



## Short communication

## Estimates of synthetic fertilizer N-induced direct nitrous oxide emission from Chinese croplands during 1980–2000

Jianwen Zou<sup>a</sup>, Yanyu Lu<sup>a,c</sup>, Yao Huang<sup>a,b,\*</sup><sup>a</sup> College of Resources & Environmental Sciences, Nanjing Agricultural University, Nanjing 210095, PR China<sup>b</sup> LAPC, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, PR China<sup>c</sup> Anhui Climate Center, Anhui Meteorological Bureau, Hefei 230031, PR ChinaA time span and regional trend of agricultural N<sub>2</sub>O emissions due to rapidly increased synthetic fertilizer N use in China.

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## ABSTRACT

There is increasing concern that agricultural intensification in China has greatly increased N<sub>2</sub>O emissions due to rapidly increased fertilizer use. By linking a spatial database of precipitation, synthetic fertilizer N input, cropping rotation and area via GIS, a precipitation-rectified emission factor of N<sub>2</sub>O for upland croplands and water regime-specific emission factors for irrigated rice paddies were adopted to estimate annual synthetic fertilizer N-induced direct N<sub>2</sub>O emissions (FIE-N<sub>2</sub>O) from Chinese croplands during 1980–2000. Annual FIE-N<sub>2</sub>O was estimated to be 115.7 Gg N<sub>2</sub>O-N year<sup>-1</sup> in the 1980s and 210.5 Gg N<sub>2</sub>O-N year<sup>-1</sup> in the 1990s, with an annual increasing rate of 9.14 Gg N<sub>2</sub>O-N year<sup>-1</sup> over the period 1980–2000. Upland croplands contributed most to the national total of FIE-N<sub>2</sub>O, accounting for 79% in 1980 and 92% in 2000. Approximately 65% of the FIE-N<sub>2</sub>O emitted in eastern and southern central China.

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## 1. Introduction

Nitrous oxide (N<sub>2</sub>O), an important atmospheric trace gas, contributes greatly to the global warming and stratosphere ozone depletion. On mass basis, the global warming potential of N<sub>2</sub>O is about 298 times higher than CO<sub>2</sub> at a 100-year horizon (IPCC, 2007a). Agricultural is recognized one of the major sources of atmospheric N<sub>2</sub>O, which accounts for 60% of global anthropogenic N<sub>2</sub>O emissions. Globally, agricultural N<sub>2</sub>O emissions have increased by nearly 17% from 1990 to 2005 (IPCC, 2007b), and are projected to increase by 35–60% up to 2030 due to increased nitrogen fertilizer use and increased animal manure production (FAO, 2003).

China is one of large agricultural countries in the world, which contains 12% of world's total crop harvest area (FAOSTAT, 2002). Synthetic fertilizer is a major nitrogen supply for Chinese agro-ecosystems. In order to feed the increasing population, great amounts of synthetic fertilizer have been applied for improving crop yield since the early 1980s. Annual consumption of synthetic nitrogen fertilizer in China increased from 9.34 Tg N in 1980 to 21.62 Tg N in 2000 (FAOSTAT, 2002), which might have induced remarkable N<sub>2</sub>O emissions as well.

Several studies have been dedicated to estimating direct N<sub>2</sub>O emissions from Chinese croplands over the last decade. By comparing a process-based DNDC model to the IPCC methodology, Li et al. (2001) gave an insight into a national inventory of N<sub>2</sub>O emissions from arable lands in China in 1990. Xing (1998) and Yan et al. (2003) estimated the direct N<sub>2</sub>O emissions from Chinese croplands in 1995 by using the IPCC methodology and summary of available data. Based on an up-scaling average of site-specific emission factors, Zheng et al. (2004) re-quantified the direct N<sub>2</sub>O emissions in the 1990s. Though great efforts have been made to quantify N<sub>2</sub>O emission from Chinese croplands, few studies provide an insight into the time span and regional trend of agricultural N<sub>2</sub>O emissions due to rapidly increased synthetic fertilizer N use in China. In this study, we estimated annual synthetic fertilizer N-induced direct N<sub>2</sub>O emissions from Chinese croplands over the period 1980–2000 by using a precipitation-rectified emission factor of N<sub>2</sub>O for upland croplands and water regime-specific emission factors for irrigated rice paddies.

## 2. Materials and methods

## 2.1. Emission factors

We compiled a worldwide database of N<sub>2</sub>O emissions from fertilized fields that were consecutively measured for more than or close to one year. Both nitrogen input (N, kg N ha<sup>-1</sup> year<sup>-1</sup>) and precipitation (P, m) have been found to be largely responsible for temporal and spatial variability in annual N<sub>2</sub>O fluxes (kg N<sub>2</sub>O-N ha<sup>-1</sup> year<sup>-1</sup>).

\* Corresponding author at: College of Resources & Environmental Sciences, Nanjing Agricultural University, Nanjing 210095, PR China. Tel.: +86 25 84396406; fax: +86 25 84396286.

E-mail address: [huangy@njau.edu.cn](mailto:huangy@njau.edu.cn) (Y. Huang).

of uplands. Thereby, we established an empirical model that consisted of a background emission of 1.49 P and a fertilizer-induced emission of 0.0186 P·N (Equation (1), Lu et al., 2006). This model has been validated to be fit agricultural N<sub>2</sub>O emissions in China well (Lu et al., 2006).

$$\text{FIE} - \text{N}_2\text{O} = 0.0186 (\pm 0.0027) \cdot P \cdot N \quad (1)$$

Here, we use the precipitation-rectified emission factor “0.0186 P” to estimate the synthetic fertilizer-induced N<sub>2</sub>O emissions (FIE-N<sub>2</sub>O, kg N<sub>2</sub>O-N ha<sup>-1</sup> year<sup>-1</sup>) from fertilized upland soils in China. The term “±0.0027” represents the 95% confidence intervals of parameter estimate for emission factor.

It is well documented that N<sub>2</sub>O emission from paddy fields shows different patterns from uplands and depends greatly on water regime (Akiyama et al., 2005; Zou et al., 2005). By summary of available field data on direct N<sub>2</sub>O emissions from paddy fields that were classified as three water management regimes, including continuous flooding (F), flooding–midseason drainage–reflooding (F–D–F), and flooding–midseason–drainage–reflooding–moist intermittent irrigation but without water logging (F–D–F–M), we established ordinary Least Square (OLS) linear regression models (Equations (2)–(4)) to identify water regime-specific emission factors (EFs) of N<sub>2</sub>O during the rice-growing season in paddy fields in China (Zou et al., 2007, 2009).

$$\text{F: FIE} - \text{N}_2\text{O} = 0.0002 (\pm 0.00006)N \quad (2)$$

$$\text{F–D–F: FIE} - \text{N}_2\text{O} = 0.0042 (\pm 0.0012)N \quad (3)$$

$$\text{F–D–F–M: FIE} - \text{N}_2\text{O} = 0.0073 (\pm 0.0022)N \quad (4)$$

Here, the EFs 0.0002, 0.0042 and 0.0073 kg N<sub>2</sub>O-N kg N ha<sup>-1</sup> were adopted to estimate the synthetic fertilizer-induced direct N<sub>2</sub>O emissions from rice paddies under the water regimes of F, F–D–F, and F–D–F–M, respectively.

## 2.2. Uncertainties calculation

Similar to the uncertainty estimate in the IPCC methodology (IPCC, 2006; Lu et al., 2006), we use the error propagation equation (IPCC, 2006 – Equation (3.1)) to combine the uncertain quantities of different sources and calculate the range of emission estimates (Equation (5)).

$$U_C = \sqrt{U_A^2 + U_E^2} \quad (5)$$

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. In this study, 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 the spatialization. The confidence interval of parameter estimates in the OLS models 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 (IPCC, 2006).

The uncertainty in N<sub>2</sub>O estimates in rice paddies under different water regimes for each year was calculated by:

$$U_R = \frac{\sqrt{(U_F \cdot x_F)^2 + (U_{F-D-F} \cdot x_{F-D-F})^2 + (U_{F-D-F-M} \cdot x_{F-D-F-M})^2}}{x_F + x_{F-D-F} + x_{F-D-F-M}} \quad (6)$$

where  $U_R$  is the uncertainty expressed as a percentage for each year in rice paddies;  $x_i$  and  $U_i$  ( $i$  represents the water regimes of F, F–D–F, and F–D–F–M) are the uncertain quantities (i.e. N<sub>2</sub>O estimates) and the percentage uncertainties (i.e.  $U_C$  in the Equation (5)) associated with them under different water regimes, respectively. Eventually, the total uncertainty in annual direct N<sub>2</sub>O estimates in Chinese croplands was calculated by (IPCC, 2006 – Equation 3.2):

$$U_{\text{total}} = \frac{\sqrt{(U_U \cdot x_U)^2 + (U_R \cdot x_R)^2}}{x_U + x_R} \quad (7)$$

where  $U_{\text{total}}$  is the total uncertainty expressed as a percentage for each year;  $x_U$  and  $x_R$  are the uncertain N<sub>2</sub>O estimates in uplands and rice paddies, respectively;  $U_U$  and  $U_R$  represent the percentage uncertainties associated with N<sub>2</sub>O estimates in uplands and rice paddies, respectively.

## 2.3. Data source and model up-scaling

Data on the annual precipitation at 670 weather stations from 1980 to 2000 were derived from the National Meteorological Information Center, China Meteorological Administration (Huang et al., 2004). By applying the interpolation algorithm

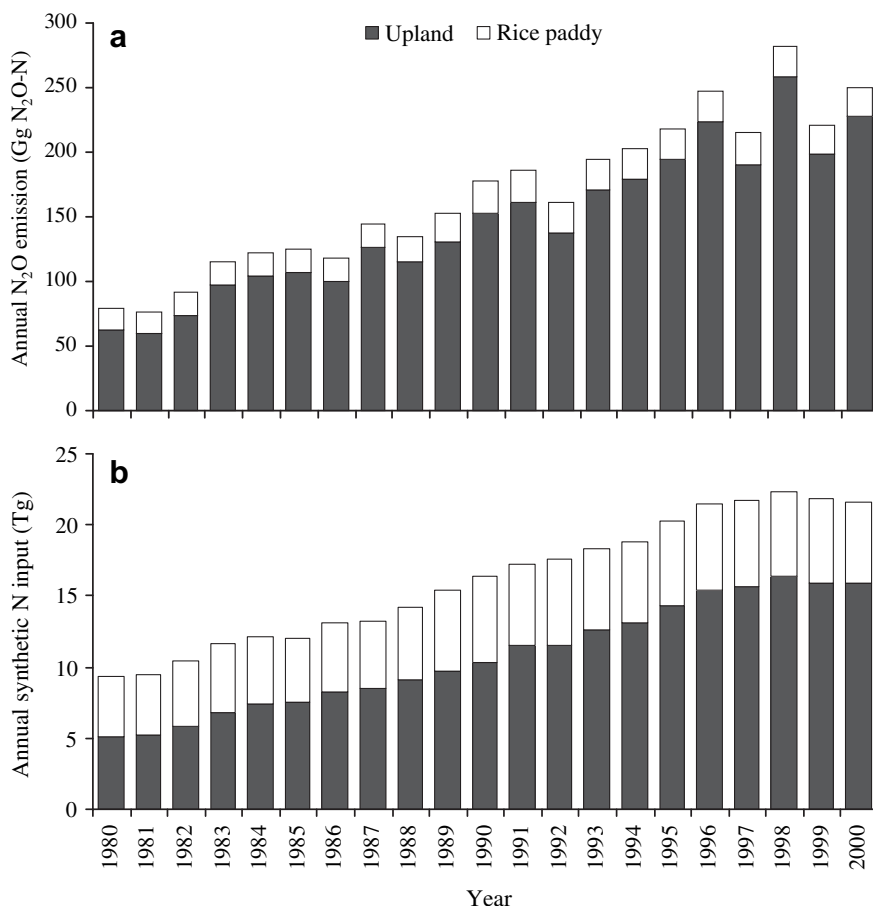
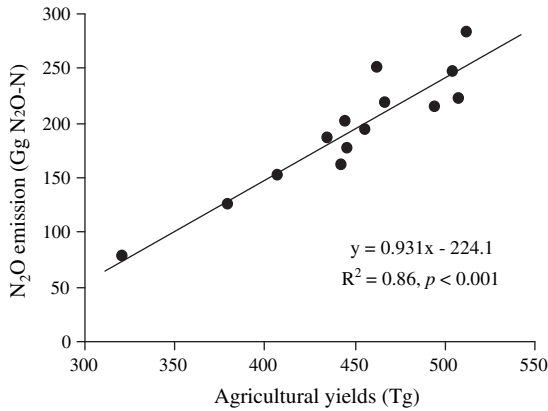


Fig. 1. Annual amounts of fertilizer-induced direct N<sub>2</sub>O emissions (a) and synthetic fertilizer N inputs (b) in Chinese croplands.



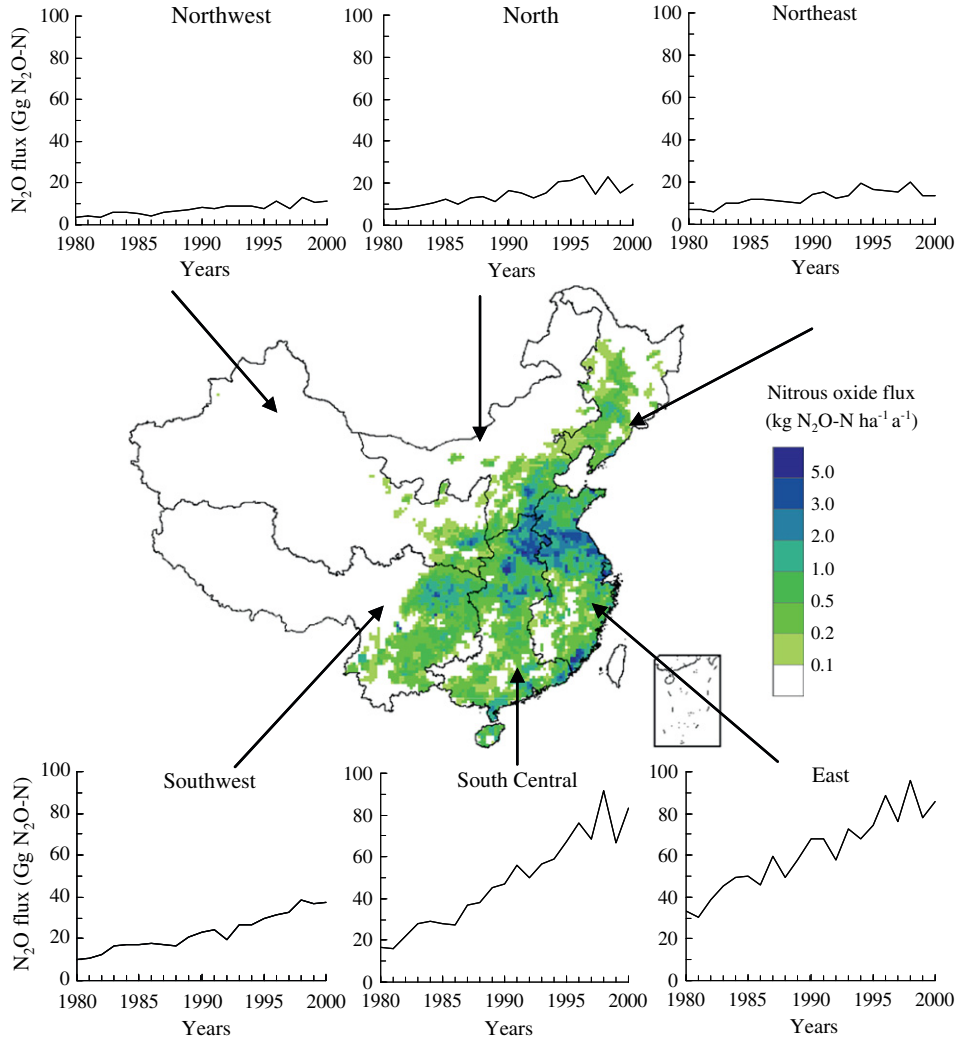
**Fig. 2.** Increases in annual FIE-N<sub>2</sub>O emissions accompanied by agricultural yields in China over the period 1980–2000.

(Thornton et al., 1997), the site-specific precipitation was interpolated into raster layers. Yearly data at county level on synthetic fertilizer N input, cropping rotation and area were obtained from the database of China Statistics annuals. Synthetic fertilizer N inputs and water management regimes for rice fields referred to Zou et al. (2009). The county level data were linked to the administrative boundary map of

China and projected onto each grid. All the input data were converted to ArcInfo grid files via GIS at a resolution of 10 km × 10 km. By linking the emission factors to the spatial database, annual amounts of synthetic fertilizer N-induced N<sub>2</sub>O emission from Chinese croplands were estimated from 1980 through 2000.

**3. Results and discussion**

Annual synthetic fertilizer-induced N<sub>2</sub>O emissions (FIE-N<sub>2</sub>O) in Chinese croplands increased from 78.5 Gg N<sub>2</sub>O–N in 1980 to 250.0 Gg N<sub>2</sub>O–N in 2000. The lowest (76.4 Gg N<sub>2</sub>O–N) and the highest (282.4 Gg N<sub>2</sub>O–N) flux of FIE-N<sub>2</sub>O occurred in 1981 and 1998, respectively (Fig. 1a). On average, annual FIE-N<sub>2</sub>O was estimated to be 115.7 Gg N<sub>2</sub>O–N year<sup>-1</sup> in the 1980s and 210.5 Gg N<sub>2</sub>O–N year<sup>-1</sup> in the 1990s, with an annual increase rate of 9.14 Gg N<sub>2</sub>O–N year<sup>-1</sup> over the period 1980–2000 (Fig. 1a). On a national scale, the direct emission factor of N<sub>2</sub>O averaged 1.02%, ranging from 0.81% in 1981 to 1.26% in 1998. Over the period 1980–2000, increases in annual FIE-N<sub>2</sub>O flux were accompanied by agricultural annual yields. Synthetic fertilizer N-induced 0.93 g N<sub>2</sub>O–N in terms of per kilogram agricultural yields in Chinese croplands (Fig. 2). Uplands constituted the major source of FIE-N<sub>2</sub>O, contributing 79–92% to the total emissions from Chinese croplands, while irrigated rice fields receiving 26–46% of the national N inputs only



**Fig. 3.** Spatiotemporal distribution of synthetic fertilizer N-induced N<sub>2</sub>O flux from Chinese croplands. The spatial distribution of annual N<sub>2</sub>O emission rate in 2000 was plotted. Northeast: Heilongjiang, Jilin, and Liaoning Provinces; North: Beijing, Tianjin, Hebei, Shanxi, and Inner Mongolia Provinces; Northwest: Shaanxi, Gansu, Ningxia, Qinghai, and Xinjiang Provinces; East: Shanghai, Jiangsu, Zhejiang, Anhui, Shandong, Jiangxi, and Fujian Provinces; Southwest: Sichuan, Chongqing, Guizhou, Yunnan, and Tibet Provinces.

accounted for 8–21% of the total FIE-N<sub>2</sub>O over the period 1980–2000 (Fig. 1a, b). The contribution of rice production in the 1990s was estimated to be 8–11%, which is fairly in agreement with the reports by Xing (1998).

The spatial distribution of annual FIE-N<sub>2</sub>O in 2000 is characterized by higher fluxes in Sichuan basin, central and southeastern China and lower fluxes in western regions (Fig. 3), which is in accordance with the spatial pattern projected by the process-oriented DNDC model (Li et al., 2001). An apparent reason is that the intensive upland-irrigated rice rotation prevails in Sichuan basin, central and southeastern China, where the application rate of synthetic fertilizer was generally higher than other agricultural regions (Zou et al., 2009). By contrast, lower application rate of synthetic fertilizer and deficient precipitation incurred lower N<sub>2</sub>O emission in western China.

The FIE-N<sub>2</sub>O in Chinese croplands showed a pronounced spatial and temporal variability over the period 1980–2000 (Fig. 3). Some 34–43% of FIE-N<sub>2</sub>O occurred in eastern China, followed by 21–33% in the south central region. Approximately 65% of the national FIE-N<sub>2</sub>O emitted from these two regions, with an annual increase rate of 6.23 Gg N<sub>2</sub>O-N year<sup>-1</sup>, while the FIE-N<sub>2</sub>O in the regions of northern, northeastern, northwestern and southwestern China accounted for about 35%, with an annual increase rate of 2.91 Gg N<sub>2</sub>O-N year<sup>-1</sup> (Fig. 3). The eastern and south central regions represent the main agricultural areas in China where the emission factor of N<sub>2</sub>O is predicted to be high due to plenty of annual precipitation. Therefore, higher nitrogen input coupled with plentiful precipitation should have resulted in higher N<sub>2</sub>O emission in these regions compared to the other regions.

In general, annual FIE-N<sub>2</sub>O estimated in this study is higher than that by using the IPCC updated default emission factors for mineral soil (0.01) and flooded rice fields (0.003) (IPCC, 2006). Applying the IPCC updated default emission factor yields that the annual FIE-N<sub>2</sub>O was, on average, estimated to be 87.7 Gg N<sub>2</sub>O-N in the 1980s and 154.6 Gg N<sub>2</sub>O-N in the 1990s, which is 24–26% lower than the current estimates (Fig. 3). In contrast, the results of this study are comparable to some previous estimates (Li et al., 2001; Xing, 1998; Yan et al., 2003; Zheng et al., 2004). Li et al. (2001) estimated the FIE-N<sub>2</sub>O in Chinese croplands in 1990 to be 130 Gg N<sub>2</sub>O-N by the DNDC model and 210 Gg N<sub>2</sub>O-N by the IPCC default emission factor of 1.25%, while our estimate of 177.2 Gg N<sub>2</sub>O-N falls within the range of their two different methodological estimates. By adopting

a similar IPCC method based on summary of available data, Yan et al. (2003) estimated the FIE-N<sub>2</sub>O in Chinese croplands to be 202 Gg N<sub>2</sub>O-N in 1995, which is highly close to the current estimate (217.7 Gg N<sub>2</sub>O-N). The direct N<sub>2</sub>O emissions from Chinese croplands were estimated to be 398 Gg N<sub>2</sub>O-N in 1995 by Xing (1998), which includes background N<sub>2</sub>O emissions and direct N<sub>2</sub>O emissions. If subtracting background N<sub>2</sub>O emissions in 1995 obtained by Yan et al. (2003) from Xing's (1998) estimate, the direct N<sub>2</sub>O emissions would be 271 Gg N<sub>2</sub>O-N in 1995, close to the estimate (275 Gg N<sub>2</sub>O-N year<sup>-1</sup> in the 1990s) by Zheng et al. (2004), which is based on an up-scaling average of site-specific emission factors. Note that their estimate of 275 (or 271) Gg N<sub>2</sub>O-N year<sup>-1</sup> represents the direct N<sub>2</sub>O emissions due to synthetic fertilizer, manure and crop residue total N inputs. In contrast, we only estimated synthetic fertilizer N-induced direct N<sub>2</sub>O emissions, and did not take into account manure and crop residue N-induced N<sub>2</sub>O emissions and background emissions in this study.

Obviously, the IPCC default methodology was the simply up-scaling of site-scale emission factors and neglected some important effect factors, which would incur large uncertainties. The estimate uncertainty of -74–186% originated from the IPCC (2006) default emission factor uncertainty range (0.003–0.03 in upland croplands and 0.000–0.006 in rice paddies) is enormous (Fig. 4). Incorporation of some key parameters into the IPCC methodology may effectively minimize the uncertainty in N<sub>2</sub>O estimates. Soil water condition is believed to be the most important to N<sub>2</sub>O emission, which is mainly dependent on precipitation in uplands and water management regime in rice paddies (e.g., Dobbie and Smith, 2003; Zou et al., 2005). Therefore, taking into account precipitation-rectified emission factors for uplands and water regime-specific emission factors for irrigated rice fields in this study is expected to minimize the uncertain in estimates of FIE-N<sub>2</sub>O emission from Chinese croplands. Indeed, the combined uncertainty was minimized to be 23% by using precipitation-rectified emission factors for uplands and water regime-specific emission factors for irrigated rice fields in this study (Fig. 4).

#### 4. Conclusion

Due to increased synthetic nitrogen application, annual fertilizer-induced N<sub>2</sub>O emission in Chinese croplands increased at a rate of approximately 9.14 Gg N<sub>2</sub>O-N year<sup>-1</sup> from 1980 to 2000. Annual fertilizer-induced N<sub>2</sub>O was estimated, on average, to be 115.7 Gg N<sub>2</sub>O-N year<sup>-1</sup> in the 1980s and 210.5 Gg N<sub>2</sub>O-N year<sup>-1</sup> in the 1990s. Uplands contributed 79%–92% to the total fertilizer-induced N<sub>2</sub>O emission over the period 1980–2000. A substantial N<sub>2</sub>O emission occurred in eastern and south central China, accounting for approximately 65% of the national total.

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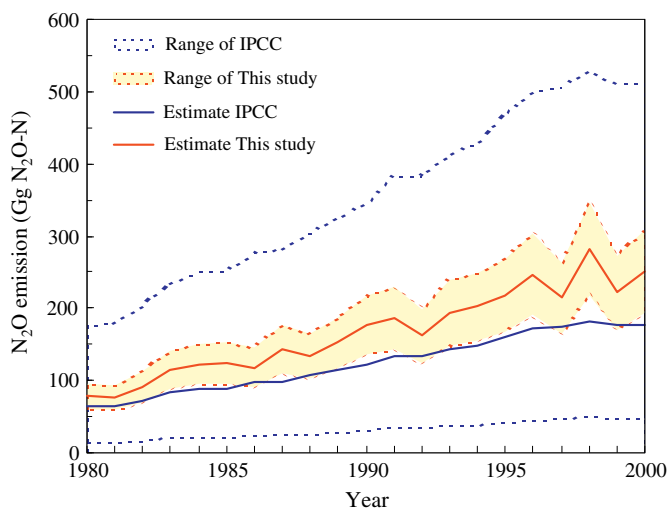


Fig. 4. Range of estimated annual amount of synthetic fertilizer N-induced N<sub>2</sub>O emissions from Chinese croplands. Range represents a 95% confidence interval of estimates.

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