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Long-term field measurements of annual methane and nitrous oxide emissions from a Chinese subtropical wheat-rice rotation system

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ABSTRACT

Long-term, year-round monitoring is essential to obtain representative estimates of methane (CH_4) and nitrous oxide (N_2O) emissions from agricultural systems, yet multiyear consecutive measurements of annual CH_4 and N_2O emissions from subtropical rice-wheat rotation systems are rare. A six-year field experiment was conducted to simultaneously monitor CH_4 and N_2O emissions from a subtropical rice-wheat rotation system under three N fertilizer application rates (0 [the control], 150 and 250 kg N ha^{-1} $season^{-1}$) in southwestern China. CH_4 and N_2O emissions showed great seasonal and inter-annual variations along with those of temporal weather patterns because emissions were significantly correlated with soil temperature and soil moisture (floodwater depth in rice season) throughout the experimental period. Seasonal cumulative CH_4 and N_2O emissions were negatively correlated in both the rice and wheat seasons across different experimental treatments and years ($P < 0.05$). Nitrogen fertilizer application significantly inhibited CH_4 emissions but enhanced N_2O emissions compared to the control. The average direct N_2O emission factors (EF_d) for the rice seasons (0.67–0.76%) were lower than those for the wheat seasons (1.05–1.37%). Annual yield-scaled global warming potential (GWP) of CH_4 and N_2O emissions for the control (2572 kg CO_2-eq Mg^{-1} grain) was over two-fold greater than for the N150 (994 kg CO_2-eq Mg^{-1} grain) and N250 (944 kg CO_2-eq Mg^{-1} grain) treatments ($P < 0.05$). However, the lowest yield-scaled GWP obtained in the study for the rice and wheat seasons were greater than the national and global averages. Thus, in addition to optimizing N fertilizer application rates, additional management practices are required to further reduce yield-scaled GWP, thereby achieving the dual goals of sustaining and/or increasing crop yields while mitigating CH_4 and N_2O emissions from the subtropical rice-wheat rotation systems.

1. Introduction

The anthropogenic greenhouse gases (GHG) nitrous oxide (N_2O) and methane (CH_4) contribute more than 20% to the total global increase in radiative forcing (IPCC, 2013). Globally, agricultural soils account for approximately 60% and 50% of total 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 regional and global estimates of N_2O and CH_4 emissions in agricultural soils remain highly uncertain due to insufficient field measurements for temporal and spatial representations of climate, soil, and agricultural management practices, particularly in subtropical and tropical regions (Bridgham et al., 2013; Stehfest and Bouwman, 2006). Agricultural soil N_2O and CH_4 emissions vary by several-fold or even orders across different experimental sites and seasons (Dobbie et al., 1999; Wagner-Riddle et al., 2007; Wang et al., 2011), because soil N_2O and CH_4 emissions are both strongly dependent on soil properties, climatic conditions and management practices (Bridgham et al., 2013; Butterbach-Bahl et al., 2013). Accordingly, multi-year continuous in situ measurements are critical to reducing uncertainty in regional and global estimates of GHG emissions by capturing intra- and inter-annual variations of N_2O and CH_4 emissions from agricultural soils.

Rice is the staple crop for nearly 50% of the current global population. However, a recent global estimate of cropland GHG emissions indicates that rice production accounts for 48% of the

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global budget of GHG emissions from croplands primarily through emissions of CH_4 from flooded rice and N_2O from N fertilizer use (Carlson et al., 2017). Numerous studies observed high CH_4 emissions but relatively low N_2O emissions from flooded rice production systems (Linquist et al., 2012), because anaerobic conditions lead to anaerobic decomposition and the associated high CH_4 fluxes and favor complete denitrification to nitrogen gas (N_2) rather than production of N_2O (Zhou et al., 2015; Zou et al., 2007). Thus, the reduction in CH_4 emissions determined by optimal water management practices is particularly important and is usually identified as the mitigation strategy for CH_4 emissions from rice cropping systems (Cai et al., 1997; Zou et al., 2005a). For example, the practice of mid-season drainage significantly reduced CH_4 emissions from rice cropping systems compared with that of continuous flooding (Feng et al., 2013). By contrast, mid-season drainage and/or intermittent irrigation regimes for mitigation of CH_4 emissions often result in the increased N_2O emissions (Zou et al., 2005b), suggesting that at the expense of mitigated CH_4 emissions, N_2O emissions increase. However, this phenomenon of "pollution swapping" has not been fully considered to date because most previous studies investigate N_2O and CH_4 emissions separately from rice-based cropping systems. Thus, measurements of combined N_2O and CH_4 emissions from rice-based cropping systems are urgently required.

Nitrogen fertilizer application is considered the most malleable management practice for mitigating N_2O and CH_4 emissions (e.g., Carlson et al., 2017). High N rates generally induce greater N_2O emissions from rice-based cropping systems (Pittelkow et al., 2013; Zou et al., 2005b; Zhou et al., 2014; Zhou et al., 2015) due to increases in N substrate availability for the processes of nitrification-denitrification to produce N_2O (e.g., Butterbach-Bahl et al., 2013). By contrast, the results for the influence of N fertilizer application on CH_4 emissions from rice-based cropping systems remain inconsistent (Banger et al., 2012; Pittelkow et al., 2013; Zhou et al., 2015). For example, N fertilizer application increases CH_4 emissions from rice paddy soils (Lu et al., 2000; Ma et al., 2013; Singh et al., 1999), because the increase in rice biomass tends to facilitate CH_4 gas transport via rice plants (Singh et al., 1999) and increases availability of carbon substrates for Methanogens in the rhizosphere (Lu et al., 2000). By contrast, Methanotrophs for CH_4 oxidation can increase with the application of ammonium-based N fertilizer and consequently lead to a decrease in CH_4 emissions from the rice systems of southeast China (Dong et al., 2011; Zou et al., 2005a).

China accounts for 19% of the global area cultivated to rice (FAOSTAT, 2014). Annual rice-wheat rotation with 13 million hectares in cultivation is the major rice-based cropping system in China (Ma et al., 2009). Numerous studies report substantial CH_4 but slight N_2O emissions in the rice season of the rice-wheat rotation system (Yao et al., 2013; Zou et al., 2005b). Although N_2O and CH_4 emissions have been measured from numerous rice-wheat rotation systems, most studies that measure CH_4 and N_2O emissions were in either the rice or wheat season, i.e., few annual field measurements of CH_4 and N_2O emissions are available (Cai et al., 1997; Khalil et al., 2008; Xu et al., 1997; Zhou et al., 2014). Of note, several studies observed significantly greater N_2O emissions in non-rice season than in the previous rice season (e.g., Zhou et al., 2014). These results highlight that field measurements of CH_4 and N_2O emissions from rice-wheat rotation systems must be conducted on an annual basis, particularly for the long-term (i.e., greater than three years); unfortunately, published studies are rare.

Therefore, we conducted a six-year field study to simultaneously measure N_2O and CH_4 emissions and crop yields from a subtropical rice-wheat rotation system in southwest China. The primary objectives of this study were to (i) gain insight into annual N_2O and CH_4 emissions from subtropical rice-wheat rotation systems through long-term, consecutive field measurements and (ii) test whether optimized N fertilizer application rates can mitigate the aggregate emissions of N_2O and CH_4 while securing crop yields in a subtropical rice-wheat rotation system under an intermittent irrigation regime.

2. Materials and methods

2.1. Site description and experimental design

The field study was conducted at the Yanting Agro-Ecological Station (YAG) of the Chinese Academy of Sciences (31°16′ N, 105°28′ E) in the Sichuan province of southwest China. The study region ranks third on rice cultivation area of China (Cai et al., 2000). Here rice paddy fields are mainly located at the bottom of valleys and commonly cultivated with rice-upland crop rotation systems. Mean annual air temperature is 17.3 °C and mean annual precipitation is 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; Zhu et al., 2009). The experimental fields were conventionally cultivated with rice-wheat rotation system, with rice cultivation from late May to September and then wheat cultivation from November to the following May. The physical and chemical properties of the top soil (0–20 cm) were: 12.4% clay (<0.002 mm) and 37.8% sand (0.02–2 mm); pH (H_2O), 8.4; bulk density, 1.12 g cm^{-3}; soil organic carbon content, 9.7 g C kg^{-1}; total N content, 1.2 g N kg^{-1}; and C:N ratio, 8.1.

The field experiment was performed over six consecutive rice-wheat rotation cycles from October 2002 to May 2008. The present study consisted of three rates of N fertilizer application (0, 150 and 250 kg N ha^{-1} $season^{-1}$) arranged in a completely randomized block design with three replicates per treatment. Urea nitrogen fertilizer was applied at rates of 150 and 250 kg N ha^{-1} for each crop season of the rice-wheat rotation system in the fertilized treatments of N150 and N250, respectively, whereas no N fertilizer was applied throughout the entire rice-wheat rotation cycle for the control (N0). In the study region, the N fertilizer application rate of 250 kg N ha^{-1} per season is very common for the rice-wheat rotation system, whereas the N fertilizer application rate of 150–180 kg N ha^{-1} $season^{-1}$ is widely recommended for Chinese cereal production systems to reduce N losses (Zhu and Chen, 2002). Additionally, phosphorus (90 kg ha^{-1} $season^{-1}$, as P_2O_5) and potassium (36 kg ha^{-1} $season^{-1}$, as K_2O) fertilizers were applied as basal fertilization for all treatments to ensure that neither phosphate nor potassium limited crop growth.

The experimental plots (4 × 5 m) were established in May 2002, i.e., one crop season before the start of field measurements. To separate adjacent experimental plots, a 60 cm wide ridge with an impermeable film inserted into the soil to a depth of 50 cm was constructed around each plot to avoid horizontal water and nutrient transfers. Throughout the experimental period, rice seedlings were transplanted in late May to early June and harvested in the middle of September in accordance with climatic conditions. In the following season, wheat was seeded in early November and harvested in the following early May. In accordance with the practice of farmers, the experimental plots were plowed to a depth of 15 cm before transplanting rice seedlings and seeding wheat. In accordance with the common local farmers' water management practice in the study region, the water management regime of intermittent irrigation with drainage/aeration prior harvest was applied in all experimental plots in the rice seasons. In contrast, the rainfed water management regime (i.e. no artificial irrigation applied) in all experimental plots during the wheat seasons.