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Further understanding CH_4 emissions from a flooded rice field exposed to experimental warming with elevated $[CO_2]$

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ABSTRACT

Elevated atmospheric CO_2 concentration ($[CO_2]$) has the potential to increase CH_4 emissions from rice fields. However, there is still inconclusive evidence due to limited data on whether elevated temperature (T_a) and $[CO_2]$ combined can modify CH_4 emission. To study this issue further, we conducted a temperature gradient field chamber (TGC) experiment in Gwangju, Korea (126°53′E, 35°10′N, alt. 33 m). Rice (*Oryza sativa* L.) was grown at two $[CO_2]$ (396 vs 673 ppmV) and two T_a [24.8 (≈ambient) vs 26.5 °C] regimes in six independent field TGCs (three each for ambient and elevated $[CO_2]$). CH_4 fluxes were measured hourly using an automated gas sampling and analyzing system during the entire season. Elevated $[CO_2]$ significantly increased total CH_4 emission by 17.4% (14.37 g/12.24 g CH_4 m^{-2}) at maturity, whereas elevated T_a only had a minor or insignificant effect (*ca.* +8.0%; 13.22 g/12.24 g CH_4 m^{-2}). However, the elevated T_a effect was significant when combined with elevated $[CO_2]$, resulting in an additive effect on CH_4 emission (+29.3%; 15.83 g/12.24 g CH_4 m^{-2}). This suggests that ongoing rising atmospheric $[CO_2]$ and T_a may have a positive feedback on projected global warming. Nevertheless, the positive effects of elevated $[CO_2]$ on CH_4 emission were greatly reduced with plant development, displaying an increase of 37.5% (or 53.2% in combination with elevated T_a), 23.4% (40.1%) and 17.4% (29.3%) at panicle initiation, full heading and grain maturity, respectively. We conclude that such seasonal dynamics of CH_4 emission were attributed to the dwindling response of plant growth, including tiller number, above- and below-ground biomass, to elevated $[CO_2]$. These are assumed to result in the reducing potential of C substrate availability for methanogens, as well as CH_4 transport capacity.

1. Introduction

There are obvious concerns about the impact of a projected increase in atmospheric CO_2 concentration ($[CO_2]$) and temperature (T_a) on CH_4 emission from flooded rice fields to the atmosphere (IPCC, 2007). Early studies showed that elevated $[CO_2]$ (550–660 ppmV) increases CH_4 fluxes from the rice soil to the atmosphere (Allen et al., 2003; Cheng et al., 2008b; Inubushi et al., 2003, 2011; Luo et al., 2008; Tokida et al., 2010; Ziska et al., 1998). Since a major part of CH_4 released from rice fields was found to be plant-mediated (Cheng et al., 2006; Sass et al., 1990), the positive effect of elevated $[CO_2]$ on CH_4 emission can be considered due to enhanced plant growth, such as root biomass (Allen et al., 2003; Ziska et al., 1998), total biomass (Inubushi et al., 2011) and tiller number (Inubushi et al., 2003). Although elevated $[CO_2]$ enhanced these plant parameters, the magnitude of $[CO_2]$-induced enhancement was largely reduced with plant development (Kim et al., 2003; Yang et al., 2006). This is due to a metabolic down-regulation of photosynthetic rates (Seneweera, 2011), which in turn could affect a potential availability of C substrate for methanogens. Given that the increased CH_4 emission with elevated $[CO_2]$ is dominated by enhanced plant growth, it could therefore be hypothesized that the effect of elevated $[CO_2]$ on CH_4 emission dwindles with plant development. However, this hypothesis has not yet been tested. Quantifying CH_4 emission with high measurement frequency permits the testing and analysis of this hypothesis. It also serves to better understand the mechanisms underlying changes in CH_4 emission with elevated $[CO_2]$.

Elevated T_a can also have many direct and indirect effects on plant C metabolic processes, such as photosynthesis, C storage and transfer, showing important consequences for CH_4 emission (Allen et al., 2003; Ziska et al., 1998). Despite such potential importance of

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Table 1
Selected properties of the soil in temperature gradient field chambers used in the present experiment.

Parameters	Values
pH (1:5)[a]	6.5 (0.1)
Total organic (C g kg^{-1})	12.3 (0.5)
Total N (g kg^{-1})	1.0 (0.2)
Available P (mg P_2O_5 kg^{-1})	13.1 (0.7)
CEC (com kg^{-1})	14.4 (0.4)
Texture	Loam[b]
Sand (g kg^{-1})	388 (11)
Silt (g kg^{-1})	378 (16)
Clay (g kg^{-1})	234 (17)

Values are the means of six replicates with standard errors in parentheses.
[a] The ratio of soil:water was 1:5.
[b] USDA classification.

elevated T_a, early studies on CH_4 emission in response to projected changes in [CO_2] and climate have mostly focused on elevated [CO_2] alone. Few studies have considered the impact of both elevating [CO_2] and T_a on CH_4 emission (Allen et al., 2003; Ziska et al., 1998), but even conflicting results have reported either positive (Allen et al., 2003) or negative (Ziska et al., 1998) interaction responses to elevated [CO_2] and T_a. Moreover, conflicting results have also been reported for elevated T_a alone, showing 18.8% increase in CH_4 emission with a 3 °C warming (Allen et al., 2003) and 46.0% decrease with a 4 °C warming (Ziska et al., 1998). A recent finding from a free-air CO_2 enrichment experiment suggested that the effect of elevated [CO_2] on CH_4 emission could be further amplified with elevated soil/water (+2 °C) temperature (Tokida et al., 2010). However, there is still inconclusive evidence due to limited data about whether elevated T_a alone and/or in combination with elevated [CO_2] increases, decreases or does not change CH_4 emission (Allen et al., 2003; Ziska et al., 1998). This is limiting our current ability to predict the impact of projected changes in [CO_2] and climate on CH_4 emission from flooded rice fields. To address this, additional studies on both elevated T_a and [CO_2] over the whole rice growing season are critical.

In the present study, we examined currently unresolved questions of whether elevated T_a alone and in combination with elevated [CO_2] would affect CH_4 emission from the flooded rice fields by employing temperature gradient field chambers (TGCs). The key objectives of this study were: (i) to quantify the magnitude of change in CH_4 emission under elevated T_a and [CO_2]; (ii) to identify seasonal dynamics in the effect of elevated [CO_2] and T_a on CH_4 emission; and (iii) to analyze the mechanisms behind changes in CH_4 emission with elevated T_a and [CO_2]. This study provides the first high-time-resolution data set in CH_4 emission from rice fields exposed to warming with elevated [CO_2].

2. Materials and methods

2.1. Experimental site and system descriptions

2.1.1. Site

The experimental site was located in the experimental paddy fields of Chonnam National University, Gwangju, Korea (126°53′E, 35°10′N, alt. 33 m). The area is typical of the agro-climate that grows a large proportion of rice crops in Korea, occupying >20% of total area harvested (approximately one million ha). Soil properties of the experimental paddy are summarized in Table 1. This site was subject to temperate monsoon climate with an annual mean temperature of 13.7 °C over the past 30 years. Annual mean precipitation was about 1520 mm, with >60% rainfall occurring from June to August (rainy season). During the rice growing season (May to September), the mean T_a was 22.7 °C, with a monthly mean minimum and maximum T_a of 12.8 °C (May) and 30.5 °C (August), respectively.

2.1.2. Temperature gradient field chambers (TGCs)

The experiment was performed using TGCs established in the paddy fields, covered by a highly transparent film, with or without CO_2 fumigation. TGCs have been described in detail by Kim et al. (2004) (also see Horie et al., 1995; Okada et al., 2000). Briefly, the TGCs consisted of six independent field chambers that had a tunnel shape of 24.0 m in length, 2.4 m in width and 2.0 m in height. Of these, three TGCs were allocated for ambient [CO_2] and the other three were allocated for elevated [CO_2]. The target [CO_2] in the TGCs assigned to the elevated [CO_2] was 660 ppmV and controlled by fumigating CO_2 mixed with air in a mixing cylinder. One side of the TGC in the longitudinal direction was fully open (air inlet); while the other side (air outlet) was closed, where three exhaust fans [two small (17.7 m^3 min^{-1}) and one large (125.0 m^3 min^{-1})] were mounted. Air from the inlet traveled towards the outlet by the exhaust fans and was gradually warmed by either incident solar radiation (clear day) or warm air provided by an electronic heating blower at nighttime (including cloudy and rainy day), creating a linear T_a gradient along the longitudinal axis of the TGCs. The T_a difference between the air inlet (∼ambient) and outlet of the TGC was set at 3 °C with natural diurnal fluctuations. To minimize the enclosure effects expected, we used highly transparent films (F-clean®, Asahi Glass, Japan) with a transmittance >90% in a wide range of radiation from short- to long-wave. In addition, an oscillating fan was placed on one side wall inside the TGCs with 4.0 m distance intervals in order to disperse CO_2 quickly throughout the TGCs and to imitate wind conditions similar to an open field.

2.2. Monitoring and data collection

2.2.1. [CO_2]

To maintain a target [CO_2] of 660 ppmV for elevated [CO_2], CO_2 was mixed with air in a mixing cylinder equipped at the air inlet of the TGCs fumigated into the TGCs for 24 h. The fumigating rate of CO_2 was computer-controlled with the solenoid valve. The [CO_2] was monitored (GMT 222, Vaisala, Switzerland) every 5 s at 1.0 m, 11.0 m and 22.0 m distances from the air inlet of the TGCs, and stored in the data logger (CR100, Campbell Scientific, USA) as an average value of 5 min. For ambient [CO_2], the [CO_2] was also monitored as was the case for the elevated [CO_2], though neither was fumigated nor controlled. On average (±s.d.) over the season, the [CO_2] in elevated and ambient [CO_2] resulted in 673.4 ± 25.9 ppmV and 396.2 ± 13.4 ppmV, respectively (see Fig. 2).

2.2.2. Air temperature (T_a)

For T_a control and monitoring, dry-bulb thermo couples were housed in a ventilated radiation shield placed at 20 cm above plant canopy at distances of 0.6 m, 8.0 m, 15.5 m and 23.0 m from the air inlet of the TGCs. As with [CO_2], T_a was continuously measured every 5 s and stored in the data logger as an average value of 5 min. Based on these data, the T_a at arbitrary distances from the air inlet of the TGCs was calculated by linear interpolation. In the current study, experimental plots were designed at 4.8–5.6 m (5.2 m in the plot center) from the air inlet of the TGCs and at 16.6–17.4 m (17.0 m). The mean T_a over the season resulted in 24.8 °C (∼ambient T_a) at 5.2 m and 26.5 °C (elevated T_a) at 17.0 m, with seasonal fluctuations from 16.3 to 29.4 °C at 5.2 m and 18.2 to 31.0 °C at 17.0 m (see Fig. 2).

2.2.3. Solar radiation (PAR), rainfall and soil redox potential (Eh)

Over the season, PAR both inside and outside the TGC was also measured by a quantum sensor (LI-COR, LI-190, Lincoln, NB, USA)