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# Nitrous oxide and methane emissions from a subtropical rice–rapeseed rotation system in China: A 3-year field case study

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ABSTRACT

Fertilizer nitrogen (N) application has been shown to impact both methane ($CH_4$) and nitrous oxide ($N_2O$) emissions from rice-based crop systems, yet the responses of $CH_4$ and $N_2O$ fluxes to N fertilizer applications in subtropical rice–rapeseed rotation systems are not well documented. A three-year field experiment was conducted to simultaneously measure the fluxes of $CH_4$ and $N_2O$ from a subtropical rice–rapeseed rotation system under three N fertilization treatments (control with no N fertilizer addition [CK], optimized N fertilizer management practice in accordance with the recommended N fertilizer application rate of 150 kg N $ha^{-1}$ $season^{-1}$ [OP], local farmers common N fertilizer management practice with 250 kg N $ha^{-1}$ $season^{-1}$ [CP]) in southwestern China. Results showed great intra- and inter-annual variations in $CH_4$ and $N_2O$ emissions along with the temporal variations of environmental conditions, emphasizing the necessity of multi-year measurements to achieve representative estimates. Nitrogen fertilization tended to increase $N_2O$ emissions and to inhibit $CH_4$ emissions. The direct $N_2O$ emission factors ($EF_d$) for the rice systems (mean: 0.99%) were higher than those for the rapeseed systems (mean: 0.71%). In addition, the rice-growing season dominated annual $CH_4$ emissions (>97%), which on average represented 87% of the annual total global warming potential (GWP) of $CH_4$ and $N_2O$ emissions across experimental treatments and years. Linking total GWP of $CH_4$ and $N_2O$ emissions with grain yields, the average annual yield-scaled GWP for the control (1467 kg $CO_2$-eq $Mg^{-1}$ grain) was significantly higher than for the OP (700 kg $CO_2$-eq $Mg^{-1}$ grain) and CP (682 kg $CO_2$-eq $Mg^{-1}$ grain) treatments ($P < 0.05$). Given the comparable area- and yield-scaled GWP between the CP and OP treatments, the OP treatment reduced local farmers' common N fertilizer application rate by 40% and tended to maintain crop grain yields, however it also reduced N surplus and off-site N losses in the subtropical rice–rapeseed rotation systems of southwestern China.



## 1. Introduction

The greenhouse gases (GHGs) nitrous oxide ($N_2O$) and methane ($CH_4$) play important roles in influencing stratospheric chemistry (Cicerone and Oremland, 1988; Ravishankara et al., 2009) and regional and global climate change (IPCC, 2013). Agricultural soils account for approximately 60% and 50% of global anthropogenic $N_2O$ and $CH_4$ emissions, respectively (Bouwman et al., 2002; Foley et al., 2011; Montzka et al., 2011; Syakila and Kroeze, 2011); however, the limited available field measurements, especially in subtropical and tropical regions, contribute to high uncertainties in the estimates of $N_2O$ and $CH_4$ emissions from the agricultural sector (Bartlett and Harriss, 1993; Stehfest and Bouwman, 2006) because agricultural $N_2O$ and $CH_4$ emissions likely vary by several times or even orders of magnitude across different sites and

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seasons (Dobbie et al., 1999; Wang et al., 2011). The magnitudes of both $CH_4$ and $N_2O$ emissions are regulated by a set of environmental factors that strongly depend on soil and climatic conditions, cropping systems and agricultural management practices (Butterbach-Bahl et al., 2013; Dobbie et al., 1999; Snyder et al., 2009). Thus, multi-year field measurements of agricultural $N_2O$ and $CH_4$ emissions in subtropical/tropical region are urgently needed to further reduce the uncertainties in regional and global GHG estimates.

Rice is the second-most important staple crop of the world and currently feeds over 3 billion people. In contrast to aerobic cereal crop systems that primarily release $N_2O$ but little $CH_4$, both $CH_4$ and $N_2O$ emissions contribute to GHG emissions from rice-based cultivation systems (Linquist et al., 2012; Pittelkow et al., 2014; Shang et al., 2011). Rice cropping systems primarily release $CH_4$, but also release low amounts of $N_2O$ due to anaerobic soil conditions under flooding conditions (Akiyama et al., 2005; Pittelkow et al., 2013); the management practice of repeated flooding and draining cycles greatly increased $N_2O$ emissions from rice cropping systems (Yao et al., 2012; Zhao et al., 2011). Thus, as tradeoffs between $N_2O$ and $CH_4$ emissions widely exist in rice-based cropping systems (Cai et al., 1997; Yan et al., 2009; Zou et al., 2005a), it is necessary to simultaneously quantify the two gas fluxes to improve our understanding and adopt climate-smart agricultural management practices for existing rice cultivation systems.

Previous studies have well documented the influences of N fertilization on $N_2O$ emissions from rice systems, with high N rates generally leading to greater cumulative $N_2O$ emissions (Pittelkow et al., 2013; Zhao et al., 2011, 2005a,b, 2009); both linear (Liu et al., 2010; Zou et al., 2005b) and nonlinear (Pittelkow et al., 2014; Van Groenigen et al., 2010) relationships between cumulative $N_2O$ emissions and N application rates were determined in previous studies. For example, linear relationships between cumulative $N_2O$ emissions and N application rates were determined in rice–wheat rotation systems of southern China (Liu et al., 2010; Zou et al., 2005b). In contrast, rice-based cropping systems widely exhibit a threshold response of $N_2O$ emission to N fertilizer application rate when N fertilizer inputs are in excess of rice requirements (Pittelkow et al., 2014; Van Groenigen et al., 2010). So far, the influences of N fertilization on $CH_4$ emissions from rice-based cropping systems are not fully understood because of the complex mechanisms of N fertilization on $CH_4$ emissions (Banger et al., 2012; Cai et al., 1997; Dong et al., 2011; Shang et al., 2011). For example, N fertilization tended to increase $CH_4$ emissions from rice paddy soils (Lu et al., 2000; Ma et al., 2013; Singh et al., 1999) through facilitation of $CH_4$ gas transport via rice plants (Singh et al., 1999) and increased carbon substrate availability for methanogens in the rhizosphere likely due to the increased exudation by enhanced plant growth (Lu et al., 2000). Recent studies, in contrast, observed inhibition of $CH_4$ emission following mineral N fertilization in rice-based cropping systems likely due to the stimulation of methanotrophs via ammonium-based N fertilizer applications (Dong et al., 2011; Yao et al., 2012; Zou et al., 2005a). Across 33 study sites and 155 data pairs worldwide, Banger et al. (2012) found that $CH_4$ emissions were stimulated at low N rates (<140 kg N ha$^{-1}$) but inhibited at high N rates (>140 kg N ha$^{-1}$) in rice-based cropping systems. Nevertheless, the application of N fertilizer is critical not only to regulating $CH_4$ and $N_2O$ emissions but also to sustaining crop yields in rice cropping systems. Therefore, integrated evaluations of agricultural N management practice through linkage of $CH_4$ and $N_2O$ emissions to crop grain yields are necessary to achieve the dual goal of sustaining productivity and minimizing the negative climate effects of rice production.

Rice cultivation occurs in approx. 23% of all arable lands of China (Frolking et al., 2002), in which 85% of rice paddies were cultivated in rice-upland crop rotation systems, e.g., rice–wheat and rice–rapeseed rotations (Mei et al., 1988). Several field measurements focused on $CH_4$ and $N_2O$ emissions only during rice seasons in the last two decades (Cai et al., 2000, 1997; Khalil et al., 2008; Xu et al., 1997; Yao et al., 2012); however, recent studies demonstrated that $N_2O$ emissions in the non-rice growing season, i.e., while upland crops are grown, are greater than those in the rice growing season (Ma et al., 2013; Zhou et al., 2014a). Nevertheless, due to the lack of simultaneous measurements of $CH_4$ and $N_2O$ emissions over annual rotation cycle (Liu et al., 2010; Shang et al., 2011; Yao et al., 2013), little is known about annual fluxes of $CH_4$ and $N_2O$ from rice–rapeseed rotation systems, which is of outstanding importance for agricultural production in south China (e.g., the Sichuan Basin). We therefore conducted a three-year field study to simultaneously quantify $N_2O$ and $CH_4$ emissions and crop grain yields from a subtropical rice–rapeseed rotation system under three N fertilization rates in the Sichuan Basin of China. The objectives of this study were to (i) fill the gaps in data on annual $CH_4$ and $N_2O$ emissions from the subtropical rice–rapeseed rotation system, (ii) characterize the influences of N fertilization on $CH_4$ and $N_2O$ emissions, and (iii) thereby optimize agricultural N fertilization rates to minimize the climatic impacts of $N_2O$ and $CH_4$ emissions while maintaining crop grain yields.

## 2. Materials and methods

### 2.1. Site description and experimental design

The field experiment was conducted at the Yanting Agro-Ecological Station (YAG) of the Chinese Academy of Sciences (31°16′N, 105°28′E) in the central Sichuan province, China. The study region is the third-largest rice cultivation area in China (Cai et al., 2000). The landscape is dominantly hilly and rice paddy fields were mainly located at the bottom of valleys. Rice paddies are commonly cultivated with rice–wheat and rice–rapeseed rotation systems. The study region has a subtropical climate with a mean annual air temperature of 17.3 °C and a mean annual precipitation of 826 mm (1981–2009). The experimental soil is classified by the Chinese Soil Taxonomy as Stagnic Anthrosols and as Hydragric Anthrosols by the FAO soil classification (Gong, 1999). The experimental field was conventionally cultivated with a rice–rapeseed rotation, with paddy rice from late May to October followed by rapeseed from November to the following May. The physical and chemical properties of the top soil (0–20 cm) were: 36.4% clay (<0.002 mm) and 13.4% sand (0.02–2 mm); pH ($H_2O$), 8.3; bulk density, 1.12 g cm$^{-3}$; soil organic carbon content, 8.6 g C kg$^{-1}$; total N content, 1.2 g N kg$^{-1}$; and C:N ratio, 7.2.

The field experiment was performed over three consecutive rice–rapeseed rotation cycles from May 2005 to May 2008. In the study region, an annual N application rate of 500 kg N ha$^{-1}$ (250 kg N ha$^{-1}$ per season) is very common for the rice–rapeseed rotation system. It should be noted that N fertilizer application rates of 150–180 kg N ha$^{-1}$ season$^{-1}$ were recommended for cereal production systems across China to reduce off-site N losses (Zhu and Chen, 2002). Therefore, the present study consisted of three N fertilizer treatments, arranged in a completely randomized block design with three replicates per treatment. The experimental N fertilizer treatments included: the local farmers' common N fertilizer management practice (CP: 250 kg N ha$^{-1}$ for rice, and 250 kg N ha$^{-1}$ for rapeseed); the optimized N fertilizer practice refers to the recommended N fertilizer application rate for Chinese cereal production systems (OP: 150 kg N ha$^{-1}$ for rice, and 150 kg N ha$^{-1}$ for rapeseed) and the control (CK, without N fertilizer addition). Nine experimental plots (three treatments with three replicates per treatment, plot size: 4 × 5 m) were established in 2004, i.e., one year prior to the start of the measurements. To avoid