52′N	118°50′E	4	6.36–12.39	250–600	900–934	15.1–15.7	1.9	6.7	19.4	Jiang et al. (2003), Zou et al. (2003)
Wuxi[a], China	31°37′N	120°28′E	7	3.38–12.99	240–500	1144–1150	15.4–18.3		6.8	15.0	Zheng et al. (2004)
Suzhou[a], China	31°16′N	120°38′E	8	2.83–15.1	180–382	512–1083	10.4–17.3	1.9	6.5	20.3	Xing and Zhu (1997), Zheng et al. (1997, 2000)
Guiyang, China	26°50′N	106°56′E	2	5.38–5.91	253–351	853–949	15.5	7.1	7.5	7.0	Xu et al. (2000a,b)

n – Number of measurements; precipitation – annual precipitation; temperature – annual mean temperature; STN – soil total nitrogen content at the depth of 0–20 cm; SOC – soil organic carbon content at the depth of 0–20 cm.

[a] Included some unpublished data.

We used a linear regression model with the personality of Ordinary Least Squares (OLS) to fit annual N_2O fluxes by key factors that had been identified by the partial correlation analyses. A *t*-test was used to examine the statistical significance of parameter estimates in the simulated OLS model. A lack of available N_2O data independent of the model made its validation impossible in this study. However, some statistical analyses could be used to test the fitness of the model. The assumptions of the OLS linear regression model strictly concern the error term (ε) that can be represented by the pattern of residuals. The residuals from the fitted model are important for checking whether the assumptions of linear regression analysis are met (Quinn and Keough, 2004). Therefore, residual distribution pattern was used to examine the fitness of simulated models. The statistical analyses were conducted using JMP IN 5.1 (SAS INC. 2003).

2.3. Uncertainties calculation

A national inventory of N_2O emissions from soils would typically contain a wide range of emission estimates. Total uncertainty in emissions inventory is generally combined by uncertainties in emission factors and activity data. Similar to the uncertainty estimate in the IPCC methodology (IPCC, 2000), we use the error propagation equation to calculate the uncertainties as follows:

$$U_C = \sqrt{U_A^2 + U_E^2} \tag{1}$$

where U_C is the combined uncertainty expressed as a percentage; U_A and U_E are the percentage uncertainties in the activity data and emission factor, respectively. Here, the activity data is the input data of the estimate method and U_A is principally determined by the reliability of the input data and the quality of spatialization. The confidence interval of parameter estimates in the OLS model was used to calculate U_E. A confidence interval of 95% that is suggested by the IPCC guidelines represents a 95% probability of containing the unknown true value. U_E was expressed as half the 95% confidence interval divided by the mean.

2.4. Cropping-specific emission factor for N_2O in rice paddies

As a major cropping type, paddy rice planting on 23% of cultivated land area in China accounts for about 20% of the world total (FAO, http://apps.fao.org). It has been well documented that N_2O emissions depend greatly on water regime in paddies (Zou et al., 2005b). The emission factor of nitrogen fertilizer for N_2O is significantly lower in rice paddies than in uplands (Ghosh et al., 2003; Akiyama et al., 2005; Zou et al., 2005a). Recently, Akiyama et al. (2005) estimated emission factors for N_2O dependent on water regime during the paddy rice-cropping season. Most paddy field measurements of N_2O in China were included in Akiyama et al.'s (2005) study. Due to a lack of statistical data on water regime that is currently practiced in paddy rice production in China, however, the emission factor of N_2O dependent on water regime could not be employed in this study. Thus, the mean emission factor for all water regimes ($0.31 \pm 0.31\%$) in rice paddies estimated by Akiyama et al. (2005) was used in this study to quantify direct N_2O emissions from rice paddies in China.

2.5. Spatialization

There are some input data that are necessary to mapping the spatial inventory of direct N_2O emissions in agriculture. The fertilized agriculture is primarily composed of cultivated croplands and grasslands in China. The N input and rice planting area data at county level were obtained from China Academe Agricultural Science and the data on fertilizer use by crop species were online available at the IFA website (http://www.fertilizer.org). The climate data from 633 sites were compiled from China Meteorological Administration. The site climate data were interpolated to surface data by Gaussian filter method (Thornton et al., 1997). Eventually, all the input data were converted to ArcInfo grid files at resolution of 10×10 km and used to generate the inventories. The inventory of N_2O in this study did not include Taiwan province because the data was unavailable.

3. Results

3.1. Factors responsible for temporal and spatial variations of N_2O emissions

A pairwise correlation analysis showed that annual N_2O flux was not significantly correlated with soil parameters including pH ($r^2 = 0.008$, $P = 0.33$), organic carbon content ($r^2 = 0.02$, $P = 0.14$) and N content ($r^2 = 0.02$, $P = 0.16$). However, it depended significantly on nitrogen input ($r^2 = 0.45$, $P < 0.0001$) and precipitation ($r^2 = 0.32$, $P < 0.0001$), and slightly on temperature ($r^2 = 0.02$, $P = 0.06$). Also, we found that nitrogen input was correlated with temperature ($r^2 = 0.03$, $P = 0.02$) and precipitation ($r^2 = 0.12$, $P < 0.0001$), but the correlation between precipitation and temperature was not pronounced ($r^2 = 0.0007$, $P = 0.71$).

A partial correlation analysis, however, indicated that N_2O was independent of temperature ($r^2 = 0.003$, $P = 0.46$), while it depended significantly on precipitation ($r^2 = 0.24$, $P < 0.0001$) and nitrogen input ($r^2 = 0.37$, $P < 0.0001$) after adjusting for all the other variables. In contrast to the pairwise correlation analysis, the partial correlation analysis showed that nitrogen input did not correlated with temperature ($r^2 = 0.01$, $P = 0.14$), and precipitation ($r^2 = 0.003$, $P = 0.42$). Based on the results of pairwise correlation and partial correlation analyses, nitrogen input and precipitation were identified to be responsible for temporal and spatial variabilities in N_2O emissions. Compared to temperature, precipitation was the most important climate factor influencing N_2O emissions. Therefore, variability in the 206 observed annual N_2O fluxes could be largely attributed to fertilizer and precipitation.

3.2. Modeling emission factor and background emission for N_2O

Similar to the IPCC methodology, dependence of N_2O emissions (N_2O–N) on nitrogen inputs (N) was quantitatively described by an OLS linear regression model IPCC-M.

$$N_2O\text{–N} = 0.423 + 0.0169\text{N} \quad (r^2 = 0.45, P < 0.0001) \tag{2}$$

Based on simulating parameters of the model IPCC-M, the emission factor of N_2O averaged 0.0169, with a stand error of 0.0013 (Table 2). The background emission was estimated to be 0.423 kg N_2O–N $\text{ha}^{-1}\,\text{yr}^{-1}$. Compared to the default model in the IPCC methodology (model IPCC-D: $N_2O\text{–N} = 1 + 0.0125$ N), obviously, the simulated model IPCC-M produced higher emission factor but lower background emission for N_2O.

If we assume that the IPCC default model IPCC-D fits N_2O emission by nitrogen input as well, then an index "R_E" can be referred to as the ratio of the observed to the predicted N_2O emissions by the model IPCC-D (i.e., $R_E = N_2O$ flux/($1 + 0.0125$ N)). Contrary to our prediction, the distribution of R_E did not center at 1 with a

Table 2
t-Tests for parameter estimates of background emission (*B*) and emission factor (EF) for N_2O emission (N_2O–N) in the OLS model IPCC-M ($N_2O\text{–N} = B + \text{EF} \cdot \text{N}$) and model IPCC-P ($N_2O\text{–N} = B \cdot \text{P} + \text{EF} \cdot \text{P} \cdot \text{N}$)

Model	Term	Estimate	Stand error	*t*-Ratio	*P*-Value
IPCC-M	*B*	0.423	0.319	1.33	0.19
	EF	0.0169	0.0013	13.01	<0.0001
IPCC-P	*B*	1.487	0.371	4.31	<0.0001
	EF	0.0186	0.0014	13.06	<0.0001

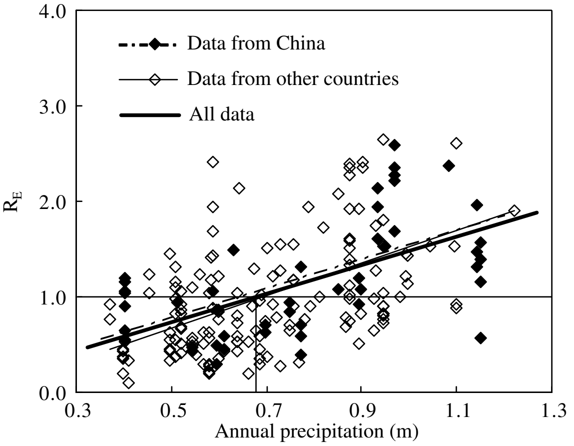

Fig. 1. Dependence of R_E on precipitation. The R_E was defined as the ratio of the observed to the predicted N_2O fluxes by the IPCC default model IPCC-D ($N_2O\text{–N} = 1 + 0.0125\text{N}$).

symmetrical pattern (the horizontal line in Fig. 1). Instead, it significantly increased with precipitation ($r^2 = 0.28$, $P < 0.0001$, Fig. 1), suggesting that the emission factor and background emission simulated by the model IPCC-D could be dependent on precipitation. No pronounced relationships between R_E and other factors including temperature and soil physiochemical parameters were found in this study. Based on the definition of R_E and the correlation between R_E and annual precipitation (P) over the entire data shown in Fig. 1, therefore, a summary model IPCC-P in which both the emission factor and background emission for N_2O were rectified by precipitation was deduced:

$$N_2O\text{–}N = (1.49 \pm 0.73)P + (0.0186 \pm 0.0027) \times P \cdot N \quad (r^2 = 0.61, P < 0.0001) \tag{3}$$

In this model, N_2O emission is described as a function of annual N input and precipitation. According to the definition by the IPCC methodology, the term "1.49 P" represents the precipitation-rectified background emission of N_2O, and "0.0186 P" is referred to as the precipitation-rectified emission factor of nitrogen input for N_2O. Thus the term "$0.0186\ P \cdot F$" accounts for direct fertilizer-induced N_2O emission. Here, "±0.73" and "±0.0027" are the 95% confidence intervals of background emission and emission factor that were rectified by precipitation, respectively. Based on the simulating parameters in this model, annual direct emission factor of fertilizer N for N_2O averaged 1.86%, ranging from 1.59% to 2.13%, and its background emission ranged from 0.76 to 2.22 kg N_2O–N $ha^{-1}\ yr^{-1}$ with an average of 1.49 kg N_2O–N $ha^{-1}\ yr^{-1}$ in the fields where annual precipitation is 1 m. When annual precipitation is about 0.67 m, N_2O emission estimated by the model IPCC-P will coincide with that predicted by the model IPCC-D (Fig. 1).

3.3. Fitness of models

A t-test showed that the background emission estimated by the model IPCC-M had a high uncertainty since it did not attain a statistical significance (Table 2). In contrast, the model IPCC-P predicted that both precipitation-rectified background emission and emission factor contributed significantly to annual N_2O flux (Table 2). Compared to the models IPCC-D and IPCC-M, the model IPCC-P markedly minimized uncertainty in the estimate of background N_2O emission. On the other hand, residuals of the model IPCC-P tended to be normal distribution and centered on zero, suggesting the model IPCC-P was strong enough to fit the N_2O dataset (Fig. 2). Nitrogen input can explain 45% of the variability in the 206 observed seasonal N_2O fluxes using the model IPCC-M ($r^2 = 0.45$, Eq. (2)), whereas it can be explained by up to 61% using nitrogen input coupled with precipitation through the model IPCC-P ($r^2 = 0.61$, Eq. (3)).

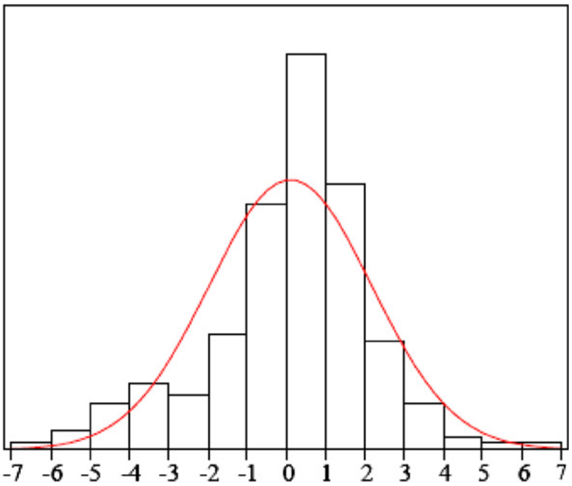

Fig. 2. Residual distribution pattern of the model IPCC-P fitting N_2O emission by N input and precipitation.

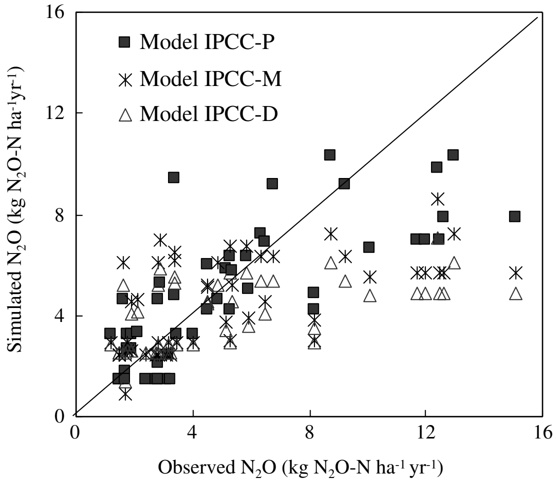

Fig. 3. Correlation of N_2O fluxes simulated by the models with observed fluxes in fertilized agricultural fields in China.

Although the simulated model IPCC-P may much weight to the regions outside of China since only 46 measurements were from China versus 160 from other countries in the entire dataset, the overlapping distribution of both dataset points tended to have the similar OLS simulating line (Fig. 1). This suggests that the IPCC-P model using the entire dataset fitted the N_2O flux data from China by nitrogen input and precipitation as well. In addition, using the nitrogen input and precipitation in the dataset allows a comparison between simulated and observed agricultural N_2O emissions in China (Fig. 3). The model IPCC-P can explain as high as 58% ($r^2 = 0.58$) of variability in 48 observed annual average N_2O fluxes, in contrast with only 33% explained by the model IPCC-M. Compare to the models IPCC-M and IPCC-D, moreover, N_2O emissions predicted by the model IPCC-P was closer to its observed fluxes ($y = 0.856x$, Fig. 3). Overall, these results strongly suggest that relative to the IPCC-M and IPCC-D models, the model IPCC-P is more suitable to quantify N_2O emissions from agricultural fertilized fields in China.

Table 3
Inter-annual variation of N_2O emissions from fertilized fields in China

Year	N input (Tg N)	Precipitation (m)	N_2O emission ($Gg\ N_2O–N$)	
			IPCC	This study
1997	21.72	0.58	360.39	291.67
1998	22.33	0.66	367.61	393.21

3.4. *Quantifying direct N_2O emissions from Chinese fertilized fields*

Annual direct N_2O emission in agricultural uplands in China was estimated by the model IPCC-P in the present study. A cropping-specific emission factor estimated by Akiyama et al. (2005) was used to quantify N_2O emissions from rice paddies in China. Nitrogen fertilizer application rate, rice planting area and precipitation were represented by a spatial inventory at the 10×10 km scale agricultural fields in China. The fertilizer N used in China amounted to 21.72 Tg N in 1997, composed of 5.95 Tg N in rice paddies and 15.77 Tg N in uplands. The total annual fertilizer-induced N_2O emission from agriculture in China was estimated to be 198.89 Gg N_2O–N, equivalent to 0.92% of the national total of synthetic fertilizer N input in 1997 (Table 3). Rice paddies received about 27.4% of the national N input but only accounted for 9.3% of fertilizer-induced N_2O emission total, whereas uplands received 72.6% of the national N input, contributing 90.7% to the total of fertilizer-induced N_2O emissions from agricultural fields in China. The background emission of N_2O from agriculture was estimated to be 92.78 Gg N_2O–N and the annual N_2O emission amounted to 291.67 Gg N_2O–N in 1997.

4. Discussion

4.1. *Uncertainties in N_2O estimates*

Uncertainty estimate is an essential element of a complete inventory of N_2O emission. Indeed, uncertainty information can provide good insights into prioritizing efforts to improve the accuracy of inventories in the future and guiding decisions on methodological choice. According to the methodology recommended by the IPCC (2000) for quantifying uncertainties (Eq. (1)), the combined uncertainty U_C estimation is determined by the value of U_A and U_E. Synthetic fertilizer production and consumption data are generally more reliable than any other data for emission estimate. Hence, the uncertainty of activity data (U_A) was principally originated from spatializing process and data other than nitrogen input in this study. The U_A and U_E for fertilizer-induced emission were estimated to be 25% and 15%, respectively. Thus, their combined uncertainty in fertilizer-induced N_2O estimate from the model IPCC-P in this study was 29%, which was greatly lower than the uncertainty of 80% originated from the IPCC default model IPCC-D. Using the same methodology, the uncertainty in background emission estimate was estimated to be 55%, and thus the gross uncertainty was 37%.

4.2. *Temporal and spatial variabilities in N_2O emissions from agricultural fields in China*

Precipitation-rectified emission factor and background emission may provide some insights into the temporal and spatial variabilities in N_2O emissions. Annual N_2O emissions from China's agriculture fields in 1997 and 1998 were estimated by both the model IPCC-P and the model IPCC-D (Table 3). Using the model IPCC-D, a similar amount of annual N input gave rise to an insignificant difference in N_2O emissions between two years. In contrast, the model IPCC-P produced that a slight higher precipitation in 1998 relative to 1997 increased annual N_2O by 34.8% (Table 3). On the other hand, the model IPCC-P showed a significant spatial distribution pattern of direct N_2O emission in agricultural fields (Fig. 4). The maximum direct N_2O emission occurred in the major district of crop production, where is characterized as humid climate in China. Three major high emission centers occurred in Sichuan basin, Central and Southeast China. By contrast, N_2O emission rarely exceeded 0.20 kg N_2O–N $ha^{-1} \cdot yr^{-1}$ in the West region, where is generally dominated by dry climate (Fig. 4).

Some factors may account for the distribution characteristic of N_2O emission in China. First, China is a multi-climate type country in which precipitation has high spatial variability. In general, precipitation is higher in East than in West China. The increase in precipitation in 1998

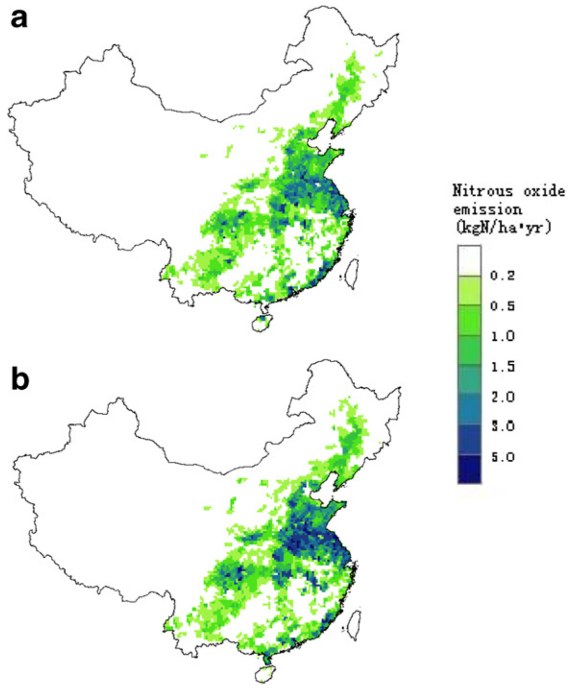

Fig. 4. The spatial distribution of direct N_2O emissions from fertilized agricultural fields in China in 1997 (a) and in 1998 (b).

relative to 1997 mainly occurred in East China. Second, agricultural ecosystem in East China is dominated by croplands in which N fertilizer is applied at high rates, whereas grasslands with low nitrogen inputs are primarily distributed in West China. Therefore, higher nitrogen input coupled with more precipitation resulted in higher N_2O emission in East than in West China. In contrast with the model IPCC-D, N_2O estimated by integrating fertilizer and precipitation into the model IPCC-P might be closer to its actual emission.

4.3. Emission factor of N_2O in Chinese fertilized fields estimated by different studies

In order to establish the national, regional and global inventories of N_2O emission, many approaches have been developed, ranging from simple regression equation to complex biogeochemistry model. For example, approaches that have been used to estimate N_2O emissions from Chinese fertilized fields include: (1) the IPCC default model (Yan et al., 2003); (2) the up-scaling average of site-scale EFs (Xing, 1998; Chen et al., 2000; Zheng et al., 2004); (3) the process-oriented model (DNDC model, Li et al., 2001). Consistent with this study, the emission factor of N_2O tended to be close to 0.90% among these studies except one estimate (Xing, 1998). However, few studies have presented the uncertainty in estimate. The uncertainty in up-scaling N_2O estimate by Zheng et al. (2004) was −79% to 135%, which is significantly higher compared to the model IPCC-P in this study.

Process-oriented model is expected to be an effective approach to minimizing the uncertainty in N_2O emission estimate. To date, only the DNDC model has been tested with a few field measurement cases in China, but large discrepancy was found between the modeled and observed seasonal patterns of N_2O emission (Cai et al., 2003). Furthermore, it includes the multiple sub-models and requires the complex data inputs, which partially limits its applicability for estimating N_2O emissions at a large scale. In contrast, the rectified emission factor has a potential to produce better estimates without the need of complex structures and input data, given it takes into account the main variables controlling N_2O emissions. Based on dataset with large samples, the statistic description of relationship between N_2O emission and environmental factors might be an effective approach to bridging the gap between site and landscape scales, and thus narrows the uncertainty of estimate.

4.4. Future modeling agricultural N_2O emission

Despite extensive knowledge of processes involved, we are not yet able to reliably predict the fate of a unit of N that is applied or deposited on agricultural fields (Mosier et al., 1998). Direct N_2O emission in agricultural fields occurs essentially with great spatial and temporal variabilities. Temporal variability exists often at the site scale, while spatial variability is mainly caused by heterogeneity in soil properties, agricultural management, and climate factors (e.g. Henault et al., 1998; Flessa et al., 2002; Dobbie and Smith, 2003; Wang et al., 2005).

The uncertainty was yet as high as 37% in this study, despite it was lower than the IPCC default model. The large uncertainty may come from the neglect of some factors, such as temperature, soil parameters and crop species. Surprisingly, N_2O emission was not significantly correlated with temperature in the partial correlation analysis. It is likely that we used annual mean temperature rather than mean temperature over the growing season in this study. On the other hand, N_2O emission was not significantly correlated with soil parameters, such as pH, soil organic carbon and N content in this study, which is consistent with some previous studies (e.g. Roelandt et al., 2005). The significant effects of soil parameters on N_2O emission in previous studies were often found at the site scale within the similar climate condition (Velthof and Oenema, 1995; Monika and Conrad, 2000; Huang et al., 2002). At a large regional scale, presumably, the impact of climate factors on N_2O emission could overwhelm soil factors effect. Also, a scarcity of measurement in some representative regions and ecosystems may be another important cause that soil parameters were not included in the models.

There is evidence that agricultural practices other than fertilizer N input are also important to N_2O emission in agricultural fields (Heinemeyer, 1998; Ruser et al., 2001). For example, the water management has shown to be important factors influencing N_2O emissions in agriculture. Irrigation was not reported in the N_2O literature, which makes it impossible to consider its effect on N_2O emissions from uplands in this study. So far, we can only distinguish N_2O emissions between uplands and rice paddies. In general, water demand for plant growth can be satisfied by precipitation on 80% area of uplands in China (Pan et al., 2005). Due to shortfall of precipitation, however, irrigated uplands account for most west region and the North China Plain. In these regions, irrigation often occurs at the winter and early spring seasons, when N_2O fluxes are generally low. In the future, obviously, irrigation should be taken into account because it would be increasingly applied in China to maintain high crop yields. Based on intensive field N_2O measurements at typical sites and regions, incorporation the major parameters such as climate factors, soil properties and agricultural practices into the simple empirical model will help to minimize the large uncertainty in agricultural N_2O estimate.

5. Conclusion

We compiled a database of N_2O emissions from fertilized fields that were consecutively measured for more than or close to one year. Both nitrogen input and precipitation were largely responsible for temporal and spatial variabilities in N_2O. An empirical model in which both emission factor and background emission for N_2O were rectified by precipitation was used to develop a spatial inventory at the 10 × 10 km scale of agricultural N_2O emission in China. The total annual fertilizer-induced N_2O emission was estimated to be 198.89 Gg N_2O–N in 1997 with the uncertainty of 29%, accounting for 0.92% of the applied N. Background emission of N_2O from agriculture was estimated to be 92.78 Gg N_2O–N and the annual N_2O emission totaled 291.67 Gg N_2O–N. The highest N_2O fluxes occurred in East China as compared with the least fluxes in West China.

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