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Research Paper

The characteristics of methane flux from an irrigated rice farm in East China measured using the eddy covariance method

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ABSTRACT

A new open-path methane analyzer (LI-7700) was adopted to measure methane (CH_4) fluxes using eddy covariance method over irrigated rice fields in Yancheng, Jiangsu Province, China, throughout the 2016 growing season. A clear seasonal variation in the daily CH_4 flux was observed. The CH_4 flux started to increase 3 days after the fields were flooded. The peak CH_4 flux was 0.37 gC m^{-2} d^{-1} and was reached during late vegetative stage (August 2). A distinct single-peak diurnal pattern of the CH_4 flux was observed during the vegetative stages. The CH_4 flux started to increase after sunrise and reached the peak at approximately 14:30 in the afternoon. Similar results were not observed during the reproductive and ripening stages. The diurnal patterns of soil temperature (Tsoil) and gross ecosystem photosynthesis (GEP) were consistent with that of the CH_4 flux. The partial F tests showed that soil temperature and volumetric water content (VWC) were the most important factors controlling CH_4 emissions from rice fields on seasonal timescale. The friction velocity (u_*) was also found related to the CH_4 emissions. Good agreements between the measured and modeled CH_4 fluxes were obtained (R^2 = 0.82, 0.86 and 0.86) using the models with different factors over the whole season. Including ambient pressure (P) and GEP in the model did not significantly improve the performance of the model. The best agreement between the measured and modeled CH_4 fluxes was achieved by running the regression separately for each growth stage (R^2 = 0.90). After the daily CH_4 series was gap-filled, the total amount of CH_4 emitted over the whole season was 19.20 ± 3.20 gC m^{-2}.

1. Introduction

Methane (CH_4) is one of the most important greenhouse gases aside from carbon dioxide (CO_2) and nitrous oxide (N_2O). The atmospheric CH_4 concentration has been increasing over the last hundreds of years due to the growing agricultural emissions as well as other anthropogenic sources (Etheridge et al., 1998; Ferretti et al., 2005). Despite the relatively low concentration in the atmosphere, CH_4 has the second largest radiative forcing due to its high global warming potential that is 25 times higher than that of CO_2 over a 100-year timescale (IPCC, 2007).

Rice fields are one of the largest anthropogenic sources of atmospheric CH_4, accounting for approximately 12–26% of the global anthropogenic CH_4 emissions (IPCC, 2007). Methanogenic microorganisms in the soil can produce CH_4 by consuming simple substrates such as H_2, CO_2 and acetate under anaerobic soil conditions (Conrad, 2002). Irrigated rice fields are often flooded with water, causing anaerobic soil conditions, which is in favor of the production of CH_4 (Neue, 1993). CH_4 produced in the soil escapes to the atmosphere via three main pathways: ebullition (release of CH_4-containing gas bubbles), diffusion and transport through the aerenchyma of rice plants (Wassmann and Aulakh, 2000). The contribution of each pathway changes with the growth stage of the rice plants (Schütz et al., 1989). Ebullition rates are generally high in the early and late seasons but low in the mid-season due to the development of plant-mediated transport. Over the whole growing season, plant-mediated transport can account for up to 90% of the total CH_4 emissions (Cicerone and Shetter, 1981; Schütz et al., 1989). In addition to transporting CH_4 from the soil to the atmosphere, rice plants also act as an active CH_4 oxidizing-site in the rhizosphere by providing oxygen through the aerenchyma system (Wassmann and Aulakh, 2000).

Over the past few decades, numerous studies have been carried out around the world to measure CH_4 emissions from rice fields. Distinct seasonal and diurnal patterns of CH_4 flux were observed in previous studies (Alberto et al., 2014; Meijide et al., 2011; Miyata et al., 2000; Satpathy et al., 1997; Weller et al., 2015; Yan et al., 2003; Yun et al.,

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2013). Positive correlations between CH_4 flux and soil temperature were observed on daily, seasonal and interannual time scales (Knox et al., 2016; Satpathy et al., 1997; Tokida et al., 2010). Soil temperature can affect the production of CH_4 by changing the growth rate of the microbial population (Schütz et al., 1990) and the rates of microbiological reactions (Conrad, 2002). Changes in soil temperature can also alter the pathway of CH_4 production because some microbial processes are more sensitive to temperature than others (Fey and Conrad, 2000). Hosono and Nouchi (1997) reported that an increase in soil and water temperature could decrease the solubility of CH_4 and increase the rate of diffusion from the soil to the atmosphere. Other meteorological factors such as friction velocity and ambient pressure can also change the transport rate of CH_4. High mechanical mixing and low ambient pressure were found to be the main triggers of ebullition events (Nadeau et al., 2013; Sachs et al., 2008; Xu et al., 2014).

Soil water condition is another critical factor that affects CH_4 production due to its effect on the anaerobic condition of the soil (Conrad, 2002). The soil VWC, which is a measurement of the soil water status, was found to be strongly related to CH_4 emissions from rice fields (Alberto et al., 2014). Floodwater can also act as a barrier, which can slow down the transport of CH_4 from the soil to the atmosphere, especially at the beginning of the season when plant-mediated transport is not fully developed. Once the water barrier was removed, the CH_4 gas trapped in the soil was released to the atmosphere in a short time, causing increases in the CH_4 flux in the next few days. The amount and duration of the increase in CH_4 emission during the drainage periods are largely determined by the amount of CH_4 trapped in the soil before drainage (Miyata et al., 2000). Increases in CH_4 flux during drainage periods were reported in several previous studies (Alberto et al., 2014; Miyata et al., 2000; Neue and Sass, 1994; Yagi et al., 1997).

High organic input at the beginning of the growing season can result in a high CH_4 concentration in the soil, causing high CH_4 emissions through ebullition (Wassmann et al., 1996). Wang et al. (2012) reported that CH_4 emission from rice fields without straw incorporation was significantly lower than that with straw incorporation (11.93 and 29.03 gC m^{-2}, respectively). A few weeks after transplanting, rice plants become the main source of the carbon substrates by producing exudates in the rhizosphere during the process of photosynthesis (Bridgham et al., 2013; Hatala et al., 2012; Huang et al., 1997). Thus, the CH_4 flux is often related to the GEP (Hatala et al., 2012; Yun et al., 2013).

The eddy covariance (EC) method is currently the most commonly used approach to measure CH_4 fluxes. Two types of fast-response CH_4 analyzers are currently available for CH_4 flux measurements: closed-path and open-path. Compared with the closed-path analyzers, the new open-path CH_4 analyzer (LI-7700, LI-COR Biosciences, Inc., USA) has the advantages of low power consumption (8 W) and being lightweight (5.2 kg). An EC system equipped with this analyzer can be powered by a solar power system, allowing the EC system to be used at remote sites (Detto et al., 2011; McDermitt et al., 2011). The LI-7700 is also equipped with a self-cleaning system, which enables the EC system to operate continuously with less manual maintenance. On-site observation experiments carried out over the past few years have shown that the EC method with the open-path analyzer is suitable for measurements of CH_4 fluxes from rice fields (Alberto et al., 2014; Kim et al., 2016; Knox et al., 2016) as well as other underlying surfaces (Dengel et al., 2011; Fortuniak et al., 2017; Koebsch et al., 2015; Morin et al., 2014; Morin et al., 2017; Nadeau et al., 2013; Podgrajsek et al., 2014; Sun et al., 2015; Yu et al., 2017).

A semi-empirical multiplicative model was developed in previous studies to investigate the quantitative relationships between daily CH_4 fluxes and the potential driving factors (Friborg et al., 2000; Sachs et al., 2008; Wille et al., 2008). Good agreements were observed between the modeled and measured CH_4 fluxes. The model has the potential of being used to gap-fill the missing daily CH_4 fluxes and estimating daily and seasonal CH_4 fluxes when measurements of CH_4 are not available.

In this study, we conducted an observation experiment of CH_4 fluxes from irrigated rice fields using the EC method with the newly developed open-path CH_4 analyzer. The main objectives of this paper were (i) identifying the main driving factors of CH_4 fluxes; (ii) investigating the distinct flux-driver relations among different growth stages; and (iii) assessing the applicability of the semi-empirical multiplicative model to estimate daily and seasonal CH_4 fluxes over the rice fields. Specifically, the following questions were raised and investigated in this study: (i) What process caused the differences in the diurnal patterns of CH_4 flux, as well as the flux-driver relations, among different growth stages? (ii) What physical mechanism caused the change in the relative importance of the driving factors throughout the season? And (iii) which factors should be included in the model?

2. Data and methods

2.1. Experimental site

The experiment was conducted at a family farm in Yancheng, Jiangsu Province, China (33°12′21.93″N, 120°16′37.70″E). The farm is approximately 50 km west of the Yellow Sea coast with an elevation of 1 m above sea level. According to local meteorological records (1984–2013), the mean annual precipitation is 1060 ± 258 mm, and the mean air temperature (Ta) is 15.1 ± 0.61 °C. Fig. 1 showed the location of the study site, where the tower was erected (the red dot). The observational site was set up in the middle of a vast and horizontal farmland. The farmland was intensively cultivated. A wheat-rice crop rotation was practiced. There were only a few bungalows within the range of 300 m of the study site. The typical footprint coverage of the flux measurements were also presented in Fig. 1. The contours represented 30%, 50%, 70% and 90% of the flux footprints. The flux footprint coverage showed that over 90% of the flux originated within the farm.

The growing season (June 16–November 5, 2016) was divided into three growth stages: vegetative (June 16–August 5), reproductive (August 6–September 30) and ripening (October 1–November 5) based on the information provided by local agrotechnical station. To prepare for transplanting, the land was flooded with water and plowed using a rotary cultivator on June 11, immediately after the winter wheat was harvested. The rice plants were transplanted using a transplanting machine on June 16.

2.2. Instruments

A 10-m tower was erected for the eddy covariance and meteorological measurements. The EC system was mounted at a height of 6.3 m above the ground. The system was equipped with an integrated CO_2/H_2O open-path gas analyzer and three-dimensional sonic anemometer (IRGASON, Campbell Scientific, Inc., USA) and an open-path CH_4 analyzer (LI-7700, LI-COR Biosciences, Inc., USA). The IRGASON was leveled and pointed to the direction of 30° north by east. The turbulence data were collected using a data logger (CR3000, Campbell Scientific, Inc., USA) at a frequency of 10 Hz.

A humidity and temperature probe (HMP45C, Vaisala, Inc., Finland) was installed on the tower at a height of 3 m above ground to measure air temperature and humidity. Soil properties, including soil temperature and VWC, were measured at 0.2 m below the ground surface using a thermometer (PT100) and a water content reflectometer (CS616, Campbell Scientific, Inc., USA), respectively. Calibrations of these probes were carried out in the laboratory after the experiment was completed. A water level logger (HOBO U20, Onset Computer Corporation, USA) was employed to record the water table position in the rice fields at a distance approximately 5 m away from the tower. The logger was placed in a PVC tube that was buried vertically below the ground surface. The water table data were logged by the logger and were manually exported. Other meteorological measurements included

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