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Seasonal assessment of greenhouse gas emissions from irrigated lowland rice fields under infrared warming

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ABSTRACT

Rice fields are considered as one of the major sources of methane (CH_4), and they also emit nitrous oxide (N_2O). A field experiment was conducted at the International Rice Research Institute, Philippines, in 2010–2011 using a temperature free-air controlled enhancement (T-FACE) system. Our objectives were to assess (i) the suitability of the T-FACE system for flooded rice fields and (ii) seasonal variations in greenhouse gas emissions with and without experimental warming.

This observation period included one wet season (WS), one dry season (DS), and a fallow season. The experimental warming, i.e., T-FACE system, was maintained by using six infrared heaters deployed in a hexagonal pattern over each plot (7.1 m^2). Set-point canopy temperatures of the warming treatment were 1.5 and 3.0 °C higher than the reference plots during daytime and nighttime, respectively. Two warming treatments (i.e., heated and reference) were arranged in a randomized complete block design with three replications. Infrared warming increased rice canopy temperature by 1.1 and 2.6 °C (0.4 °C below the targeted set-point) during daytime and nighttime, respectively. On the other hand, only a marginal (0.4–0.5 °C) increase was observed for both water and soil temperatures, likely because flood irrigation water flowed across the field. The warming (elevated canopy temperature) had no significant effects on CH_4 or N_2O emissions during the dry, wet, and fallow seasons. However, diel and seasonal variations in CH_4 emissions were observed during the rice-growing and fallow periods. CH_4 emissions were higher during the early afternoons, which was positively correlated with both soil and air temperatures. Similarly, CH_4 emission rates increased with rice growth stage up to the reproductive stage. Moreover, cumulative CH_4 emissions were 1.5 times higher in the 2011 DS than in the 2010 WS (50 and 34 g CH_4 m^{-2}, respectively). The 2-month fallow season (late May–early July 2011) under continuous flooding emitted 51 g CH_4 m^{-2}, which is similar to that in the 2011 DS. On the other hand, N_2O emissions were not detected throughout the growing season, but an emission peak was observed after final drainage at maturity during the 2011 DS. Both rice-growing and fallow seasons were the major sources of CH_4 emissions as long as the field was continuously flooded, while N_2O was not detectable in continuously flooded soil. Infrared warming did not affect rice yields or yield components, probably because the general growing temperatures were near optimum, and the warming treatment was not sufficiently large to cause a significant effect.

1. Introduction

The atmospheric concentration of major greenhouse gases (GHGs) has been rising since pre-industrial times. The concentration of carbon dioxide (CO_2) increased from a pre-industrial value of about 280 to 379 ppm, methane (CH_4) from 715 to 1774 ppb, and nitrous oxide (N_2O) from 270 to 319 ppb in 2005. Although the atmospheric concentrations of CH_4 and N_2O are lower than CO_2, they have 25 and 298 times more global warming potential (GWP) than CO_2 on a 100-year time horizon, respectively (Solomon et al., 2007). Globally, agricultural CH_4 and N_2O emissions increased by

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17% from 1990 to 2005, with an average annual emission increase of 60 Mt CO_2 eq. y^{-1} (Smith et al., 2007). With the rising concentrations of GHGs, global air temperature increased by 0.3–0.6 °C over the 20th century and is predicted to increase by 1.1 to 6.4 °C by 2100 (IPCC, 2007).

Rice fields are one of the major sources of CH_4 in the global CH_4 budget (Adhya et al., 1994; Kruger et al., 2001; Minami and Neue, 1994; Wassmann et al., 2000), with an estimated contribution of approximately 18% of the 596 Tg global CH_4 flux in 2005 (Denman et al., 2007). Moreover, substantial N_2O emissions may occur with the application of mid-season drainage and/or intermittent irrigation, which are done to mitigate CH_4 emissions (Bronson et al., 1997a; Hua et al., 1997; Johnson-Beebout et al., 2009; Minami, 1997; Yu et al., 2007), and during the fallow period (Bronson et al., 1997b; Cai et al., 1997; Hou et al., 2000; Wassmann et al., 2004). Irrigation management involving alternate wetting and drying favors the soil microbial processes of nitrification and denitrification, which lead to N_2O emissions (Khalil et al., 2004; Wang et al., 2011).

The magnitude of CH_4 emissions from rice fields is a function of climate, management, and edaphic factors (Minami and Neue, 1994; Yan et al., 2005), which vary from one location to another. Moreover, significant temporal, namely seasonal (Lu et al., 2000; Gaihre et al., 2011; Singh and Dubey, 2012) and diel (Cheng et al., 2008; Schutz et al., 1990; Wang et al., 1997; Wassmann et al., 1994; Watanabe et al., 2001) variations in CH_4 emissions occur. CH_4 emissions increase with rice growth with 2–3 peaks in emissions from tillering to maturity stage (Gaihre et al., 2013; Meijide et al., 2011; Singh and Dubey, 2012). Early-season peak emissions appear in soils with high organic matter and those with organic amendments (Wassmann et al., 2000). On the other hand, mid and late-season peaks from flowering to maturity stages are due to supply of plant-borne C through root exudates and decaying root tissues (Neue et al., 1997). In general, dissolved organic C in the root zone increased with plant growth and reached a maximum between flowering and maturation; thus, CH_4 emissions followed the same pattern (Lu et al., 2000). Diel variations in emission rates are correlated with – and possibly controlled by – temperature. Thus, emission rates are highest during early afternoon when both air and soil temperatures reach at their maximum, and they are lowest during early morning when temperatures are at their minimum (Schutz et al., 1990; Wang et al., 1997; Wassmann et al., 1994; Watanabe et al., 2001).

In addition, variations in CH_4 emissions occur between rice-growing seasons. The monsoon climates of Asia that account for the bulk of global rice production encompass, two distinct seasons. In the wet season (WS) rainfall is typically sufficient to sustain a rice crop while additional irrigation is required for a viable rice crop in the dry season (DS). Generally, the DS has higher emissions than the WS, which is associated with higher plant biomass (Sass et al., 1990; Wassmann et al., 1994; Ziska et al., 1998). However, lower emissions during the DS have also been reported (Corton et al., 2000). Both rice-growing seasons and fallow seasons can be significant sources of CH_4 and N_2O depending upon the moisture status of the soil. Significant CH_4 emissions may occur during the wet fallow season, while N_2O emissions occur if the soil is alternately wet and dry (Bronson et al., 1997b). Thus, the estimated CH_4 budget has shown large spatio-temporal variations (Chakraborty et al., 2006). In spite of considerable efforts to quantify CH_4 emissions from rice fields, the estimates of the source strength are still attached to major uncertainties (Wassmann et al., 2010). More field measurements are necessary to narrow down the uncertainties, to come up with a reliable global CH_4 budget, and to identify effective mitigation measures (Neue et al., 1997).

Concern is growing that variations in emissions may increase further with a global increase in temperature (Tokida et al., 2010). An increase in temperature usually accelerates the decomposition of organic matter (Conant et al., 2008), which in turn stimulates methanogenic activities and results in higher CH_4 emissions (Fey and Conrad, 2000; Minami and Neue, 1994; Rath et al., 2002; Schulz et al., 1997; Yang and Chang, 1998). Most studies conducted under controlled laboratory and greenhouse conditions have shown greater CH_4 emissions under elevated temperatures (Allen et al., 2003; Devevre and Horwath, 2000; Fey and Conrad, 2003; Yang and Chang, 1998; Yao and Conrad, 2000). In contrast with those results, decreased CH_4 emissions with increased temperature have also been reported, particularly above a certain temperature threshold. A decrease in CH_4 emissions with an increase in temperature was observed above 37 °C in the laboratory (Yang and Chang, 1998), at 4 °C above ambient temperature in the greenhouse and an open-top chamber (Schrope et al., 1999; Ziska et al., 1998), and above 34.5 °C in the field (Parashar et al., 1993). These results show the inconsistency of the effect of elevated temperatures on CH_4 and N_2O emissions. It remains unclear whether increased temperature with future climate change will generate positive or negative feedback on GHG emissions (Dijkstra et al., 2012). However, very few studies have been conducted under field conditions with warming water/soil (Parashar et al., 1993; Tokida et al., 2010) and air (Ziska et al., 1998) to investigate the effects of temperature on CH_4 emissions. More experiments with warming the entire ecosystem compartment (e.g. air/canopy, water and soil) in open fields are needed to simulate the effect of future climate change on GHG emissions.

Several experiments have been conducted in controlled environments to study the effects of predicted global warming on rice. Though some closed chambers can manipulate temperatures, other environmental conditions are unnatural (Kimball et al., 2008). Such closed chambers rarely provide realistic environmental parameters such as solar radiation, light, wind speed, CO_2 concentration, and relative humidity (White et al., 2012). The growth mediums provided in the controlled environment systems rarely match field conditions. Hence, results extrapolated from such studies may not be representative of field conditions. Open-top chambers (OTCs) have been used to study the effects of different temperature regimes on rice since the chambers can heat both air and soil. However, sunny days are necessary for the heating, and the majority of warming occurs only during daytime (Ziska et al., 1996, 1998). Since the Earth continues to warm globally, there is a need for a methodology that will warm open-field plots in order to study the likely effects of global warming on soil–plant processes (Kimball et al., 2008).

A promising approach recently being used to investigate the impact of global warming on cropping and natural ecosystems is the use of hexagonal arrays of infrared (IR) heaters over open fields, i.e., the temperature free-air controlled enhancement (T-FACE) system (Kimball, 2005; Kimball et al., 2008; Rehmani et al., 2011; Wall et al., 2011). These IR heaters can warm the vegetation and bare soil surface directly (Kimball et al., 2008). The temperature rise of a rice canopy through IR warming is essentially the same as the warming expected from global warming (Kimball, 2011).

The T-FACE system has been used mostly in upland crops (Wall et al., 2011; White et al., 2012) and on grazing land (Hu et al., 2010; Luo et al., 2010; Morgan et al., 2011; Rui et al., 2011). Studies on the performance of T-FACE in open paddy fields are limited. To our knowledge, only Rehmani et al. (2011) tested its performance on rice canopy temperature. They demonstrated that it produced a uniform increase in plant canopy temperature; however, its effect on water/soil temperature has not yet been studied. Moreover, the effect of infrared warming on soil processes such as GHG emissions from irrigated rice fields still needs to be tested.

This field experiment conducted with infrared warming forms part of a series of experiments on effects of temperature on GHG

Table 1
Physicochemical characteristics of soil at the experimental site.

Soil property	Value
pH	6.6
Organic C (%)	1.25
Total N (%)	0.15
Available K (cmol$_c$ kg^{-1})	1.39
Available P-Olsen (mg kg^{-1})	50.50
Available P-Bray (mg kg^{-1})	14.00
CEC (cmol$_c$ kg^{-1})	25.25
Bulk density (g cm^{-3})	1.15
Particle size (%)	
Sand	17.5
Silt	44.0
Clay	22.5

emissions with different approaches. The experiment on elevated temperature in all ecosystem compartments (i.e., air, water and soil) in walk-in growth chambers along with rice straw incorporation has been reported elsewhere (Gaihre et al., 2013). While, experiment on elevated water/soil temperature in greenhouse will be reported separately. In this paper, we present a performance evaluation of T-FACE and assess the temporal variations in GHG emissions in rice-growing and fallow seasons in irrigated lowland rice fields with the following specific objectives:

- To test the performance of infrared warming (T-FACE system) on temperature increase in plant canopy, water, and soil.
- To determine the effect of infrared warming on CH_4 and N_2O emissions and rice growth.
- To assess the temporal (seasonal and diel) variations in CH_4 and N_2O emissions during rice-growing and fallow seasons in flooded conditions.

2. Materials and methods

2.1. Site description and crop management

A field experiment was conducted at the IRRI Experiment Station (block UQ, Laguna, Philippines, latitude 14°08′34″N, longitude 121°15′58″E, 21 masl) during the 2010 WS, 2011 DS, 2011 fallow season (May–July 2011), and 2011 WS under irrigated conditions. The area had been under lowland rice cultivation for at least 4 years. WS rice was grown from June to October and DS rice from January to April every year. The daily average solar radiation (SR), air temperature, and rainfall during the experimental period are shown in Fig. 1. The soil is classified as an *Aquandic Epiaquoll* (Dobermann et al., 2000) and its physicochemical properties (0–15-cm depth) are presented in Table 1.

Rice seedlings (*Oryza sativa* L. cv. Angelica) were transplanted at 0.2 m × 0.2 m plant distance (plant density of 25 hills m^{-2}) on 21 June 2010 and 20 January 2011 for the 2010 WS and 2011 DS, respectively. Rice straw (6.5 t ha^{-1}) harvested from the previous crop was incorporated into the soil 27 days and 87 days before transplanting of rice seedlings for the 2010 WS and 2011 DS, respectively. The field was continuously flooded throughout the growing season (Fig. 2) until final drainage. Final drainage was done on 6 October 2010 (106 days after transplanting, DAT) for the WS and on 28 April 2011 (98 DAT) for the DS. However, during the 2010 WS, the field remained flooded even after final drainage due to continuous rainfall (Figs. 1 and 2a). Rice plants were harvested on 20 October 2010 (121 DAT) and 20 May 2011 (120 DAT), respectively, for the WS and DS.

Urea (46–0–0), single superphosphate (SSP) (0–16–0), and muriate of potash (MOP) (0–0–60) were applied at 80–30–30 kg N–P_2O_5–K_2O ha^{-1} in the WS and at 120–30–30 kg N–P_2O_5–K_2O ha^{-1} in the DS. SSP and MOP were applied during land preparation as basal, while urea was applied in three splits: at 14 DAT, at maximum tillering (35 DAT), and at panicle initiation (65 DAT).

2.2. Experimental warming

The T-FACE apparatus was employed to warm the 3.0-m-diameter (7.01 m^2) plots as an experimental unit for the 2010 WS (4 August–20 October 2010; 44–121 DAT), 2011 DS (7 February–20 May 2011; 18–120 DAT), and a fallow season (26 May–15 July 2011; 6–56 DAH, days after harvesting). The set-point canopy temperature of heated plots was 1.5 and 3.0 °C higher than in the reference plots during daytime and nighttime, respectively. This temperature regime was chosen based on the statement by the IPCC (2001) that nighttime minimums were increasing at a rate about twice as fast as daytime maximums [although the IPCC (2007) backed away from such a conclusion] and because previous T-FACE experiments used these particular day- and nighttime set-point differences (Kimball, 2005; Kimball et al., 2008; Wall et al., 2011). Both heated and reference plots were arranged in a randomized complete block design with four replications. The warming treatments were not employed during the 2011 WS when diel variations of CH_4 and N_2O emissions were determined.

The design of the T-FACE system and its deployment in the field have already been described in detail (Kimball et al., 2008; Wall et al., 2011; Rehmani et al., 2011). In brief, six ceramic infrared heaters (1000 W, 240 V, 245 mm long × 60 mm wide) fitted in reflector housings [model ALEX-F (254 mm long × 98.6 mm wide × 89.4 mm high) (Mor Electric Heating Associated Inc., Comstock Park, MI, USA)] were arranged per plot in hexagonal arrays during two rice-growing seasons and one fallow season. The heaters were suspended from steel pipes in a hexagonal configuration at a height of 1.2 m (0.8 times the plot radius) above the plant canopy. The height of the heaters was adjusted based on plant height. The heaters were tilted at 45° from horizontal toward the plot center. Canopy temperature was sensed in each plot using infrared thermometers (IRTs; Model IRR-P, Apogee Instruments Inc., Logan, Utah, USA), with factory-supplied calibration coefficients for each sensor. A data logger (Model CR1000, Campbell Scientific, Logan, UT, USA) was used to measure signals from the IRTs of reference and heated plots and then compute rice canopy temperatures that were corrected for radiation from the heaters that was reflected from the rice canopies. Following Kimball (2005), the infrared heaters were controlled to achieve target canopy temperature increases in the heated plots compared with the corresponding reference plots using a proportional–integral–derivative (PID) control algorithm. Current/voltage output modules (Model SDM-CV04, Campbell Scientific, Logan, Utah, USA) were used to supply 0–10-V control signals to dimmers (Model LCED-2484 240V, 35A; Kalglo Electronics Co., Inc.) which modulated the voltages supplied to the infrared heaters.

Temperatures of floodwater and soil (5-cm depth) were monitored daily (1400 to 1500) throughout the growing season using mercury thermometers.

2.3. Collection and analysis of gas samples

Greenhouse gas emissions were measured using the “closed chamber” technique. Each closed chamber had a cover and a base. A plastic pail (110 L) was used as the chamber cover. The chamber base was a transparent plastic sheet (0.55-m height and 0.50-m diameter) that was permanently installed in the field by inserting it down to the 10-cm soil depth. It was retained in the field up to the last day of gas sampling. The chamber cover was placed over the chamber base and made airtight during each gas sampling time using water as a sealing material. Each chamber was equipped

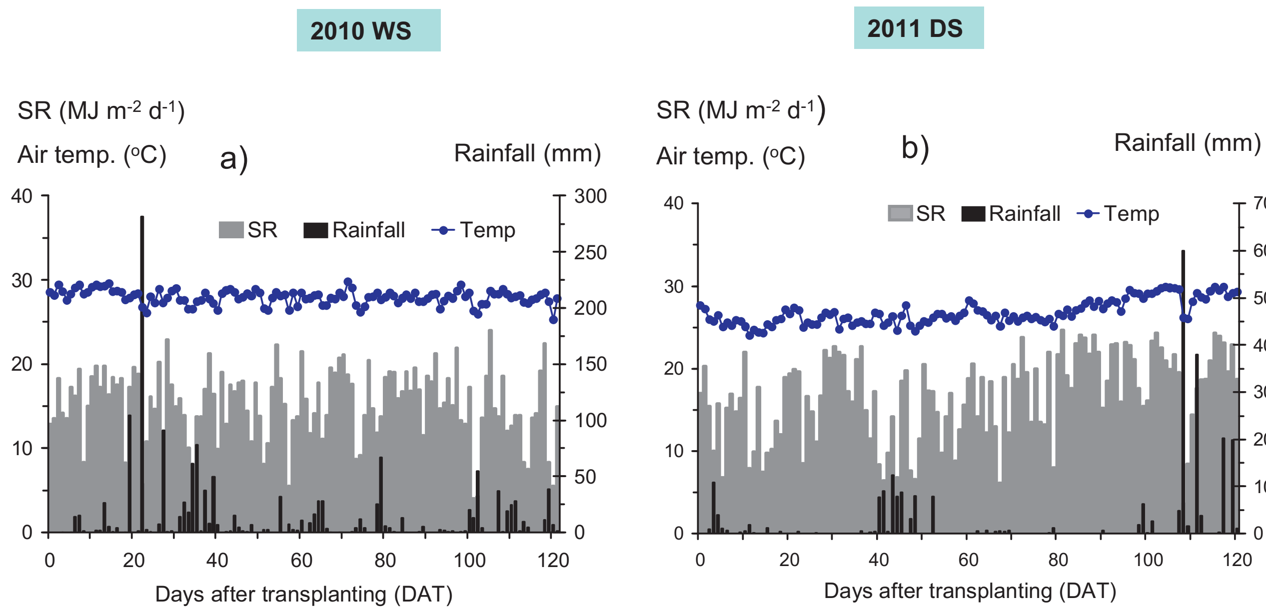

Fig. 1. Daily average of solar radiation (SR), rainfall, and air temperature during 2010 wet season (21 June to 20 October) and 2011 dry season (20 January to 20 May).

with a battery-powered fan to ensure thorough mixing of the air inside the chamber. A thermometer was used to measure the inside temperature during gas sampling. This temperature was used to calculate the emission rates of CH_4 and N_2O. A rubber septum was fixed in the chamber wall to collect the gas samples. Each base included four rice hills. Once the chamber was made airtight, the gas samples were collected from the chamber headspace using a 60-mL PVC syringe with stainless steel needle. Gas sampling was conducted once a week at 1400 throughout the growing season for a two-crop cycle, i.e., the 2010 WS and 2011 DS and one fallow season (26 May–15 July 2011) from both reference and heated plots. Four gas samples were taken at 10-min intervals for 30 min. Moreover, diel variations in CH_4 and N_2O emission rates were determined at 42 (active tillering), 63 (panicle initiation), 90 (flowering), and 112 DAT (maturity period) in the 2011 WS. The gas sampling was conducted every 3 h from 0500 to 2000 from six replicate chambers without using infrared heaters.

The mixing rates of CH_4 and N_2O in the gas samples were measured simultaneously using a gas chromatograph (Shimadzu GC-14B, Shimadzu Corporation, Kyoto, Japan) with a flame ionization detector (FID) and electron capture detector (ECD) as described by Gaihre et al. (2013). Gas samples were analyzed within one week of collection. The emission rates of CH_4 and N_2O were determined from the slope of the linear regression curves of CH_4 and N_2O concentrations against chamber closure time. Only those samples showing a linear relation ($r^2 > 0.8$) for at least three sampling points were used for calculating emission rates. When the last sampling point was not linear with the previous three, that point was rejected. The daily emissions of the respective gases were expressed as $mg\,m^{-2}\,d^{-1}$ (Gaihre et al., 2013). Seasonal cumulative CH_4 and N_2O emissions were estimated from daily emission rates. The total cumulative emissions were estimated from the fallow season also. GWP was calculated based on a 100-year time frame as suggested by the IPCC (2007) using the following formula:

$$GWP = CH_4\,\text{emissions} \times 25 + N_2O\,\text{emissions} \times 298$$

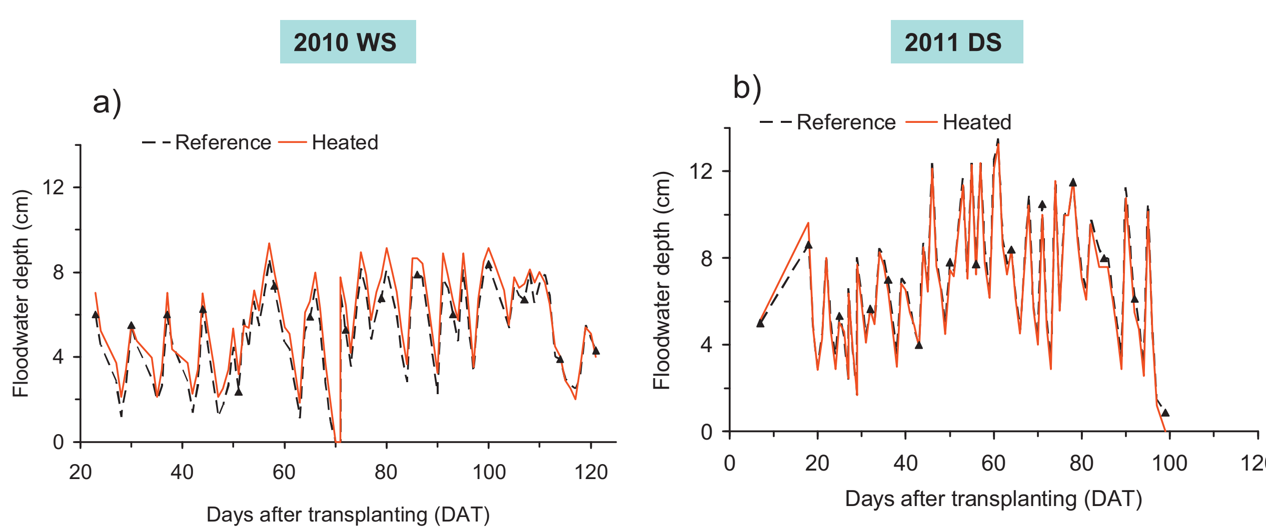

Fig. 2. Floodwater levels during (a) 2010 WS and (b) 2011 DS; marked data points indicate gas sampling days.

Table 2
Test of fixed effects of infrared warming on temperatures at plant canopy, water, and soil in 2010 WS and 2011 DS.

Temperature (°C)	2010 WS		2011 DS	
	F value	*Pr* > *F*	*F* value	*Pr* > *F*
Canopy temp. (daytime)	25.58	<0.0001	23.10	<0.0001
Canopy temp. (nighttime)	583.21	<0.0001	594.60	<0.0001
Water temperature	67.55	<0.0001	14.36	<0.0004
Soil temperature	30.27	<0.0001	17.23	<0.0001

Table 3
Tests of fixed effects of canopy temperature and days after transplanting (DAT) on CH_4 emission rates in 2010 WS and 2011 DS.

Effect	2010 DS			2011 DS		
	DF	*F* value	*Pr* > *F*	DF	*F* value	*Pr* > *F*
Temperature	1	0.23	0.6469	1	0.19	0.6791
DAT	14	5.43	<0.0001	17	16.95	<0.0001
Temperature × DAT	14	0.85	0.6109	17	0.83	0.6531

2.4. Rice growth and yield

Plant height and number of tillers were recorded on every gas sampling date. The weight of total plant biomass, grain yield, and percent filled and unfilled grains were measured at maturity.

2.5. Data analysis

Analysis of variance (ANOVA) as a test of fixed effect of infrared warming and DAT on different parameters was done using SAS mixed procedure (SAS V9.1) (SAS Institute, 2003). ANOVA of some selected parameters was done using CropStat 7.2 and mean comparison was done with LSD values at the 5% level. The combined ANOVA of cumulative CH_4 and N_2O was done with statistical tool for agricultural research (STAR 1.0).

3. Results

3.1. Temperatures: Plant canopy, water, and soil

Infrared warming was done throughout the duration of the rice-growing season in the 2010 WS (4 August–20 October; 44–121 DAT), 2011 DS (7 Feb–20 May; 18–120 DAT), and a fallow season (26 May–15 July; 6–56 DAF). However, canopy temperatures only for earlier growth stages during the 2010 WS (44–101 DAT) and 2011 DS (18–51 DAT) are presented herein (Fig. 3). Although canopy temperatures in the 2011 fallow season are not shown in this report, seasonal average canopy temperatures measured from the reference and heated plots were 26.23 and 28.16 °C for the 2010 WS and 26.12 and 28.94 °C for the 2011 DS, respectively (Fig. 3). The increase in daily maximum, mean, and minimum temperatures observed from heated plots was significantly different from the corresponding reference plots (Table 2). The increase in canopy temperature during daytime varied from 0.99 to 1.44 °C (1.19 °C) while during nighttime it was from 2.49 to 2.65 °C (2.61 °C) for the 2010 WS. Similarly, the increase varied from 0.92 to 1.5 °C (1.14 °C) and from 1.78 to 2.61 °C (2.51 °C) during daytime and nighttime, respectively, for the 2011 DS.

The temperatures of the floodwater (Fig. 4a and b) and soil (Fig. 4c and d) varied within the range of 26–33 °C during the 2010 WS and 25–37 °C during the 2011 DS. The average growing-season temperature of water and soil was higher during the DS than the WS by 0.2 and 0.5 °C, respectively. Infrared warming significantly ($p < 0.0001$, Table 2) increased both water and soil (5-cm depth) temperatures in the 2010 WS and 2011 DS (Fig. 4). However, the magnitude of the increase was much smaller than the increase in canopy temperature. The average seasonal increases in water temperature in heated plots above the reference plots were 0.56 and 0.41 °C, while the increase in soil temperature was 0.42 and 0.37 °C, respectively, for the 2010 WS and 2011 DS.

Table 5
Analysis of variance of cumulative CH_4 and N_2O in a season and temperature treatment.

Effect/source	CH_4			N_2O		
	DF	*F* value	*Pr* > *F*	DF	*F* value	*Pr* > *F*
Season	2	0.77	0.4908	2	34.19	0.0001
Temperature	1	2.66	0.1372	1	1.33	0.9127
Season × Temperature	2	0.12	0.8924	2	1.32	0.3152
Pooled error	23			23		

3.2. Seasonal variation in CH_4 and N_2O emissions in reference and heated plots

The CH_4 emission rates from both reference and heated plots showed highly significant seasonal variations, i.e., with days after transplanting (DAT) (Fig. 5a and b). However, the effect of warming (temperature) and its interaction with DAT was not significant for CH_4 emission rates (Table 3). CH_4 emission rates increased with rice growth and peak emissions were observed during flowering stage (85–90 DAT), and they decreased toward maturity stage in both reference and heated plots in both the 2010 WS and 2011 DS (Fig. 5a and b). CH_4 emission rates showed two peaks. The early-season peak emissions appeared from 30 to 40 DAT, while the mid-season peak occurred from 80 to 90 DAT. CH_4 emission rates declined gradually (2010 WS) to rapidly (2011 DS) after final drainage at crop maturity.

CH_4 emission rates showed high standard deviation throughout the growing season, and were particularly higher in the 2010 WS than in the 2011 DS (Fig. 5a and b). Average seasonal emission rates between the reference plots (388 and 476 $mg\,m^{-2}\,d^{-1}$) and heated plots (308 and 412 $mg\,m^{-2}\,d^{-1}$) were not significantly different ($p > 0.05$) in both the 2010 WS and 2011 DS, respectively (Table 4). Nevertheless, the cumulative CH_4 emissions differed with rice growth stages and were higher during the maturity period in the 2010 WS, while they were observed to be higher during the reproductive period in the 2011 DS (data not shown). N_2O emissions were negligible throughout rice growth in both reference and heated plots in the 2010 WS and 2011 DS (Fig. 5c and d). However, peak emissions were observed after harvesting of rice in the 2011 DS in both reference and heated plots. Both average emission rates and cumulative emissions over seasons were not significantly different between reference and heated plots (Table 4).

Differences in emission rates and cumulative emissions of both CH_4 and N_2O were observed between the WS and DS, with higher emissions in the 2011 DS than in the 2010 WS. The total cumulative CH_4 emissions were approximately 1.5 times higher in the 2011 DS than in the 2010 WS (Table 4). However, these differences were below statistical significance (Table 5). The emissions during fallow season are described separately under Section 3.3. On the other hand, cumulative N_2O emissions were significantly higher in the 2011 DS than in the 2010 WS (Table 5). Global warming potential (GWP), calculated based on the cumulative emissions of CH_4 and N_2O, showed no significant difference between reference and heated plots ($p > 0.05$) in both seasons (Table 4). However, a comparison of GWP between WS and DS planting showed approximately 1.5 times higher GWP in the DS than in the WS.

3.3. CH_4 and N_2O emissions in the fallow period after dry-season rice

Continuous measurements of CH_4 and N_2O emissions from 26 May to 15 July 2011 (6–56 DAH) were conducted in the same experimental setup after harvesting the rice in DS 2011. All the rice straw harvested (7.4 $t\,ha^{-1}$) from the previous crop was incorporated (22 May 2011) thoroughly into the field. The frequency of rainfall (Fig. 6c) during this period made the field continuously flooded (0.1–7.0 cm). CH_4 emission rates were negligible for the first 2 weeks of flooding. The emission rates increased rapidly thereafter, with peak emissions between 30 and 40 days of flooding, and then declining (Fig. 6a). The highest emission rates recorded were 2600 and 2080 $mg\,m^{-2}\,d^{-1}$ for reference and heated plots, respectively. During the 2-month fallow period, cumulative CH_4 emissions were 57 and 44 $g\,m^{-2}$ for

Table 4
Cumulative CH_4 and N_2O emissions and global warming potential from reference and heated plots during 2010 WS and 2011 DS.

Temperature treatment	2010 WS		GWP[†] ($g\,CO_2$ eq. m^{-2})	2011 DS		GWP[†] ($g\,CO_2$ eq. m^{-2})
	CH_4 ($g\,m^{-2}$)	N_2O ($g\,m^{-2}$)		CH_4 ($g\,m^{-2}$)	N_2O ($g\,m^{-2}$)	
Reference plot	38.0 ± 11[a]	0.18 ± 0.03[a]	1005 ± 265[a]	54.0 ± 13[a]	0.29 ± 0.04[a]	1445 ± 723[a]
Heated plot	31.0 ± 12[a]	0.13 ± 0.04[a]	802 ± 307[a]	47.0 ± 8[a]	0.35 ± 0.06[a]	1278 ± 639[a]

Within a column, numbers followed by same letters are not significantly different by LSD at the 0.05 level. † Global warming potential based on 100-year time frame (IPCC, 2007).

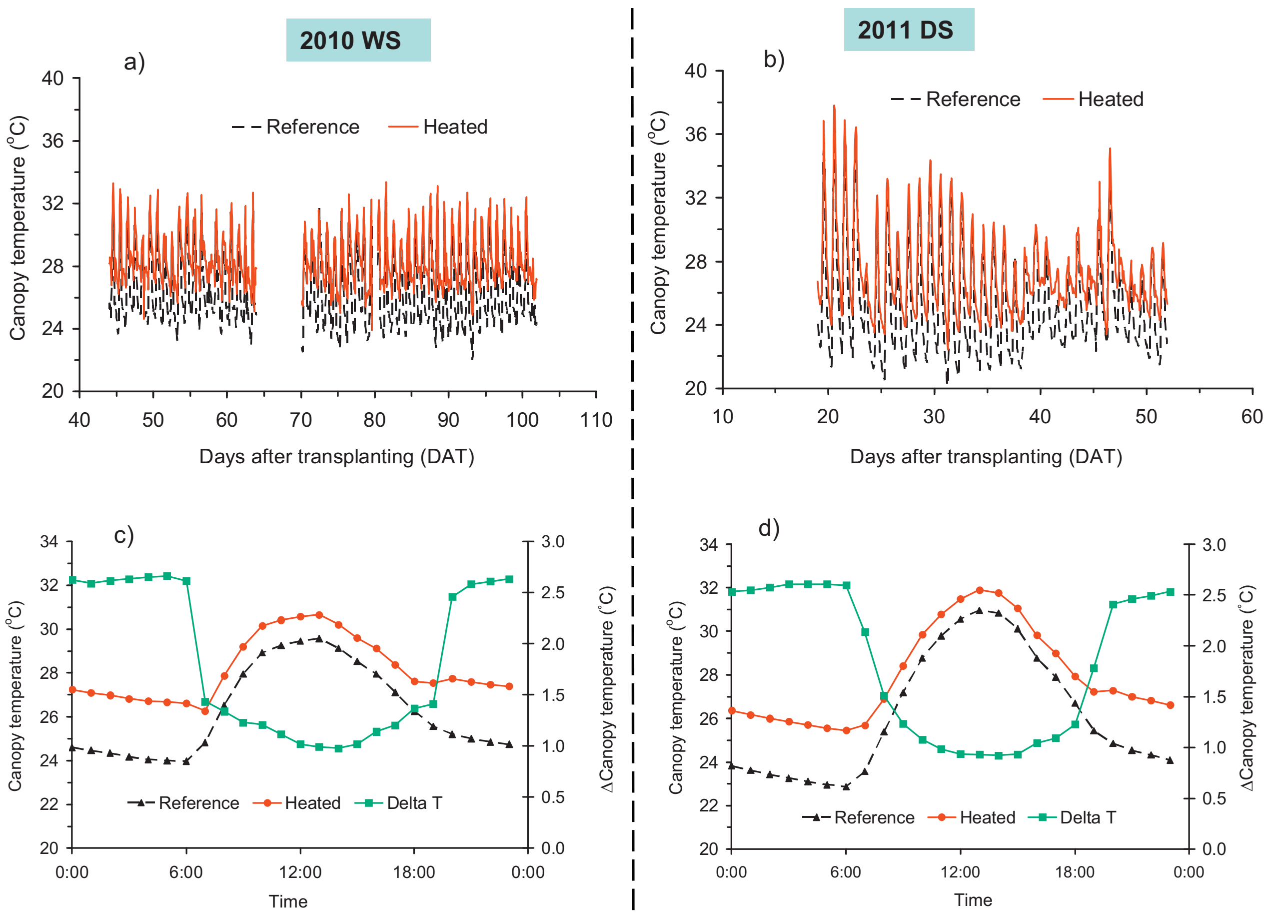

Fig. 3. (a) and (b) Hourly average rice canopy temperatures in reference and heated plots during 2010 WS (4 August to 4 October) and 2011 DS (8 Feb–12 March) ($n = 4$); (c) and (d) hourly average canopy temperatures and rise of canopy temperature in the heated plots during 2010 WS and 2011 DS versus time of day. Each hourly value in (c) and (d) is the average of 58 and 57 days for 2010 WS and 2011 DS, respectively.

reference and heated plots, respectively. Those amounts were similar to the amounts of CH_4 emitted during the 2011 DS. However, the emission rates were not significantly different between reference and heated plots ($p > 0.05$). On the other hand, N_2O emission rates were negligible throughout the fallow period in both reference and heated plots (Fig. 6b).

3.4. Diel variations in CH_4 and N_2O emissions

CH_4 emission rates increased from 0800 and the highest emissions were observed from 1100 to 1400 (Fig. 7a). However, those emission rates were not significantly different from 0500 to 2000 ($p > 0.05$) at any of the growth stages, i.e., 42 DAT (active tillering), 63 DAT (panicle initiation) 90 DAT (flowering), and 112 DAT (maturity) (Fig. 7a). Nevertheless, the emission rates were positively correlated with both air ($r = +0.25$, $n = 24$) and soil ($r = +0.57$, $n = 24$) temperatures (Fig. 7c and d).

The average CH_4 emission rates at 42, 63, and 90 DAT did not vary significantly, but relatively lower emissions were observed at 112 DAT, i.e., when the field was drained. On the other hand, N_2O emissions were negligible at 42, 63, and 90 DAT when the field was continuously flooded (3–10 cm). Higher emissions were observed at 112 DAT after draining the rice field. The emission rates did not differ significantly according to the time of day (Fig. 7b).

3.5. Rice growth and yield

There were no significant differences in plant height and number of tillers between reference and heated plots throughout the growing period in the 2010 WS and 2011 DS (data not shown). The highest numbers of tillers were observed around 60 DAT in both seasons. Similarly, straw weight, grain weight, harvest index, number of panicles hill^{-1}, spikelets panicle^{-1}, and spikelet sterility also showed no significant differences with temperature treatments in both seasons ($p > 0.05$) (Table 6). However, there were differences in straw weight and grain weight between the WS and DS, which were relatively higher during the 2011 DS than in the 2010 WS (Table 6).

4. Discussion

4.1. Performance of T-FACE

The target set-point differences for the increase in canopy temperatures of the heated plots compared with the reference plots were 3.0 °C at night and 1.5 °C during daytime. Generally, the infrared heater was able to provide greater warming in calm nighttime conditions (2.51–2.65 °C) than in daytime (1.14–1.19 °C) (Fig. 3), probably because of lower wind speed and closed stomata (Kimball, 2005; Luo et al., 2010; Wall et al., 2011). These results are in close agreement with previous studies (Kimball et al., 2008; Rehmani et al., 2011; Wall et al., 2011). Although fluctuations occurred with a rise in temperature, the T-FACE system was able to raise the canopy temperatures of the heated plots close to the target point (0.4 °C below the set-point difference).

The magnitude of warming of both water and soil was lower (0.4 to 0.6 °C) than the increase in canopy temperature. Unlike in our study, previous studies reported increased soil temperature by 1.3 °C in wheat fields (Wall et al., 2011) and by 1.7 °C (Kimball et al., 2008) and 2.0 °C (Wan et al., 2002) on grassland at 10-cm depth. The soil temperature increase reported by Kimball et al. (2008) was similar to the amount of the nighttime canopy temperature increase. Similarly, Hu et al. (2010), Luo et al. (2010), and Rui et al.

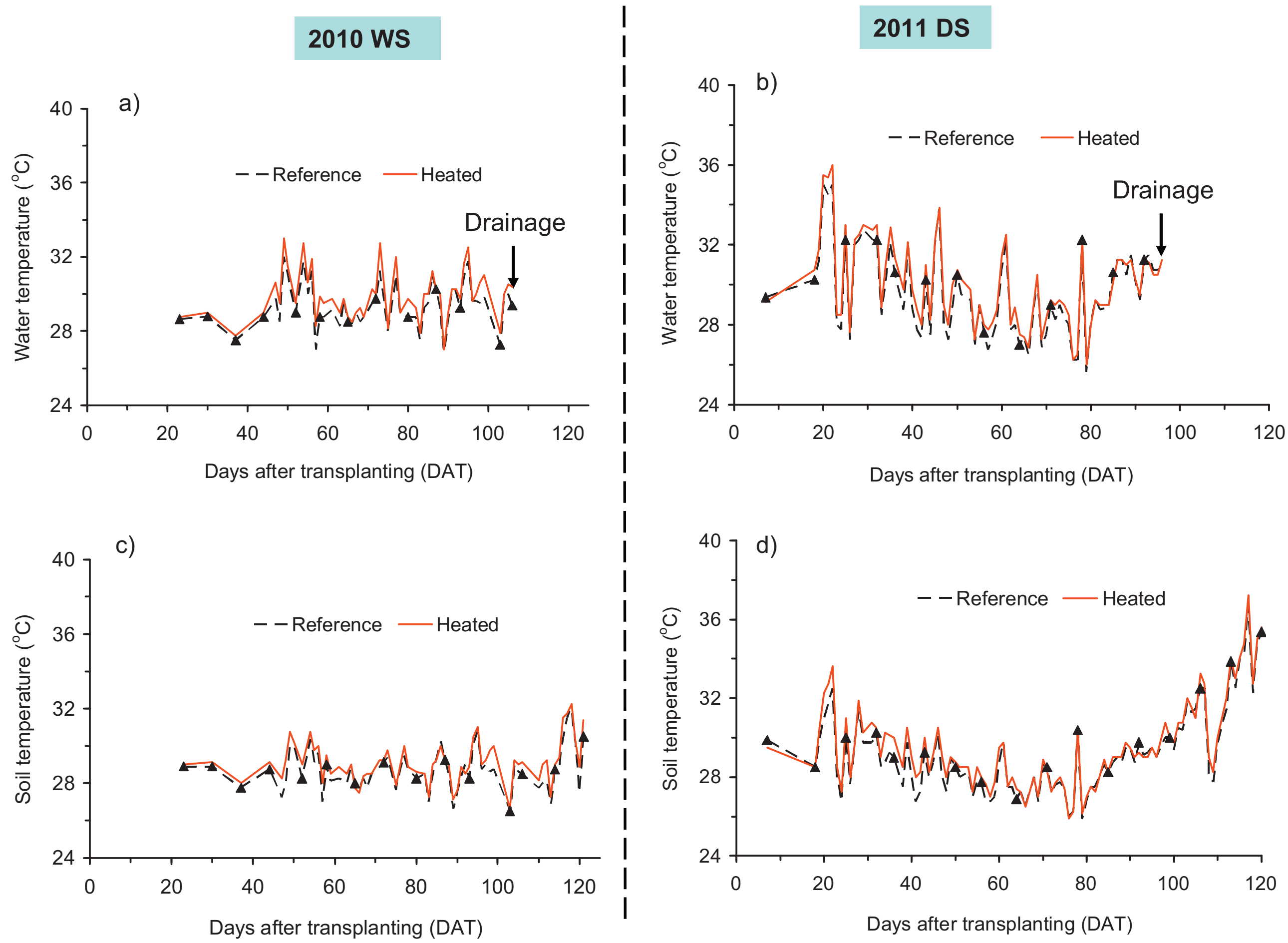

Fig. 4. Daily average water temperature ((a) and (b)) and soil temperature ((c) and (d)) during 2010 WS (14 July to 20 October 2010) and 2011 DS (27 January to 27 May 2011); data are average of four replicate plots monitored during gas sampling time (1400–1500). Marked data points represent gas sampling days.

(2011) reported significant increases in soil temperature from 0 to 40-cm depth on grazing land. The lower increase in soil temperature in our study than in those for upland crops is probably due to standing water, which may act as an insulating body that keeps the soil temperature uniform. Moreover, the floodwater was flowing freely between reference and heated plots. Therefore, in order for the warming of water and soil to be similar to the increase in canopy temperature in experimental plots, each experimental plot should have controlled irrigation that restricts the free flow of water.

4.2. Seasonal variation in CH_4 and N_2O emissions

CH_4 emissions from continuously flooded rice fields showed significant seasonal variation ($p < 0.001$). Emissions increased with rice growth until the flowering stage, and then they declined in both reference and heated plots in both the 2010 WS and 2011 DS (Fig. 5a and b). Different patterns of seasonal emissions are already well documented (Adhya et al., 1994; Gaihre et al., 2011; Hou et al., 2000; Lu et al., 2000; Neue and Sass, 1994; Singh and Dubey, 2012; Yang and Chang, 1999). Seasonal emission patterns are regulated by labile C, particularly dissolved organic carbon (DOC) in the root zone (Lu et al., 2000; Zhan et al., 2011). In general, two emission peaks appeared, i.e., an early-season peak at tillering stage (30–40 DAT) and a mid-season peak at flowering stage (80–90 DAT). Early-season peak emissions occur if the soil has high OM or organic amendments have been added (Neue et al., 1997; Wassmann et al., 2000), while late peak emissions at the reproductive stage are due to an increase in available C from root exudates (Gaihre et al., 2011; Lu et al., 2000; Neue et al., 1997; Yao et al., 2000). The substances from rhizodeposition are readily available for methanogenesis and transformation efficiency is high (Aulakh et al., 2001; Kimura et al., 2004). Hence, the rice plant at flowering to ripening stages offers

Table 6
Effect of canopy temperature on yield and yield-contributing components in 2010 WS and 2010 DS.

Yield and yield-contributing components	2010 WS		2011 DS	
	Reference plot	Heated plot	Reference plot	Heated plot
Straw weight (g DW m^{-2})	733.31[a]	794.22[a]	881.83[a]	889.61[a]
Grain weight (g DW m^{-2})	389.25[a]	487.64[a]	489.91[a]	556.09[a]
Harvest index	0.35[a]	0.38[a]	0.36[a]	0.38[a]
No. of panicles $hill^{-1}$	13.13[a]	13.05[a]	13.70[a]	13.75[a]
Spikelets $panicle^{-1}$	77.25[a]	81.41[a]	97.17[a]	92.38[a]
Sterility (%)	30.97[a]	19.64[a]	26.31[a]	20.64[a]

Within a row and within a season, numbers followed by same letters are not significantly different by LSD at the 0.05 level.

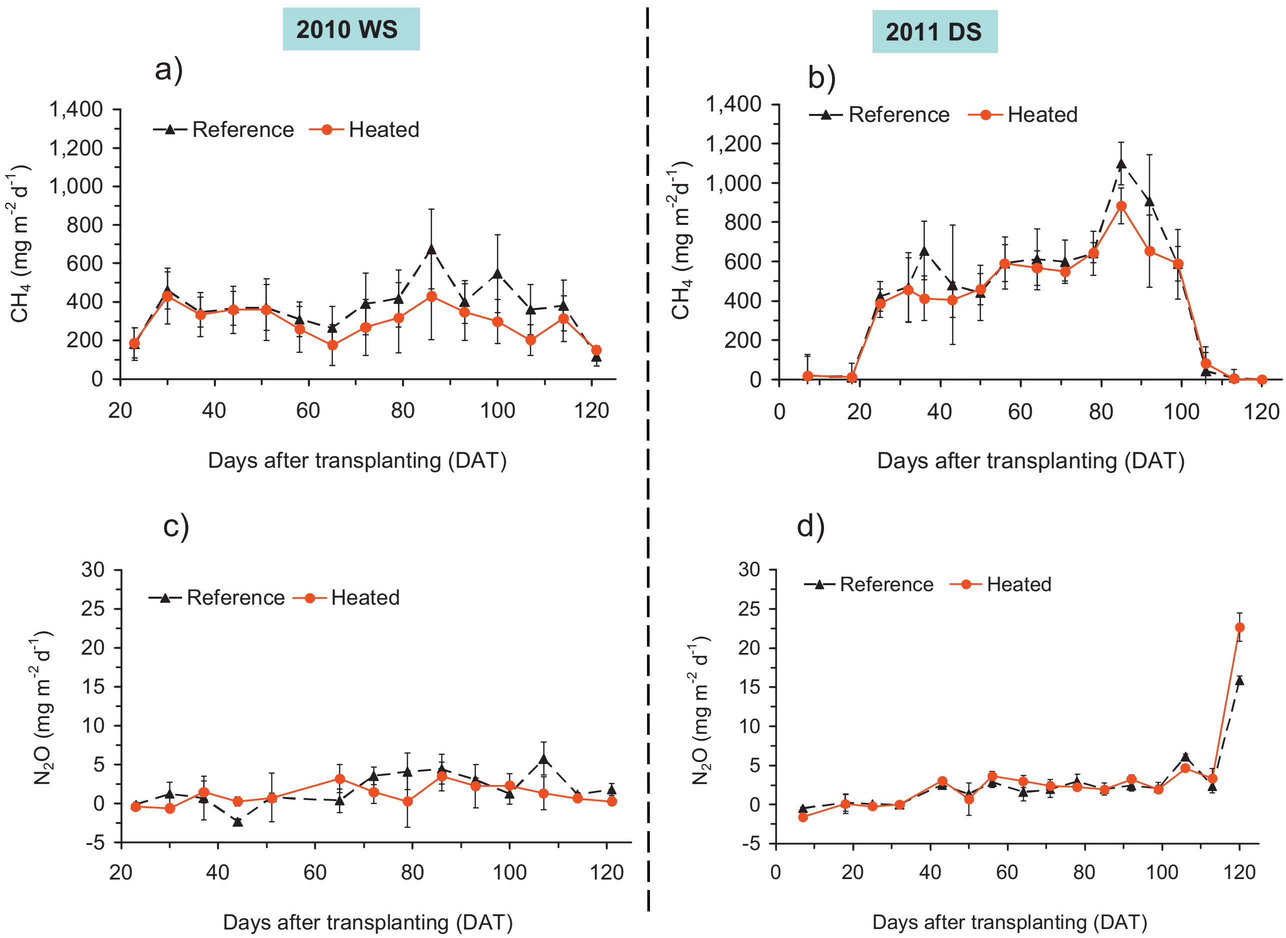

Fig. 5. Seasonal variations in ((a) and (b)) CH_4 and ((c) and (d)) N_2O emission rates from reference and heated plots during ((a and (c)) 2010 WS and ((b) and (d)) 2011 DS; vertical bars indicate the standard error of means ($n = 4$).

a relatively favorable ecological niche for a methanogenic microbial community (Singh and Dubey, 2012). Moreover, the higher CH_4 emissions at the flowering stage are associated with the increased CH_4 transport capacity of rice due to well-developed aerenchyma tissues (Adhya et al., 1994). CH_4 transport capacity increased with plant growth, and this was higher when there was high root volume during the reproductive stage (Yao et al., 2000). Decreasing CH_4 emissions after 90 DAT toward maturity were probably due to the decreasing DOC with reduced root exudates (Zhan et al., 2011) and to the decreasing transport capacity of the aerenchyma tissues. Moreover, in our study, the field was drained at maturity stage; hence, CH_4 emissions declined due to drying of the field.

N_2O emissions were not detected throughout the rice-growing period in both the WS and DS. This result is in good agreement with earlier studies stating that N_2O emissions from continuously flooded fields are usually negligible (Bronson et al., 1997b; Chen et al., 1997). In continuously flooded soil, the large amount of N_2O would be further reduced to N_2 before being emitted from the soil. Some emissions were observed after harvesting of rice in the 2011 DS, probably because of the nitrification of the accumulated NH_4 during the flooding period (Buresh et al., 2008; Khalil et al., 2004). However, emissions did not occur in the 2010 WS even after harvest of the rice probably because the soil was still saturated. There is an inverse relationship between CH_4 and N_2O emissions. N_2O emissions can be observed only during non-flooded periods, before transplanting of rice or immediately after drainage of the field when CH_4 emissions are not evident (Hou et al., 2000). This inverse relationship reveals that there is a risk of increasing N_2O emissions when water management strategies such as alternate wetting and drying are adopted to reduce CH_4 emissions (Bronson et al., 1997b; Wassmann et al., 2004).

The higher CH_4 emissions during the DS than in the WS can be explained by the differences in plant growth, solar radiation, and temperature between the two seasons. These results are consistent with previous findings (Huang et al., 1997; Sass et al., 1990; Wassmann et al., 1994) that showed the positive correlation between total seasonal CH_4 emissions and aboveground biomass of rice. The positive correlation can be found under ideal cropping conditions, in which climate factors and the availability of carbon substrate from sources other than rice plants are similar (Sass et al., 1990; Sass and Cicerone, 2002). The positive correlation between rice biomass and CH_4 emissions suggests that photosynthetically fixed C is allocated uniformly within the rice plant, which also led to greater rhizodeposition (Tokida et al., 2010). In contrast, Corton et al. (2000) observed higher emissions during the WS than in the DS even though aboveground biomass was higher during the DS, suggesting that grain yield and aboveground biomass alone are not good predictors of CH_4 emissions. The higher CH_4 emissions during the WS were explained by the higher labile organic C (Corton et al., 2000) and higher soil temperature (Bronson et al., 1997a). On the other hand, Denier van der Gon et al. (2002) reported a negative correlation between grain yield and CH_4 emissions. This could be due to the availability of more photosynthetic C as root exudates since it was not being used in seed production. In their study, however, they removed the spikelets to reduce the plants' capacity to store photosynthetically fixed C in grains and assumed that it would be

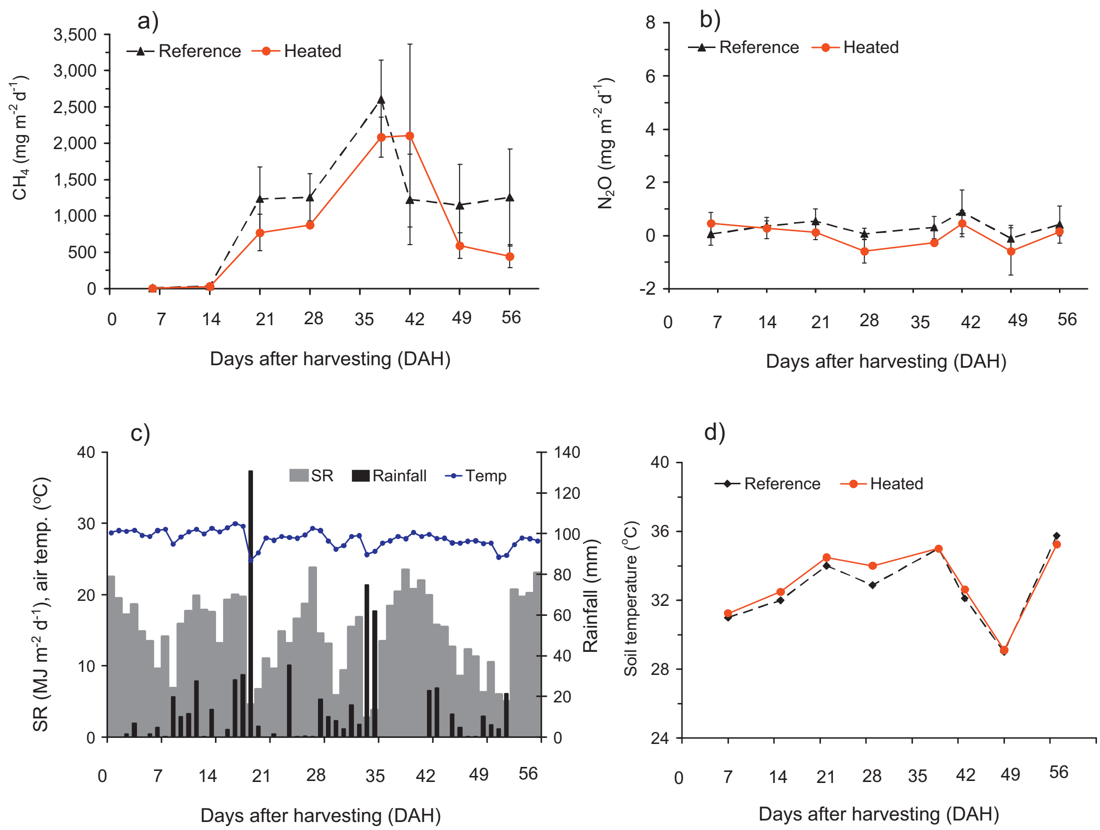

Fig. 6. Temporal changes in (a) CH_4, and (b) N_2O emission rates, (c) daily solar radiation, air temperature and rainfall; and (d) soil temperature during fallow period (20 May–15 July 2011) after harvesting of dry season rice; vertical bars in (a) and (b) indicate the standard error of means ($n = 4$).

available as root exudates. Therefore, low rice yield with removal of spikelets increased CH_4 emissions. Nevertheless, most of the CH_4 emitted from rice fields could be derived from photosynthetic C fixed by rice plants; thus, a positive correlation is expected between rice yield and CH_4 emissions as long as there is uniform allocation of photosynthetic C within different parts of the rice plant (Sass and Cicerone, 2002). Thus, the additional allocation of photosynthetic C to grain instead of roots might reduce CH_4 emissions as demonstrated by Denier van der Gon et al. (2002). Moreover, rice cultivars vary in their exudation of fixed C (Aulakh et al., 2001). In our study, however, the same variety was used for both the WS and DS and the difference in CH_4 emissions might be due to other climatic factors such as solar radiation and/or temperature. The DS is usually characterized by strong solar radiation and high temperature, which may affect both rice growth and CH_4 emissions (Wassmann et al., 1994). Since N_2O emissions were negligible, global warming potential was determined solely by CH_4 emissions. Therefore, with CH_4 emissions, GWP was higher in the DS than in the WS.

4.3. CH_4 and N_2O emissions during the fallow period

CH_4 and N_2O emissions during the fallow season depend on soil moisture status. A fallow rice field is generally considered a sink for CH_4 and a source of N_2O as long as the field remains dry (Liu et al., 2007). It is well known that a dry fallow favors nitrification and produces N_2O, while a wet fallow enhances methanogenesis and produces CH_4 (Bronson et al., 1997b). In our study, the CH_4 emission rate was very high, especially after 3–4 weeks of soil flooding. These emissions could have resulted from decaying roots, stubble, and incorporated rice straw. It is well known that rice straw increases CH_4 emissions since it has easily decomposable C that releases more methanogenic substrate (Bronson et al., 1997a; Corton et al., 2000). CH_4 emissions in fields without rice plants essentially occurred by ebullition of gas bubbles (Nouchi et al., 1994). Significant emissions occurred for the first 3–4 weeks and declined thereafter, probably due to a decline in easily decomposable C. On the other hand, N_2O emissions were negligible as the soil was continuously flooded due to frequent rainfall throughout the fallow season. Moreover, N_2O emissions might have decreased because of rice straw incorporation into the soil since it immobilizes soil N and reduces the amount of available N for nitrification and denitrification (Muhammad et al., 2011; Yao et al., 2010). Wang et al. (2011) reported a 50% reduction in N_2O emissions from a rice-growing field with rice straw incorporation. This result reveals that a wet fallow season, especially when rice straw is incorporated into the soil, is not a significant source of N_2O, but it acts as a significant source of CH_4 emissions. In only a 2-month fallow period, the amount of CH_4 emitted almost equaled the amount of CH_4 emitted in the DS.

4.4. Diel variation in CH_4 and N_2O emissions

CH_4 emission rates generally show diel variation, lower in the early morning and higher in the early afternoon to late afternoon. Schutz et al. (1990) observed positive correlation of diel soil temperature pattern and CH_4 emissions, as other factors that affect CH_4 emissions do not change markedly in such a short period. Emissions, in general, increased with temperature, and were highest during early afternoon (Wang et al., 1997) to late afternoon (Holzapfel-Pschorn and Seiler, 1986) when both air and soil temperatures were at their maximum, and were lowest during early morning when temperatures were at their minimum. Similar diel variations are also reported for N_2O emissions and the maximum emission rates were found during 1000 to 1300 (Hou et al., 2000). Those emission rates coincided with the temperature variation in

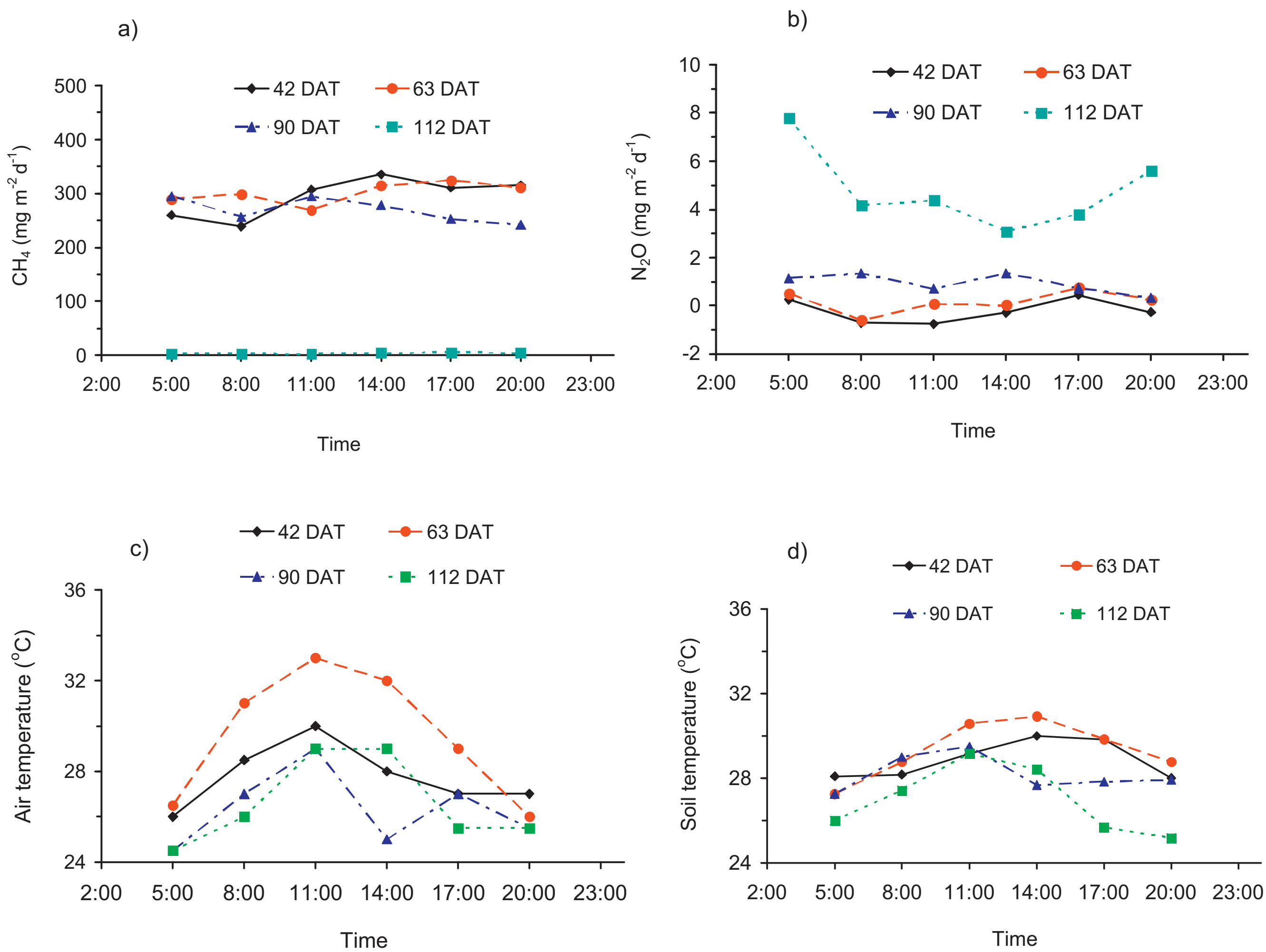

Fig. 7. Diel variations (0500–2000) of (a) CH_4, and (b) N_2O emission rates, (C) air temperature, and (d) soil temperature at different growth stages of rice in 2011 WS ($n = 6$).

the upper soil layer. However, Cheng et al. (2008) observed higher emissions during the day than those at night, even though the air and soil temperatures were similar between day and night. These results suggest when temperature is within optimum range, the net plant photosynthesis may contribute greatly to CH_4 emissions. In our study, diurnal variations in CH_4 and N_2O emissions were not significantly different though both air and soil temperatures differed with time. However, higher CH_4 emission rates were observed from 1100 to 1400, showing positive correlation with both air and soil temperatures. The lack of distinct diel variation may also be due to a smaller change in soil temperature, which was within the range of 27–30 °C (Fig. 7).

4.5. Effect of temperature on CH_4 and N_2O emissions

Temperature plays a key role in CH_4 emissions (Fey and Conrad, 2003). However, previous studies showed that the effect of temperature on CH_4 emissions is not consistent (Dijkstra et al., 2012). In our study, elevated canopy temperature (1.1–2.6 °C above ambient) had no significant effect on CH_4 emissions. One reason may be that the increase in canopy temperature may not have altered plant photosynthesis significantly. Then, the net carbon in plant biomass and the potential availability of C for methanogens in heated plots would not be significantly changed compared to those plants from reference plots (Yun et al., 2012). Another reason might be that the water/soil temperature was only marginally elevated (0.4–0.6 °C) vis-à-vis canopy temperature.

It is well known that soil processes such as plant-root respiration and microbial activities are directly controlled by soil temperature. Fey and Conrad (2000) demonstrated increased steady-state CH_4 production rates with soil temperature. Similarly, Wang et al. (1997) reported that methanogenesis was controlled by soil temperature irrespective of ambient air temperature. However, methanogens are mesophilic organisms, and higher CH_4 emissions were observed between soil temperature of 30 and 35 °C and emission rates declined beyond 35 °C (Minami and Neue, 1994; Parashar et al., 1993; Rath et al., 2002; Schulz et al., 1997). In our study, soil temperature was within the optimum range for methanogens in both seasons. An increase in only air or canopy temperature may have no effect on soil processes. A small increase in water/soil temperature may not have affected methanogenesis since the temperature range in the experiment was already within the optimum range for soil microbial processes. Nevertheless, significantly higher emissions were observed when both water and soil temperatures were elevated along with air temperature (Gaihre et al., 2013). Similarly, elevation of soil temperature (+2 °C) increased methane emission by 40% (Tokida et al., 2010) to 50% (Pereira et al., 2013).

High temperature may affect transpiration rate. Chanton et al. (1997) observed that a small amount of CH_4 was transported due to transpiration rate-induced bulk flow. However, it is well accepted that stomata are not responsible for the transport of CH_4 from the rice plant to the atmosphere (Nouchi et al., 1990). For this reason, CH_4 transport by the plant was not significantly affected by transpiration rate (Brynes et al., 1995; Nouchi et al., 1990) because CH_4 is mostly released from the culm, which is an aggregation of leaf sheaths, but not from the leaf blade. The aerenchyma tissue of the rice plant is the most important path for the transport of CH_4 from anoxic soil to the atmosphere (Groot et al., 2005). Hence, the factors that affect its transport capacity may alter CH_4 emissions and this might be affected by temperature. Hosono and Nouchi (1997) studied the effect of temperature on CH_4 transport capacity of rice plants. They observed that transport capacity was directly affected by root-zone temperature rather than by air temperature. Those results also suggest that only increasing plant canopy temperature (1.1 to 2.6 °C, daytime/nighttime) with a marginal increase in water/soil temperature would not affect CH_4 emission rates, unless there is a significant increase in photosynthesis, which may provide more C for methanogens thorough increased root exudates.

4.6. Effects on growth and yield

An increase in canopy temperature may affect aboveground plant processes such as photosynthesis and respiration. In our study, however, there was no significant difference in biomass weight and rice yield between reference and heated plots (Table 6). Hence, it can be assumed that this increase in canopy temperature did not increase photosynthesis significantly. This might be because the temperatures were on a flat optimum range for rice growth in the humid tropics and the warming treatment might not be large enough to cause a significant effect on rice yield. Therefore, an increase in canopy temperature (1.1 to 2.6 °C) had little effect on rice yield. Ottman et al. (2012) found similar results that an increase in temperature had little effect on yield when wheat was planted at its normal time of year (mid-winter) (14.9 °C). However, in late (spring) plantings when the temperature (22.2 °C) was above optimum, infrared warming exacerbated yield decreases. Therefore, when the temperature is above optimum, it induced spikelet sterility and decreased rice yield (Gaihre et al., 2013; Shah et al., 2011). A 50% higher rice yield was observed at temperature 29/21 °C, while yield was almost zero at higher temperature (37/29 °C) because of temperature-induced spikelet sterility (Ziska et al., 1996).

5. Conclusions

T-FACE increased canopy temperature by 1.1 and 2.6 °C during daytime and nighttime, respectively (0.4 °C below the targeted set-point increase). However, only a marginal increase occurred in both water and soil temperatures, which was likely due to the continuous flow of floodwater across the field. To study the effect of warming on soil processes, another experiment is needed with controlled irrigation between heated and reference plots so that water/soil temperature would also be elevated uniformly as in an upland crop. Because water and soil temperatures increased only marginally, the elevated canopy temperature (1.1–2.6 °C above ambient) did not have significant effects on either CH_4 or N_2O emissions. This suggests that increase of air/plant canopy temperature (2–3 °C) alone may not affect emissions of greenhouse gases. However, emissions increased significantly when soil and water have also been exposed to higher temperature (Gaihre et al., 2013).

Nevertheless, CH_4 emission rates showed seasonal variation, with higher emissions during flowering stage and lower toward harvesting stage. Diel variation in CH_4 emissions was positively correlated with both soil and air temperature, which were higher from 1100 to 1400. Cumulative CH_4 emissions and global warming potential differed with growing season: they were 1.5 times higher during the DS than in the WS. During both the rice-growing (continuously flooded) and wet fallow seasons, a significant amount of CH_4 but not of N_2O was emitted. Since only 2 months of wet fallow emitted an amount of CH_4 similar to that during the DS, emissions from fallow fields should be included in estimates of total CH_4 budgets of rice fields. No effects of the infrared warming treatment were found on rice yield or yield components, probably because the general growing temperatures were near optimum, and the warming treatment was not large enough to cause the rice to experience damaging temperatures.

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References

Adhya, T.K., Rath, A.K., Gupta, P.K., Rao, V.R., Das, S.N., Parida, K.M., Parashar, D.C., Sethunathan, N., 1994. Methane emission from flooded rice fields under irrigated conditions. Biol. Fertil. Soils 18, 245–248.

Allen Jr., L.H., Albrecht, S.L., Colon-Guasp, W., Covell, S.A., Baker, J.T., Pan, D., Boote, K.J., 2003. Methane emissions of rice increased by elevated carbon dioxide and temperature. J. Environ. Qual. 32, 1978–1991.

Aulakh, M.S., Wassmann, R., Bueno, C., Rennenberg, H., 2001. Impact of root exudates of different cultivars and plant development stages of rice (*Oryza sativa* L.) on methane production in paddy soil. Plant Soil 230, 77–86.

Bronson, K.F., Neue, H.U., Aba, E.B., Singh, U., 1997a. Automated chamber measurements of methane and nitrous oxide flux in a flooded rice soil: I. Residue, nitrogen, and water management. Soil Sci. Soc. Am. J. 61, 981–987.

Bronson, K.F., Neue, H.U., Aba, E.B., Singh, U., 1997b. Automated chamber measurements of methane and nitrous oxide flux in a flooded rice soil: II. Fallow period emissions. Soil Sci. Soc. Am. J. 61, 988–993.

Brynes, B.H., Austin, E.R., Tays, B.K., 1995. Methane emissions from flooded rice soils and plants under controlled conditions. Soil Biol. Biochem. 27, 331–339.

Buresh, R.J., Reddy, K.R., Van Kessel, C., 2008. Nitrogen transformation in submerged soils. In: Schepers, J.S., Raun, W.R. (Eds.), Nitrogen in Agricultural Systems. Agronomy Monograph 49. ASA, CSSA, and SSSA, Madison, WI, USA, p. 401.

Cai, Z., Xing, G., Yan, X., Xu, H., Tsuruta, H., Yagi, K., Minami, K., 1997. Methane and nitrous oxide emissions from rice paddy fields as affected by nitrogen fertilizers and water management. Plant Soil 196, 7–14.

Chakraborty, A., Bhattacharya, D.K., Li, B.L., 2006. Spatiotemporal dynamics of methane emission from rice fields at global scale. Ecol. Complexity 3, 231–240.

Chanton, J.P., Whiting, G.J., Blair, N.E., Lindau, C.W., Bollich, P.K., 1997. Methane emission from rice: stable isotopes, diurnal variations, and CO_2 exchange. Global Biogeochem. Cycles 11, 15–27.

Chen, G.X., Huang, G.H., Huang, B., Yu, K.W., Wu, J., Xu, H., 1997. Nitrous oxide and methane emissions from soil–plant systems. Nutr. Cycling Agroecosyst. 49, 41–45.

Cheng, W., Sakai, H., Hartley, A., Yagi, K., Hasegawa, T., 2008. Increased night temperature reduces the stimulatory effect of elevated carbon dioxide concentration on methane from rice paddy soil. Global Change Biol. 14, 644–656.

Conant, R.T., Steinweg, J.M., Haddix, M.L., Paul, E.A., Plante, A.F., Six, J., 2008. Experimental warming shows that decomposition temperature sensitivity increases with soil organic matter recalcitrance. Ecology 89, 2384–2391.

Corton, T.M., Bajita, J.B., Grospe, F.S., Pamplona, R.R., Assis Jr., C.A., Wassmann, R., Lantin, R.S., Buendia, L.V., 2000. Methane emission from irrigated and intensively managed rice fields in Central Luzon (Philippines). Nutr. Cycling Agroecosyst. 58, 37–54.

Denier van der Gon, H.A.C., Kropff, M.J., Breemen, N.V., Wassmann, R., Lantin, R.S., Aduna, E., Corton, T.M., Van Laar, H.H., 2002. Optimizing grain yields reduces CH_4 emissions from rice paddy fields. Proc. Nat. Acad. Sci. U.S.A. 99, 12021–12024.

Denman, K.L., Brasseur, G., Chidthaisong, A., Ciasis, P., Cox, P.M., Dickinson, R.E., Hauglustaine, D., Heinze, C., Holland, E., Jacob, D., Lohmann, U., Ramachandran, S., Silva Dias, P.L., Wofsy, S.C., Zhang, X., 2007. Couplings between changes in the climate system and biogeochemistry. In: Solomon, S., et al. (Eds.), Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge (UK) and New York (USA), pp. 501–587.

Devevre, O.C., Horwath, W.R., 2000. Decomposition of rice straw and microbial carbon use efficiency under different soil temperatures and moistures. Soil Biol. Biochem. 32, 1773–1785.

Dijkstra, F.A., Prior, S.A., Runion, G.B., Torbert, H.A., Tian, H., Lu, C., Venterea, R.T., 2012. Effects of elevated carbon dioxide and increased temperature on methane and nitrous oxide fluxes: evidence from field experiment. Front. Ecol. Environ. 10, 520–527, doi: 10.1890/120059.

Dobermann, A., Dawe, D., Roetter, R.P., Cassman, K.G., 2000. Reversal of rice yield decline in a long-term continuous cropping experiment. Agron. J. 92, 633–643.

Fey, F., Conrad, R., 2000. Effect of temperature on carbon and electron flow and on the archael community in methanogenic rice field soil. Appl. Environ. Microbiol. 66, 4790–4797.

Fey, F., Conrad, R., 2003. Effect of temperature on the rate limiting step in the methanogenic degradation pathway in rice field soil. Soil Biol. Biochem. 35, 1–8.

Gaihre, Y.K., Tirol-Padre, A., Wassmann, R., Aquino, E., Pangga, G.V., Sta-Cruz, P.C., 2011. Spatial and temporal variations in methane fluxes from irrigated lowland rice fields. Philipp. Agric. Sci. 94, 335–342.

Gaihre, Y.K., Wassmann, R., Pangga, G.V., 2013. Impact of elevated temperatures on greenhouse gas emissions in rice systems: interaction with straw incorporation studied in a growth chamber experiment. Plant Soil 273, 857–875, http://dx.doi.org/10.1007/s11104-013-1852-4.

Groot, T.T., Van Bodegom, P.M., Meijer, H.A.J., Harren, F.J.M., 2005. Gas transport through the root-shoot transition zone of rice tillers. Plant Soil 277, 107–116.

Holzapfel-Pschorn, A., Seiler, W., 1986. Methane emission during a cultivation period from an Italian rice paddy. J. Biophys. Res. 99, 11803–11814.

Hosono, T., Nouchi, I., 1997. The dependence of methane transport in rice plants on the root zone temperature. Plant Soil 191, 233–240.

Hou, A.X., Chen, G.X., Wang, Z.P., Cleemput, O.V., Patrick, W.H., 2000. Methane and nitrous oxide emission from a rice field in relation to soil redox and microbial processes. Soil Sci. Soc. Am. J. 64, 2180–2186.

Hu, Y., Chang, X., Lin, X., Wang, Y., Wang, S., Duan, J., Zhang, Z., Yang, X., Luo, C., Xu, G., Zhao, X., 2010. Effects of warming and grazing on N_2O fluxes in an alpine meadow ecosystem on the Tibetan plateau. Soil Biol. Biochem. 42, 944–952.

Hua, X., Guangxi, X., Cai, Z., Tsuruta, H., 1997. Nitrous oxide emissions from three rice paddy fields in China. Nutr. Cycling Agroecosyst. 49, 23–28.

Huang, Y., Sass, R., Fisher, F., 1997. Methane emission from Texas rice paddy soils. 2. Seasonal contribution of rice biomass production to CH_4 emission. Global Change Biol. 3, 491–500.

IPCC (Intergovernmental Panel on Climate Change), 2007. Summary for policymakers. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.), Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1–18.

IPCC (Intergovernmental Panel on Climate Change), 2001. Climate change 2001. In: Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K., Johnson, C.A. (Eds.), The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, p. 881.

Johnson-Beebout, S.E., Angeles, O.R., Alberto, M.C.R., Buresh, R.J., 2009. Simultaneous minimization of nitrous oxide and methane emission from rice paddy soils is improbable due to redox potential changes with depth in a greenhouse experiment without plants. Geoderma 149, 45–53.

Khalil, K., Mary, B., Renault, P., 2004. Nitrous oxide production by nitrification and denitrification in soil aggregates as affected by O_2 concentration. Soil Biol. Biochem. 36, 687–699.

Kimball, B.A., 2005. Theory and performance of an infrared heater for ecosystem warming. Global Change Biol. 11, 2041–2056, http://dx.doi.org/10.1111/j. 1365-2486.2005.01028.x.

Kimball, B.A., 2011. Comment on the comment by Amthor et al. on "Appropriate experimental ecosystem warming methods" by Aronson and McNulty. Agric. For. Meteorol. 151, 420–424.

Kimball, B.A., Conley, M.M., Wang, S., Lin, X., Luo, C., Morgan, J., Smith, D., 2008. Infrared heater arrays for warming ecosystem field plots. Global Change Biol. 14, 309–320.

Kimura, M., Murase, J., Lu, Y., 2004. Carbon cycling in rice field ecosystems in the context of input, decomposition and translocation of organic materials and fates of their end products (CO_2 and CH_4). Soil Biol. Biochem. 36, 1399–1416.

Kruger, M., Frenzel, P., Conrad, R., 2001. Microbial processes influencing methane emission from rice fields. Global Change Biol. 7, 49–63.

Liu, X., Liu, H., Ahao, P., Sun, G., Lin, Y., Rao, X., Wang, Y., 2007. Characteristics of CO_2, CH_4 and N_2O emissions from winter-fallowed paddy fields in hilly areas of South China. Front. Agric. China 1, 418–423.

Lu, Y., Wassmann, R., Neue, H.U., Huang, C., 2000. Dynamics of dissolved organic carbon and methane emissions in flooded rice soils. Soil Sci. Soc. Am. J. 64, 2011–2017.

Luo, C.Y., Xu, G.P., Chao, Z.G., Wang, S.P., Lin, S.W., Hu, Y.G., Zhang, Z.H., Duan, J.C., Chang, X.F., Su, A.L., Li, Y.N., Zhao, X.Q., Du, M.Y., Tang, Y.H., Kimball, B., 2010. Effect of warming and grazing on litter mass loss and temperature sensitivity of litter and dung mass loss on the Tibetan plateau. Global Change Biol. 16, 1606–1617, http://dx.doi.org/10.1111/j.1365-2486.2009.02026.x.

Meijide, A., Manca, G., Goded, L., Magliulo, V., Tommasi, P.D., Seufer, G., Cescatti, A., 2011. Seasonal trends and environmental controls of methane emissions in a rice paddy field in northern Italy. Biogeosciences 8, 3809–3821.

Minami, K., 1997. Atmospheric methane and nitrous oxide: sources, sinks and strategies for reducing agricultural emissions. Nutr. Cycling Agroecosyst. 49, 203–211.

Minami, K., Neue, H.U., 1994. Rice paddies as a methane source. Clim. Change 27, 13–26.

Morgan, J.A., LeCain, D.R., Pendall, E., Blumenthal, D.M., Kimball, B.A., Carrillo, Y., Williams, D.G., Heisler-White, J., Dijkstra, F.A., West, M., 2011. C4 grasses prosper as carbon dioxide eliminates desiccation in warmed semi-arid grassland. Nature 476, 202–206.

Muhammad, W., Vaugham, S.M., Dalal, R.C., Menzies, N.W., 2011. Crop residues and fertilizer nitrogen influence residue decomposition and nitrous oxide emission from a vertisol. Biol. Fertil. Soils 47, 15–23.

Neue, H.U., Sass, R.L., 1994. Trace gas emissions from rice fields. Environ. Sci. Res. 48, 119–145.

Neue, H.U., Wassmann, R., Kludze, H.K., Wang, B., Lantin, R.S., 1997. Factors and processes controlling methane emissions from rice fields. Nutr. Cycling Agroecosyst. 49, 111–117.

Nouchi, I., Hosono, T., Aoki, K., Minami, K., 1994. Seasonal variation in methane flux from rice paddies associated with methane concentration in soil water, rice biomass and temperature, and its modeling. Plant Soil 161, 195–208.

Nouchi, I., Mariko, S., Aoki, K., 1990. Mechanism of methane transport from the rhizosphere to the atmosphere through rice plants. Plant Physiol. 94, 59–66.

Ottman, M.J., Kimball, B.A., White, J.W., Wall, G.W., 2012. Wheat growth response to increased temperature from varied planting dates and supplemental infrared heating. Agron. J. 104, 7–16.

Parashar, D.C., Gupta, P.K., Rai, J., Sharma, R.C., Singh, N., 1993. Effect of soil temperature on methane emission from paddy fields. Chemosphere 26, 247–250.

Pereira, J., Figueiredo, N., Goufo, P., Carneiro, J., Morais, R., Carranca, C., Coutinho, J., Trindade, H., 2013. Effect of elevated temperature and atmospheric carbon dioxide concentration on the emissions of methane and nitrous oxide from Portuguese flooded rice fields. Atmos. Environ. 80, 464–471.

Rath, A.K., Ramakrishnan, B., Sethunathan, N., 2002. Temperature dependence of methane production in tropical rice soils. Geomicrobiol. J. 19, 581–592.

Rehmani, M.I.A., Zhang, J., Li, G., Ata-Ui-Karim, S.T., Wang, S., Kimball, B.A., Yan, C., Liu, Z., Ding, Y., 2011. Simulation of future global warming scenarios in rice paddies with an open-field warming facility. Plant Methods 7, 41.

Rui, Y., Wang, S., Xu, Z., Wang, Y., Chen, C., Zhou, X., Kang, X., Lu, S., Hu, Y., Lin, Q., Luo, C., 2011. Warming and grazing affect soil labile carbon and nitrogen pools differently in an alpine meadow of the Qinghai-Tibet Plateau in China. J. Soils Sediments 11, 903–914, http://dx.doi.org/10.1007/s11368-011-0388-6.

SAS Institute Inc., 2003. Proceedings of the 28th Annual SAS® Users Group International Conference , Cary, NC: SAS Institute Inc.

Sass, L.S., Cicerone, R.J., 2002. Photosynthate allocations in rice plants: food production or atmospheric methane? Proc. Nat. Acad. Sci. U.S.A. 99, 11993–11995.

Sass, R.L., Fisher, F.M., Harcombe, P.A., Turner, F.T., 1990. Methane production and emission in a Texas rice field. Global Biogeochem. Cycles 4, 47–68.

Schrope, M.K., Chanton, J.P., Allen, L.H., Baker, J.T., 1999. Effect of CO_2 enrichment and elevated temperature on methane emissions from rice, *Oryza sativa*. Global Change Biol. 5, 587–599.

Schulz, S., Matsuyama, H., Conrad, R., 1997. Temperature dependence of methane production from different precursors in a profundal sediment (Lake Constance). FEMS Microbiol. Ecol. 22, 207–213.

Schutz, H., Seiler, W., Conrad, R., 1990. Influence of soil temperature on methane emission from rice paddy fields. Biogeochemistry 11, 77–95.

Shah, F., Huang, J., Cui, K., Nie, L., Sah, T., Chen, C., Wang, K., 2011. Impact of high-temperature stress on rice plant and its traits related to tolerance. J. Agric. Sci. 149, 545–556.

Singh, A., Dubey, S.K., 2012. Temporal variation in methanogenic community structure and methane production potential of tropical rice ecosystem. Soil Biol. Biochem. 48, 162–166.

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., Omara, F., Rice, C., Scholes, B., Sirotenko, O., 2007. Agriculture. In: Metz, B., Davidson, O.R., Bosch, P.R., Dave, R., Meyer, L.A. (Eds.), Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 498–540.

Solomon, S., Qin, D., Manning, M., Alley, R.B., Berntsen, T., Bindoff, N.L., Chen, Z., Chidthaisong, A., Gregory, J.M., Hegerl, G.C., Heimann, M., Hewitson, B., Hoskins, B.J., Joos, F., Jouzel, J., Kattsov, V., Lohmann, U., Matsuno, T., Molina, M., Nicholls, N., Overpeck, J., Raga, G., Ramaswamy, V., Ren, J., Rusticucci, M., Somerville, R., Stocker, T.F., Whetton, P., Wood, R.A., Wratt, D., 2007. Technical summary. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.), Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 19–91.

Tokida, T., Fumoto, T., Cheng, W., Matsunami, T., Adachi, M., Katayangi, N., Matsushima, M., Okawara, Y., Nakamura, H., Okada, M., Sameshima, R., Hasegawa, T., 2010. Effect of free-air CO_2 enrichment (FACE) and soil warming on CH_4 emission from a rice paddy field: impact assessment and stoichiometric evaluation. Biogeosciences 7, 2639–2653.

Wall, G.W., Kimball, B.A., White, J.W., Ottman, M.J., 2011. Gas exchange and water relations of spring wheat under full-season infrared warming. Global Change Biol. 17, 2113–2133, http://dx.doi.org/10.1111/j.1365-2486.2011.02399.x.

Wan, S., Luo, Y., Wallace, L.L., 2002. Change in microclimate induced by experimental warming and clipping in tallgrass prairie. Global Change Biol. 8, 754–768.

Wang, B., Neue, H.U., Samonte, H.P., 1997. The effect of controlled soil temperature on diel CH_4 emission variation. Chemosphere 35, 2083–2092.

Wang, J.Y., Xia, J.X., Xiong, Z.Q., Khalil, M.A.K., Xing, G.X., 2011. Water regime-nitrogen fertilizer-straw incorporation interaction: field study on nitrous oxide emissions from a rice agroecosystem in Nanjing, China. Agric. Ecosyst. Environ. 141, 437–446.

Wassmann, R., Neue, H.U., Ladha, J.K., Aulakh, M.S., 2004. Mitigating greenhouse gas emissions from rice–wheat cropping system in Asia. Environ. Develop. Sustainability 6, 65–90.

Wassmann, R., Nelson, G.C., Peng, S.B., Sumfleth, K., Jagadish, S.V.K., Hosen, Y., Rosegrant, M.W., 2010. Rice and global climate change. In: Pandey, S., et al. (Eds.), Rice in the Global Economy: Strategic Research and Policy Issues for Food Security. International Rice Research Institute, pp. 411–432.

Wassmann, R., Neue, H.U., Lantin, R.S., Aduna, J.B., Alberto, M.C.R., Andales, M.J., Tan, M.J., Denier Van Der Gon, H.A.C., Hoffmann, H., Papen, H., Rennenberg, H., Seiler, W., 1994. Temporal patterns of methane emissions from wetland rice fields treated by different modes of N application. J. Geophys. Res. 99, 16457–16462.

Wassmann, R., Neue, H.U., Lantin, R.S., Makarim, K., Chareonslip, N., Buendia, L.V., Rennenberg, H., 2000. Characterization of methane emissions from rice fields in Asia. II. Differences among irrigated, rainfed, and deepwater rice. Nutr. Cycling Agroecosyst. 58, 13–22.

Watanabe, A., Yamada, H., Kimura, M., 2001. Effects of shifting growth stage and regulating temperature on seasonal variation of CH_4 emission from rice. Global Biogeochem. Cycles 15, 729–739.

White, J.W., Kimball, B.A., Wall, G.W., Ottman, M.J., 2012. Cardinal temperatures for wheat leaf appearance as assessed from varied sowing dates and infrared warming. Field Crops Res. 137, 213–220.

Yan, X.Y., Yagi, K., Akiyama, H., Akimoto, H., 2005. Statistical analysis of the major variables controlling methane emission from rice fields. Global Change Biol. 11, 1131–1141.

Yang, S.S., Chang, H.L., 1998. Effect of environmental conditions on methane production and emission from paddy soil. Agric. Ecosyst. Environ. 69, 69–80.

Yang, S.S., Chang, H.L., 1999. Diurnal variation of methane emission from paddy fields at different growth stages of rice cultivation in Taiwan. Agric. Ecosyst. Environ. 76, 75–84.

Yao, H., Conrad, R., 2000. Effect of temperature on reduction of iron and production of carbon dioxide and methane in anoxic wetland rice soils. Biol. Fertil. Soils 32, 135–141.

Yao, H., Yagi, K., Nouchi, I., 2000. Importance of physical plant properties on methane transport through several rice cultivars. Plant Soil 222, 83–93.

Yao, Z., Zhou, Z., Zheng, X., Xie, B., Mei, B., Wang, R., Butterbach-Bahl, K., Zhu, J., 2010. Effect of organic matter incorporation on nitrous oxide emissions from rice–wheat rotation ecosystems in China. Plant Soil 327, 315–330.

Yu, K., Bohme, F., Rinklebe, J., Neue, H.U., Delaune, R.D., 2007. Major biogeochemical processes in soils: a microcosm incubation from reducing to oxidizing conditions. Soil Sci. Soc. Am. J. 71, 1406–1417.

Yun, S.I., Kang, B.M., Lim, S.S., Choi, W.J., Ko, J., Yoon, S., Ro, H.M., Kim, H.Y., 2012. Further understanding CH_4 emissions from a flooded rice field exposed to experimental warming with elevated [CO_2]. Agric. For. Meteorol. 154-155, 75–83.

Zhan, M., Cougui, C., Wang, J., Jiang, Y., Cai, M., Yue, L., Shahrear, A., 2011. Dynamics of methane emission, active soil organic carbon and their relationships in wetland integrated rice–duck systems in southern China. Nutr. Cycling Agroecosyst. 89, 1–13, http://dx.doi.org/10.1007/s10705-010-9371-7.

Ziska, L.H., Manalo, P.A., Ordonez, R.A., 1996. Intraspecific variation in the response of rice (*Oryza sativa* L.) to increased CO_2 and temperature: growth and yield response of 17 cultivars. J. Exp. Bot. 47, 1353–1359.

Ziska, L.H., Moya, T.B., Wassmann, R., Namuco, O.S., Lantin, R.S., Aduna, J.B., Abao Jr., E., Bronson, K.F., Neue, H.U., Olszyk, K., 1998. Long-term growth at elevated carbon dioxide stimulates methane emission in tropical paddy rice. Global Change Biol. 4, 657–665.