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Contribution of N Fertilization to N_2O Emissions from Crop Lands of China and Mitigation Options

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1. Introduction

Application of nitrogen fertilizers is a crucial approach for food security of China. For meeting the increasing food demands, the consumption of synthetic N fertilizers in China increased from 0.54 Tg N in 1961 to 26.64 Tg N in 2005. With the increase in N consumption for agricultural production, N use efficiency decreases and excess application occurs frequently, particularly in the east coastal regions and for vegetable and cash crop production. Meanwhile, the negative impacts of N consumption on environment, ecosystems and human health become serious (Galloway et al., 2008).

Nitrous oxide (N_2O) is one of important greenhouse gases, which concentration are increasing at the atmosphere and considered as the origination of global warming. According to the IPCC assessment report (IPCC, 2007a), the global atmospheric N_2O concentration increased from a pre-industrial value of about 270 ppb to 319 ppb in 2005. More than a third of all N_2O emissions are anthropogenic and are primarily due to agriculture. N_2O also contributes to stratospheric ozone depletion (IPCC, 2001). The presentation will focus on N_2O emissions induced by application of synthetic N fertilizers to croplands of China and options for mitigating N_2O emissions.

2. Processes of N_2O production

In China, synthetic N fertilizers are dominated by ammonium and urea and nitrate-based fertilizers are negligible. Under aerobic conditions, ammonium applied into soils or released from hydrolysis of urea and mineralization of soil organic N will be oxidized by nitrifiers into nitrite, which is further oxidized into nitrate. During the process of ammonium oxidation into nitrite, N_2O is produced as a by-product and emitted from soil to the atmosphere. Since soil is heterogeneous and there exist anaerobic microsites, such as inside aggregates in aerobic soil. Nitrate diffused from bulk aerobic soil into anaerobic microsites will be reduced step by step into NO_2^-, NO, and N_2O, and eventually, into N_2 gas. The process is termed as denitrification, in which process, N_2O is an intermediate product. In certain anaerobic conditions, dissimilatory NO_3^- reduction to NH_4^+ (DNRA) takes place and N_2O is also produced as a by-product in the process. The processes of N transformation in soil are described in Fig. 1. Because nitrification and denitrification always take place simultaneously in soil, it is difficult to distinguish the processes which produce N_2O under field conditions.

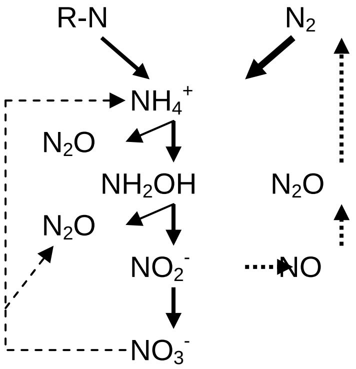

Fig. 1 Processes of N transformation and N_2O production in soil. Coarse solid arrow: N fixation; middle solid arrow: nitrification; fine solid arrow: by product; coarse dotted arrow: denitrification; fine dotted arrow: dissimilatory NO_3^- reduction to NH_4^+ (DNRA)

There also exist aerobic microsites in anaerobic soils, such as interface between floodwater and soil surface and rice rhizosphere in flooded rice fields. These aerobic microsites are able to oxidize NH_4^+ into NO_3^-, which is reduced after diffused into anaerobic bulk soil. Thus, coupled nitrification and denitrification also takes place, so does N_2O emissions in flooded rice fields. Because floodwater layer slows N_2O release from bulk soil to the atmosphere and denitrification is strong under anaerobic conditions, entrapped N_2O produced from coupled nitrification and denitrification is easily further reduced into N_2 gas. Thus, N_2O emission is usually negligible when rice fields are flooded.

3. N_2O emissions from croplands of China

Chinese croplands are composed of upland and flooded rice fields. Rice harvested area was accounted for the range of 18-20% of total crop harvested area. In China, rice plants grow in the period from April to November, varying from south to north. Upland crops, such as winter wheat, oil seed-rape, etc. are usually planted in the same fields in the off-rice season. So, rice fields are not pure rice production fields, but rice-based ecosystems.

Field measurements of N_2O emissions from croplands in China started in the early 1990's and the papers reporting N_2O emissions were firstly published in 1995 (Yu et al., 1995; Wang et al., 1995). Since then, the data on N_2O emissions from Chinese uplands and rice fields has been accumulated substantially. Field measurements indicate that uplands are N_2O source. Peaked N_2O fluxes are usually observed after N fertilization and rainfall event or irrigation in uplands. Across the country, there is a trend that N_2O emissions factor (EF), defined as ratio of N_2O-N loss to N applied, increased with increasing precipitation in uplands (Lu et al., 2006). N_2O emissions from flooded rice fields used were regarded as negligible due to complete denitrification. Now, it has been confirmed that N_2O emissions are negligible only in continuously flooded rice fields. Substantial N_2O emissions from rice fields usually are often observed after mid-season drainages and drainage for harvesting. Therefore, N_2O emissions from rice fields during the rice growing period are closely related with water regimes and increase with the number of mid-season drainage (Zou et al., 2007; 2009). N_2O emissions also take place during the winter crop season in rice-based ecosystems (Xing, 1998). However, N_2O emission factor in rice fields is smaller than that in uplands.

The first estimate of N_2O emission from croplands in China was made by Wang et al. (1995). This was an exploration of N_2O emission measured at the same site located at North China to whole country. After that, a number of N_2O emissions from croplands of China were made by using different methodologies. Obviously, total N_2O emission of 122 Gg N from croplands was underestimated (Table 1). It is very strange that except the first estimate, total emissions from croplands in China estimated by applying different methodologies vary in a very narrow range, although N_2O emissions are sporadic and have very large temporal and spatial variations (Table 1). Estimated total N_2O emissions from croplands of China ranged from 310 to 476 Gg N/yr. Xing (1998) estimated that N_2O emissions from uplands contributed 78% of total emissions and rice-based ecosystems contributed 22%. For rice-based ecosystems N_2O emissions mainly occur during the off-rice season, accounted for 60% of annual emissions from these ecosystems.

Yan et al. (2003) applied the methodology of revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories and estimated N_2O emissions from synthetic N fertilizer (FSN), animal excreta used for fertilizer (FAW), biological fixed N (FBN), N from crop residue returned to croplands (FCR), and soil native N in croplands, which is termed as background emission. Total N_2O emissions from croplands in China were estimated to be 476.3 Gg N in 1995, of which 202.4 Gg N from application of synthetic N fertilizer, accounted for 42%. Li et al. (2001) applied IPCC methodology and estimated total N_2O emissions from croplands in China to be 360 Gg N in 1990, of which 210 Gg N from the synthetic N fertilizers, accounted for 58%. By using DeComposition-DeNitrification (DNDC) model, they estimated the value to be 310 Gg N, 130 Gg N, and 42%, respectively. These estimates indicate that synthetic N fertilizers dominate N sources for N_2O emissions from croplands in China; while, on average, background N_2O emissions (43%) rather than synthetic N fertilizer (30%) dominated the total N_2O emissions from croplands in East, Southeast and South Asia (Yan et el., 2003).

It shall be noted that the N_2O emissions from synthetic N fertilizer estimated above are termed as direct emissions. There are substantial indirect N_2O emissions from synthetic N fertilizers applied to croplands. Synthetic N fertilizers applied to croplands are also lost as NOx emissions and through NH_3 volatilization and leaching or runoff of NO_3^-. Indirect N_2O emissions occur through re-deposition and transformation of

NH_3 and NO and through re-distribution of NO_3^- in landscapes. Yan et al. (2003) estimated the synthetic N fertilizers induced NH_3 volatilization to be 3.56 Tg N and NO emissions to be 106 Gg N from croplands in China in 1995. Assuming that EF of lost N was similar as that of synthetic N applied to croplands, volatilized NH_3 alone would produce N_2O about 36 Gg N. Therefore, indirect N_2O emissions from synthetic N fertilizers applied to croplands should not be neglected.

N_2O emission factor of synthetic N fertilizer varies greatly, mainly dependent on water regimes, N application rate, soil properties, etc. Generally, EF is larger in uplands than in rice-based ecosystems. The default values of EF are 1% for uplands and 0.3% for rice fields in the revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2007b). Li et al. (2001) estimated by DNDC model that the EF of synthetic N fertilizers ranged from 0.25% to 4% at county-scale and a national average was 0.82% in China. By using a statistical model for uplands and default EF of IPCC Guidelines for rice fields (0.3%), Lu et al. (2007) estimated overall EF of synthetic N fertilizers ranged from 0.25% to 2.25% with average of 0.92%, very close to the average of 0.93% in East, Southeast and South Asia estimated by Yan et al. (2003). However, for uplands alone, calculated from the estimates made by Lu et al. (2007), the averaged EF of synthetic N fertilizers in China was 1.15%, larger than the default value (1%) given in the 2006 IPCC Guidelines (IPCC, 2007b).

Synthetic N fertilizer induced N_2O emissions from croplands increase with increasing their application to croplands. By applying a regional nitrogen cycle model, named IAP-N, Zheng et al. (2008) estimated N_2O emissions from Chinese agricultural sector and cultivated soils from 1961 to 2004. Their estimate indicated that on average, N_2O from cultivated soils increased by 8.6 Gg N every year during the period. The increase in synthetic N fertilizers applied to cultivated soils made a unique contribution to the increment of N_2O from the cultivated soils. On average, N_2O emissions increase by 1.59% of the increment of synthetic N fertilizers applied to cultivated soils.

4. Mitigation options

In China, synthetic N fertilizers are almost all ammonium-based. The form of N released from organic N mineralization and urea hydrolysis is also ammonium. It can be inferred from N transformation in soils (Fig. 1) that if nitrification of ammonium is inhibited, denitrification is also restricted by the lack of nitrate substrate. Consequently, N_2O emission can be mitigated. There are two ways keeping nitrification and denitrification activities at low level. One is to apply nitrification inhibitors along with application of synthetic N fertilizers to inhibit nitrification, and another is to stabilize soil conditions, particularly soil moisture. Except in the soils that nitrification and denitrification are very weak, nitrification and denitrification is usually restricted by substrates, *i.e.* NH_4^+ and NO_3^-, respectively. Application of ammonium-based fertilizers into aerobic soils stimulates nitrification. If aerobic conditions are maintained, applied NH_4^+ is usually nitrified completely within one week. After that time, inorganic N in soil is dominated by NO_3^- and nitrification is controlled by organic N mineralization and aerobic conditions constrain denitrification. As a consequence, N_2O emission is usually small during the period of stabilized soil moisture. However, if soil becomes wetter due to rainfall or irrigation, denitrification of NO_3^- is stimulated and N_2O produced from denitrification increases. This is why peaked N_2O fluxes are usually observed after each rainfall event or irrigation. In flooded rice fields, nitrification is inhibited naturally by the lack of O_2 and inorganic N is dominated by NH_4^+. Drainage of flooded water creates aerobic conditions, which stimulates nitrification of NH_4^+ and N_2O emission. Therefore, N_2O emissions usually occur during the drainage period in rice fields. Plow also destroys stabilized soil conditions, stimulating organic mineralization, and increasing NH_4^+ for nitrification, and thus produces and emits N_2O.

Preventing excess application of synthetic N fertilizers is extremely important in mitigating N_2O emissions from croplands. Excess application N fertilizers not only increase substrate of NH_4^+ for nitrification and denitrification, but also increase EF value (Lu et al., 2007). Unfortunately, excess application of N fertilizers is common in China, particularly for vegetable production. Generally, N use efficiency is low in China. All the practices which enable to enhance N use efficiency may reduce N_2O emission if N application rate is reduced correspondently.

Preventing unnecessary irrigation of uplands is also an important option for mitigating N_2O emissions from uplands. Mid-season drainage is an effective option for mitigating CH_4 emissions from rice fields, but usually stimulates N_2O emission (Cai et al., 1997). However, compared to continuously flooded rice fields, global warming potential (GWP) of CH_4 and N_2O emissions is usually smaller in rice fields drained in mid-season than in continuously flooding (Yan et al., 2009).

Theoretically, application of nitrification inhibitors enables to mitigate N_2O emissions through inhibiting nitrification. Numerous researches have been done on the effects of nitrification inhibitors on N use efficiency and N_2O emissions. Application of nitrification inhibitors mitigated N_2O emissions from uplands in most case studies, but not all (Mosier et al., 1996). Application of nitrification inhibitors to rice fields at appropriate time may mitigate both CH_4 and N_2O emissions (Li et al., 2008).

In rice fields, N_2O emissions induced by ammonium sulfate are usually smaller than those induced by urea and ammonium bicarbonate, although the differences are usually not statistically significant. But CH_4 emissions may be larger in rice fields applied with ammonium sulfate than with urea and ammonium bicarbonate (Cai et al., 1997).

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Table 1 Estimated synthetic N fertilizer induced N_2O emissions and total N_2O emissions from croplands in China

Reference	Year	Methodology	N_2O emission (Gg N/yr)	
			Fert. induced	Total
Wang et al., 1995	1990	Scaling up based on field measurement at single site		122
Xing, 1998	1995	Scaling up based on N_2O emissions measured in upland and rice fields		398
Li et al., 2001	1990	DNDC model	130	310
		IPCC methodology	210	360
Yan et al., 2003	1995	IPCC methodology	202.4	476.3
Zheng et al., 2007	2004	IPA-N model		399
Lu et al., 2007	1997	IPCC methodology. EF for uplands was calculated from precipitation and N application rate; EF for rice fields was 0.31%	199	
	1991-2000		204	