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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