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A three-year experiment of annual methane and nitrous oxide emissions from the subtropical permanently flooded rice paddy fields of China: Emission factor, temperature sensitivity and fertilizer nitrogen effect

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ABSTRACT

Annual CH_4 and N_2O emissions from these rice production systems that accounts for over 10% of national rice cultivation of China are rarely reported. To improve understanding of greenhouse gas emissions from croplands in China, we measured methane (CH_4) and nitrous oxide (N_2O) emissions from the subtropical permanently flooded rice paddy fields through a 3-year field experiment that utilized three nitrogen fertilizer application rates (0 [N0], 150 [N150] and 250 [N250] kg N ha^{-1}) in southwestern China. Results showed that seasonal patterns of CH_4 and N_2O emissions were consistent with temporal weather patterns. The average annual cumulative CH_4 fluxes were in the range of 794 to 883 kg CH_4-C ha^{-1} yr^{-1} and N_2O fluxes ranged from 1.61 to 3.10 kg N_2O-N ha^{-1} yr^{-1} across the experimental treatments. The Q_{10} values (soil temperature sensitivity coefficient) of CH_4 and N_2O emissions were 2.72–3.67 and 3.32–6.05, respectively, for the three treatments. Inconsistent with our hypothesis, the nitrogen fertilizer application did not increase seasonal and annual N_2O emissions over three years, compared to the control. Thus, the annual direct N_2O emission factors (EF_d) averaged 0.07%, which was substantially lower than the IPCC default value of 0.30% for rice paddy fields. Nitrogen fertilizer application significantly decreased the mean seasonal global warming potential (GWP) and yield-scaled GWP for the rice season, whereas this was not true on an annual basis if fallow season was also considered. Since CH_4 emission was the major contributor to total GWP, it is necessary to propose mitigation options, which could include draining the floodwater layer and introducing upland crops during the fallow season. However, it will be challenging to reduce N_2O emissions and retain soil organic carbon if the floodwater layer is drained and upland crops are introduced during the fallow season.

1. Introduction

The greenhouse gases (GHG) nitrous oxide (N_2O) and methane (CH_4) contribute more than 20% to the global increase in radiative forcing (IPCC, 2013) and play important roles in influencing stratospheric chemistry (Ravishankara et al., 2009). 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). Rice is the staple crop for approximately 50% of the global population (Maclean, 2002). Due to flooding practices and N fertilizer use during the rice growing process, rice production accounts for approximately 48% of global cropland greenhouse gas emissions (Carlson et al., 2017). Because CH_4 and N_2O emissions from rice production vary substantially across different sites and seasons (e.g., Cai et al., 2003; Zhou et al., 2015a,b; Zou et al., 2007), uncertainties in the regional and global estimates of N_2O and CH_4 emissions are high (Yan et al., 2003).

Permanently flooded rice is a type of rice production system in China. It consists of a single rice crop season and a fallow season, as a floodwater layer covers the field until the next rice is planted. Such a rice planting schedule is prevalent in the mountainous regions of south and southwest China and includes more than 2.7 million cultivated hectares (Cai et al., 2003). Several studies have demonstrated that rice system contributes substantial CH_4 emissions through soil anaerobic organic matter decomposition (e.g., Carlson et al., 2017; Cai et al., 2003). Therefore, understanding CH_4 emissions from permanently flooded rice systems should be a priority to mitigate greenhouse gas emissions in rice paddy fields. Meanwhile, nitrogen fertilizer application (directly and indirectly) mediates the microbial activities of methanogens that produce CH_4 and methanotrophs that oxidize CH_4,

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which can affect CH_4 emissions (e.g., Banger et al., 2012). Yao et al. (2013) reported that N fertilizer significantly decreased CH_4 emissions from rice-wheat rotation systems because ammonium-based fertilizers stimulate Methanotroph-mediated CH_4 oxidation, thereby inhibiting CH_4 emissions from soil (Bodelier and Laanbroek, 2004). However, some studies reported an increase in CH_4 emission from rice production following N fertilizer application (Lu et al., 2000; Ma et al., 2013; Singh et al., 1999). For example, excess N increases root exudates and carbon substrates that stimulate CH_4 production, enhance plant growth, and facilitate CH_4 gas transport (Ma et al., 2013; Singh et al., 1999). Thus, the scope and magnitude of the effect of N fertilization on CH_4 emissions from rice production remain unclear (e.g., Singh et al., 1999; Zhou et al., 2015a,b; Zou et al., 2005).

Soil microbial nitrification-denitrification processes are a major source of N_2O emissions (Wagner-Riddle et al., 2007). In contrast with upland soils, besides N fertilization effect water regimes often affect N_2O emissions in rice paddy soils. Thus, IPCC (2006) differentiated water regimes and recommended N_2O emission factors (EFs) of 0.22% for rice with continuous flooding and 0.37% for rice with midseason drainage. Zou et al. (2007) reported that the EFs of Chinese rice systems averaged 0.02% for continuous flooding and 0.42% for midseason drainage. It is noteworthy that the dataset from Zou et al. (2007) only included three field studies on continuously flooded rice, which were conducted during a single rice season two decades ago. Pittelkow et al. (2013) recently conducted two-year field measurements of N_2O emissions from a water-seed rice system with continuous flooding in California, U.S.A. and estimated the seasonal and annual EFs to be 0 to 0.39%. Understanding N_2O emissions from permanently flooded rice systems is essential to improve the knowledge of N_2O emissions from rice paddy soils.

Soil temperature is a key regulator of soil CH_4 and N_2O emissions (e.g., Bodelier and Laanbroek, 2004; Butterbach-Bahl et al., 2013). Thus, CH_4 and N_2O emissions exhibit substantial temperature sensitivity in various ecosystems. This sensitivity is described by the coefficient Q_{10}, which is the proport ional change in rate given a 10 °C change in temperature (e.g., Venterea, 2007; Yvon-Durocher et al., 2014). For example, the Q_{10} of CH_4 emissions from wetland ecosystems range from 1.7 to 28 and depend significantly on different biotic (e.g., carbon substrate supply, microbial community) and abiotic (e.g., floodwater depth) variables (Yvon-Durocher et al., 2014). Similarly, previous studies reported that the Q_{10} of N_2O emissions could vary largely across sites and seasons (e.g., Wagner-Riddle et al., 2010) because responses to temperature are also highly dependent on soil moisture, quantity and quality of C and N substrates (Morley and Baggs, 2010; Giles et al., 2012; Breuer and Butterbach-Bahl, 2005). However, most of the Q_{10} values of CH_4 and N_2O emissions were determined in natural ecosystems and the Q_{10} values from rice paddy fields are rarely reported.

Subtropical permanently flooded rice paddy fields account for over 10% of total rice cultivation in China (Cai et al., 2003; Perlman et al., 2014; Zhou et al., 2015a,b). However, few field studies have measured annual CH_4 and N_2O emissions from subtropical permanently flooded rice systems, and there are no data on annual N_2O emissions. We conducted field measurements of N_2O and CH_4 emissions from a subtropical permanently flooded rice system in southwestern China over a 3-year period. The aim of this study was to quantify multiyear measurements of annual CH_4 and N_2O emissions, thereby investigating the factors that impact CH_4 and N_2O emissions and assessing the effects of N fertilization on CH_4 and N_2O emissions from Chinese subtropical permanently flooded rice systems. We hypothesized that fertilizer N application might increase N_2O emissions and environmental factors of soil temperature and floodwater depth might regulate CH_4 and N_2O emissions.

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 southwestern China. This region has a typical subtropical climate (Zhou et al., 2015a,b). The average annual precipitation was 847.6 mm during the study period (May 2004–May 2007), approximately 76% of which occurred during the rice-growing period each year (Fig. 1). The temporal variations in floodwater depth were consistent with rainfall patterns and floodwater depth ranged from 0 to 14.8 cm throughout the experimental period. The mean minimum daily air temperature and mean maximum daily air temperature during the experimental period were 12.8 °C and 21.4 °C, respectively. The average soil temperature in the surface soil (5 cm) ranged from 2.7 to 30.0 °C, and there were no significant N fertilization effects on soil temperature throughout the experimental years.

The soil is classified as Stagnic Anthrosols by the Chinese Soil Taxonomy and Hydragric Anthrosols by the FAO soil classification (Gong, 1999). The experimental fields are located at the valley bottom and are conventionally cultivated with a permanently flooded rice-fallow rotation system. This system includes a single rice crop and fallow season with a floodwater layer, from rice harvest to the next rice planting.

The field study was performed over three consecutive cropping years from May 2004 to May 2007. For each cropping year, the rice season started in May and rice was harvested early September. This varied slightly every year in accordance with climate conditions and local practices. The field experiment consisted of three N fertilizer rates (0, 150 and 250 kg N ha^{-1}) and was arranged as a randomized complete block design with three replicates per treatment. In the N-

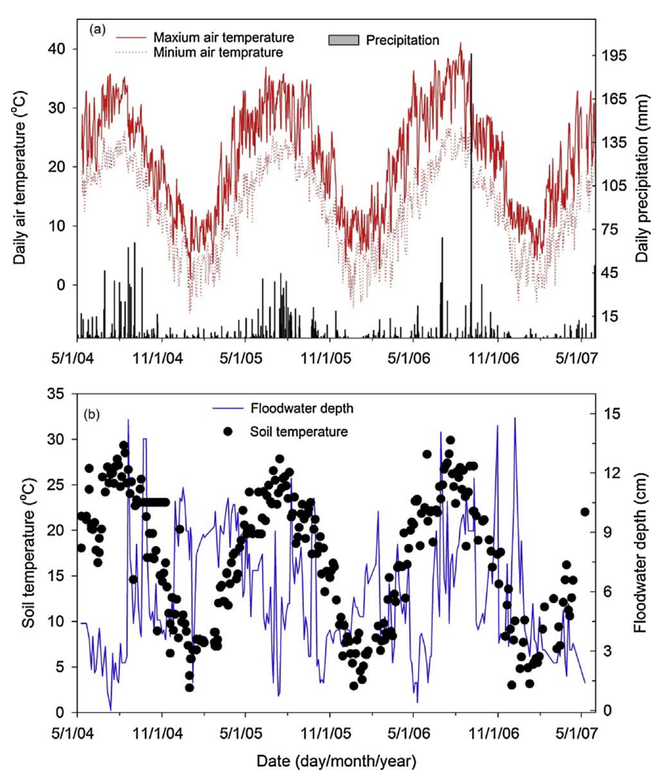

Fig. 1. Daily precipitation (mm), daily maxium and minium air temperature (a) and seasonal variations in soil temperature (at 5 cm soil depth) and flooding water depth throughout the experimental years of 2004–2007.