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Effects of elevated atmospheric CO_2 concentration and temperature on the soil profile methane distribution and diffusion in rice–wheat rotation system

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ABSTRACT

The aim of this experiment was to determine the impacts of climate change on soil profile concentrations and diffusion effluxes of methane in a rice–wheat annual rotation ecosystem in Southeastern China. We initiated a field experiment with four treatments: ambient conditions (CKs), CO_2 concentration elevated to ~ 500 μmol/mol (FACE), temperature elevated by *ca.* 2°C (T) and combined elevation of CO_2 concentration and temperature (FACE + T). A multilevel sampling probe was designed to collect the soil gas at four different depths, namely, 7 cm, 15 cm, 30 cm and 50 cm. Methane concentrations were higher during the rice season and decreased with depth, while lower during the wheat season and increased with depth. Compared to CK, mean methane concentration was increased by 42%, 57% and 71% under the FACE, FACE + T and T treatments, respectively, at the 7 cm depth during the rice season ($p < 0.05$). Mean methane diffusion effluxes to the 7 cm depth were positive in the rice season and negative in the wheat season, resulting in the paddy field being a source and weak sink, respectively. Moreover, mean methane diffusion effluxes in the rice season were 0.94, 1.19 and 1.42 mg C/(m^2·hr) in the FACE, FACE + T and T treatments, respectively, being clearly higher than that in the CK. The results indicated that elevated atmospheric CO_2 concentration and temperature could significantly increase soil profile methane concentrations and their effluxes from a rice–wheat field annual rotation ecosystem ($p < 0.05$).

Introduction

Methane (CH_4) is identified as a key greenhouse gas (GHG) with high global warming potential. It is estimated that global CH_4 emissions from rice fields are 31–112 Tg per year, contributing 5%–19% of the global CH_4 emissions (IPCC, 2007). The great challenge for rice cultivation is to increase production while attenuating CH_4 emissions from rice paddy fields. This challenge is particularly crucial for China, where rice paddy fields account for approximately 19% of the total world rice cultivated area of 159 M ha (FAOSTAT, 2012).

However, CH_4 emission from soil has been shown to be highly variable (Bousquet et al., 2007; Aronson and Helliker,

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2010; Dong et al., 2011). There is considerable uncertainty regarding the CH_4 budgets in paddy soils due in large part to a lack of information about soil CH_4 processes as well as to the spatial and temporal variability in soil fluxes and the paucity of field data (Ambus and Robertson, 2006). Although previous surface flux studies have provided essential information about the net balance between the soil and the atmosphere (Bousquet et al., 2007), they provided limited information about the gross levels of CH_4 production and consumption in soils. CH_4 is a common constituent in soil gas and is produced by a series of complex processes. First, a microbial consortium consisting of fermentative bacteria hydrolyze complex organic compounds (polysaccharides, proteins, and neutral fats) to CO_2, H_2 and acetate. Then, these compounds are reduced to CH_4 by methanogenic microbes known as methanogens (Thauer et al., 2008). However, 30%–90% of the CH_4 produced is oxidized by another group of bacteria, called methanotrophs, under aerobic conditions (Thauer et al., 2008). These processes are driven largely by soil moisture, temperature and CO_2 reduction, and there may exist strong spatial gradients in soil moisture and organic matter distribution in rice field ecosystems (Kimura et al., 2004). Because the flux of gases between the deep subsurface and the atmosphere is driven by the concentration gradient from the soil to the atmosphere, investigating the CH_4 concentration in subsoil is useful for understanding the mechanisms of CH_4 production, oxidation, and transportation.

CH_4 emission is very important for the long–term and large–scale prediction of climate change feedback. Depending on population growth and energy use scenarios, atmospheric CO_2 is expected to reach levels of 450–550 μmol/mol by 2100 (IPCC, 2007). It is likely that by 2050, enhanced [CO_2] and other GHGs including CH_4 in the atmosphere will result in an average temperature increase of 1.5–2.0°C (IPCC, 2013). There is a strong concern that both increasing [CO_2] levels and rising temperatures could lead to a positive feedback on global warming by increasing the emissions of CH_4 in rice agriculture (Allen et al., 2003). Elevated CO_2 levels were found to increase plant C/N ratios and nitrogen–use efficiency and influenced the soil–atmosphere exchange of CH_4 (Inubushi et al., 2003; Xu et al., 2004). Because the concentration of CO_2 in soil gas is much higher (10–50 times) than that in the atmosphere, increasing levels of atmospheric CO_2 may not directly influence below-ground processes (van de Geijn and van Veen, 1993). Most below-ground responses are likely to be the result of the indirect effects of CO_2, such as faster root growth and increased rhizodeposition (Mosier et al., 2002; Martín-Olmedo et al., 2002). Elevated [CO_2] not only directly increases biomass both above ground and in the roots by photosynthesis, but also indirectly increases the amounts of CH_4 in the soil (Cheng et al., 2005). Other studies have found that temperature increases stimulate microbial activity and may lead to higher rates of CH_4 production in submerged soils (Fey and Conrad, 2000).

At present, we are far from being able to predict future CH_4 emissions. Firstly, because most early studies focused on only one component of climate change (that is, either [CO_2] or warming in one ecosystem), we have little quantitative understanding of how the climate of an ecosystem influences the response of soil CH_4 efflux to increasing [CO_2] and temperature and whether the interactive effects of the two factors are small. Secondly, under field conditions, the air temperature, the solar radiation and its interception by the crop canopy, and even the wind speed can greatly affect CH_4 efflux (Kuwagata et al., 2008). Such studies in field conditions are complex, difficult and expensive to execute. Thirdly, previous studies have focused primarily on relative changes in CH_4 emissions in response to high [CO_2] and temperature, giving rise to our limited understanding of the soil profile concentrations of CH_4 and its diffusion efflux, and necessitating further understanding of CH_4 production mechanisms and behavior under paddy ecosystems (Tian et al., 2012).

Therefore, we established a free-air CO_2 enrichment and temperature elevation research platform (T-FACE) with the aim of exploring the interactions between [CO_2] elevation and warming in a rice–wheat rotation ecosystem. The main objectives of this experiment were: (1) To evaluate the effects of elevating CO_2 to 500 μmol/mol and warming (+2°C) on CH_4 concentration profiles at four depths under completely open-field conditions; and (2) To explore the production location, oxidation, and diffusion process of CH_4 in the soil profiles under different climate change scenarios.

1. Materials and methods

1.1. Experimental site description

This study was conducted as part of T-FACE experiments at Changshu, Jiangsu, China (31°30′N, 120°33′E). The station is located in the Taihu Lake region, which is in the center of the Yangtze River Delta and belongs to the northern subtropical humid climatic zone. Rice–wheat rotation is the typical cropping system in this area. The experiment included two crops per year, *i.e.*, rice (June–October) and wheat (November–May). The soil of the experimental field was classified as Gleyi–Stagnic Anthrosol (23.0% sand, 70.0% silt and 7.0% clay) according to the FAO soil taxonomy system. The main soil physical and chemical properties at different depths are shown in Table 1. The annual precipitation during our experiment period in 2012 and 2013 was approximately 1350 mm, consisting of 1042.8 mm during the rice season and 307.2 mm during the wheat season, while the mean seasonal air temperatures were 22.0 and 14.3°C during the rice and wheat season, respectively.

1.2. Experimental set-up

On the free-air CO_2 enrichment and temperature elevation research platform of T-FACE, which was initiated in April, 2011,

Table 1 – Soil physical and chemical properties at different depths in the experimental field in Changshu, Jiangsu Province, China. SOM: Soil Organic Matter.

Soil depth (cm)	pH (H_2O)	SOM (g/kg)	Total Nitrogen (g/kg)
0–7	6.3	25.8	1.6
7–15	6.4	20.9	1.4
15–30	6.0	13.3	1.0
30–50	5.6	12.9	0.9