Journal of Sustainable Energy & Environment

14 (2023) 17-22

Estimate of methane (CH_4) and carbon dioxide (CO_2) emissions from a rain-fed rice field by eddy covariance technique

Alongkorn Kanyatrakul[1,2], Arnon Settsoongnern[1,2], Amnat Chidthaisong[1,2,*], Pariwate Varnakovida[3], Tiwa Pakoktom[4] and Monthira Yuttitham[5]

[1]*The Joint Graduate School of Energy and Environment, King Mongkut's University of Technology Thonburi, Bangkok 10140, Thailand*
[2]*Center of Excellence on Energy Technology and Environment, Ministry of Higher Education, Science, Research and Innovation, Bangkok, Thailand*
[3]*KMUTT Geospatial Engineering and Innovation Center (KGEO), Faculty of Science, King Mongkut's University of Technology Thonburi, Bangkok 10140, Thailand*
[4]*Department of Agronomy, Kasetsart University, Kamphaeng Saen, Nakhon Pathom 73140, Thailand*
[5]*Faculty of Environment and Resource Studies, Mahidol University, Nakhon Pathom, Thailand*
[*]*Coressponding author: amnat.chi@kmutt.ac.th*

Abstract: Climate change induced by emissions of greenhouse gases from sources associated with human activities has caused devastating impacts and is regarded as one of the most challenging threats to humankind. Quantifying the amounts of greenhouse gas emissions is an important first step towards mitigation. This study aimed to estimate the emissions of methane (CH_4) and carbon dioxide (CO_2) from one of the most important emission sources in Thailand, which is rice cultivation, by using the eddy covariance technique. It was found that the average CH_4 emission throughout the year was 0.06 mg CH_4/m^2. The annual emission of approximately 1.37 kg CH_4/ha/d was estimated. This was comparable to that provided by the IPCC for the baseline emission (i.e., 1.3 kg CH_4/ha/d). On the other hand, results reveal that the rice field acted as a net carbon sink, with an annual CO_2 uptake of -72.60 mg CO_2/m^2/y, equivalent to 8.41 tons C/ha/y. During the growing season, an amount of CO_2 uptake of -52.30 mg CO_2/m^2, equivalent to 5.89 tons C/ha/y was estimated. The calculated emissions during the fallow season were approximately 2.57 tons C/ha/y. We observed no significant relationship between CH_4 emissions and CO_2 fluxes.

Keywords: Eddy covariance, Methane flux (CH_4), Carbon dioxide flux (CO_2), Rain-fed rice field.

1. Introduction

At present, the impact of climate change is one of the most challenging threats to mankind [1]. Climate change is induced by global warming, which is in turn caused by greenhouse gas (GHG) emissions to the atmosphere such as methane (CH_4), carbon dioxide (CO_2), and others. Increasing the concentrations of these greenhouse gases has caused an increase in the greenhouse effect and global warming [2]. The Intergovernmental Panel on Climate Change (IPCC) reported that the world temperature has increased by around 1.1 °C since the start of the industrial revolution [2].

Mitigation of GHG emissions is necessary to slow down climate change and its impacts. CH_4 emissions from rice fields account for around 10% of global CH_4 emissions [2] and 55% of all greenhouse gas emissions from the agricultural sector in Thailand [3]. Approximately half of this CH_4 emission in Thailand comes from rice cultivation.

The emissions of CH_4 and CO_2 from rice fields are usually quantified using two methods, the chamber method and the eddy covariance method [4]. The eddy covariance method measures gas flux, or its change, by directly measuring the movement of gases [5], such as CH_4 between ecosystems and the atmosphere of the entire rice field. On the other hand, the chamber method is confined to a measurement of one square meter at most. Moreover, covering the rice plants with the chamber is also considered a disadvantage. This is because it can change the environmental conditions, which may affect emissions, plant growth, and physiological functions. Furthermore, emission interpolation from an area covered by the closed chamber to the field scale is usually associated with large uncertainty [6]. Eddy covariance measurements can cover an entire rice field. This provides a better representation with a non-disruptive approach to the rice ecosystem when compared to when a chamber is employed. However, the eddy covariance method also has some disadvantages when compared to the chamber method. High cost, intensive maintenance, the requirement of high technical skills, and the requirement of multidisciplinary knowledge are listed as such disadvantages.

As global efforts to mitigate greenhouse gas emissions intensify, it is increasingly important to quantify the emissions of CH_4 and CO_2 from rice fields and to understand the environmental factors that influence the emissions. Most of the eddy measurements of CH_4 and CO_2 have been done on irrigated rice. However, in rainfed rice, factors that control the emissions, especially rainfall and flooding water, are different and more dynamic than in irrigated rice. Employing a high-frequency measurement and covering the entire rice field by using eddy covariance will help us improve our understanding of emission dynamics and achieve an accurate estimate. Therefore, the purpose of this study is to quantify the emissions of greenhouse gases (CH_4 and CO_2) from rice fields and to understand the factors affecting their emissions. By improving our understanding of the CH_4 and CO_2 cycles in rice fields, we could develop more effective strategies for mitigating greenhouse gas emissions and promoting sustainable agricultural practices.

2. Methodology

2.1 Study site description

The study was carried out in 2016 in the rain-fed rice Ratchaburi Campus (KMUTT-Ratchaburi), Ratchaburi Province, western Thailand (latitude: 13°35'10.2"N, longitude: 99°30'42" E), as shown in Fig. 1. The soil texture was loamy sand, with a sand particle content of more than 70% and a small fraction of clay content. Rice was cultivated one crop cycle per year under rain-fed conditions with the rice cultivar Suphan-Buri 1, a non-photosensitive variety. In 2016, rice was planted in August, with a planting duration of approximately 120 days.

Figure 1. Location of the study site in Ratchaburi, Thailand (PRT site).

2.2 Measurement of gas exchanges by eddy covariance technique

The Eddy covariance method relies on measuring the fluctuations in wind speed, wind direction, and gas concentrations in the atmosphere. The wind speed and direction were measured by the CSAT3 anemometer (Campbell Scientific Inc, USA). The concentrations of CO_2 were measured by an open-path CO_2/H_2O detector (EC150, Campbell Scientific Inc., USA). The concentrations of CH_4 were measured by LI-7700 Open Path (LI-COR Biosciences Inc., Lincoln, USA). All of these measurements were done at a frequency of 10 Hz and at a height of 7 m. In addition, microclimate variables including air temperature (Ta), relative humidity (RH), and cumulative rainfall (Rainfall) were measured with a WXT520 weather transmitter. Soil sensors were installed to measure the soil temperature (Ts), and soil water content (SWC) at a depth of about 5 cm from the soil surface. All raw data were collected and sent to the data logger (CR1000, Campbell Scientific Inc., USA), which was configured to collect data every 30 minutes. The Eddy covariance method calculates greenhouse gas flux by measuring turbulent fluctuations in vertical wind velocities and the concentration of gases. CH_4 and CO_2 fluxes were determined using the following equation (1):

$$F = \rho w' c' \tag{1}$$

where F is the turbulent flux, ρ is the air density (g m^{-3}), w' is the mean instantaneous deviation of the vertical wind speed (m s^{-1}), and c' is the mean concentration of gases [7].

2.3 Data analysis and processing

In processing the eddy covariance data, Eddy-Pro software (version 7.0.9, LI-COR, Biosciences Inc., Lincoln, NE, USA) was used. The outputs from the Eddy-Pro software usually show some missing data (e.g., from malfunctions and damages of the gas analyzers and collecting software, etc.). From here, TOVi software (version 2.9, LI-COR Biosciences Inc, Lincoln, NE, USA) was used for quality control (QC) and missing gap filling. Several methods are available for this purpose, such as simple linear interpolation, the linear regression method, the marginal distribution sampling method (MDS), etc. To avoid introducing erroneous correlations between CH_4 flux or CO_2 flux and other factors in the data set, it has been recommended that meteorological factors be used as independent variables in the fitting process using linear regression and the MDS method [4]. This study employed meteorological factors for filling CH_4 and CO_2 data gaps, and a simple linear interpolation method was used. This was done to ensure that the data gaps were filled in a manner that did not introduce any unwanted correlations between the CH_4 and CO_2 fluxes and other factors.

3. Results and Discussion

3.1 The wind rose and the wind direction

As mentioned above, sufficient turbulent conditions are necessary for the eddy covariance method. At our study site, the wind rose analysis shows that turbulence occurs in all seasons. Our analysis indicates that the southwest (SW) wind was dominant (about 31%), followed by the west (24%), the south (23%), and the southeast (22%), respectively. From the collected data, the annual calm wind frequency was about 4% and the average wind speed was about 1.54 m/s. Footprint analysis confirmed that rice field dispersal had no notable impact on flux data due to the fact that most of the footprints were within the rice field area near the flux tower, as shown in Fig. 2.

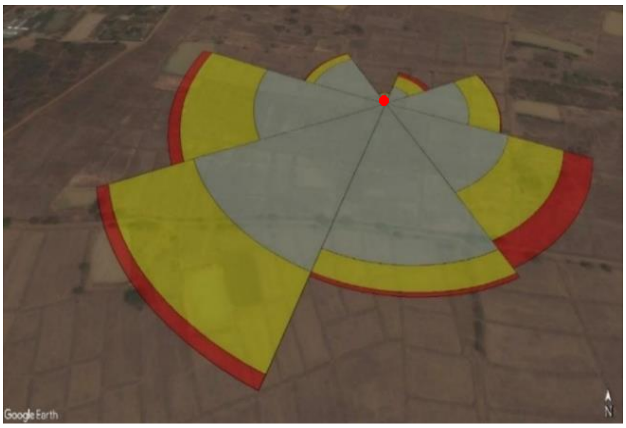

Figure 2. The Google Earth image of the study area, the eddy covariance tower is marked with a red dot in the center, and the wind rose was dominated in the South-West direction.

3.2 Micro-climate conditions

The mean patterns of air temperature (Tair), soil temperature (Tsoil), soil water content (SWC), and cumulative Rainfall (rainfall) at the site in 2016 are provided in Fig. 3.

The mean annual air temperature (T_{air}) at the PRT site was about 28.79°C in 2016. The maximum temperature of 35.23°C in April and a minimum of 22.92°C in December 2016 were detected (see Fig. 3). Soil temperature (T_{soil}) at a depth from the surface of about 5 cm had generally the same seasonal trend as found for air temperature (T_{air}). However, less fluctuation was found when compared to T_{air} due to the soil mass factor and water cover above the sensor. In 2016, the annual average T_{soil} temperature was

27.69°C. On the other hand, soil water content (SWC) was relatively low during days 1-120 (fallow season) and increased during the rainy season until the end of the year. It is noted that from 2015 until the beginning of 2016, it was an El Niño year (with low rainfall and high air temperatures). The annual cumulative rainfall in 2016 was 1133.70 mm. Most of the rainfall was found during the 153rd to 310th days of the year (June to November), as shown in Fig. 3.

3.3 Variations of CO_2 exchanges

The seasonal average of net ecosystem CO_2 exchange (NEE) varied between -1.12 and 0.57 mg $CO_2/m^2/d$ in 2016 (a positive value means net CO_2 emissions into the atmosphere, and the negative value refers to the net CO_2 adsorption by the ecosystem), as shown in (see Fig. 4). The patterns of seasonal CO_2 exchange were in line with the biological activity of the rice plant (e.g., rice growth). In 2016, one crop cycle was cultivated between the 8th of August and the 5th of December, during the growing season, the total CO_2 exchange was -52.30 mg CO_2/m^2/season. For the whole year, the total uptake was -72.60 mg $CO_2/m^2/y$.

Throughout the year, the Net Ecosystem Exchange (NEE) varied between -1.27 and 0.26 mg $CO_2/m^2/d$. On the other hand, Gross Primary Production (GPP) was between -1.19 and 0.44 mg $CO_2/m^2/d$, and Ecosystem Respiration (RE) was between 0.36 and 0.54 mg $CO_2/m^2/d$ (see Fig. 5). During the growing season, the total NEE was -52.30 mg CO_2/m^2/season.

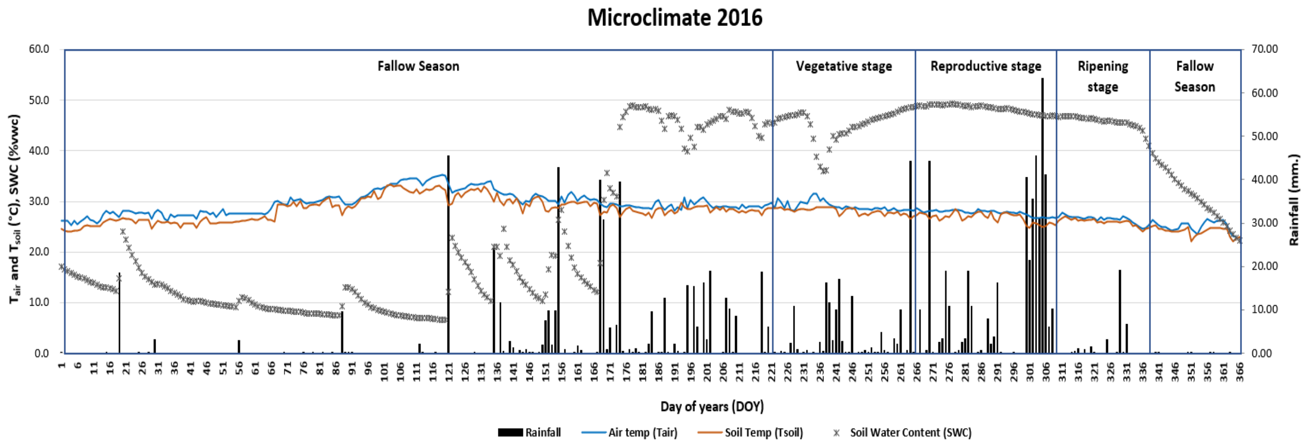

Figure 3. Daily micro-climate variables include average air temp (blue), soil temp (brown), soil water content (gray cross), and rainfall (black bar) in rice fields (2016).

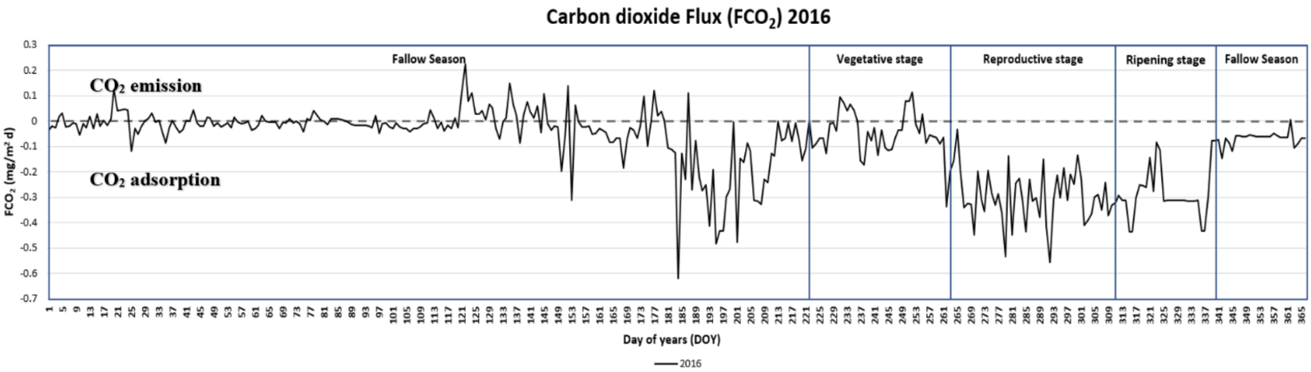

Figure 4. Daily net ecosystem CO_2 exchange in rice fields in 2016.

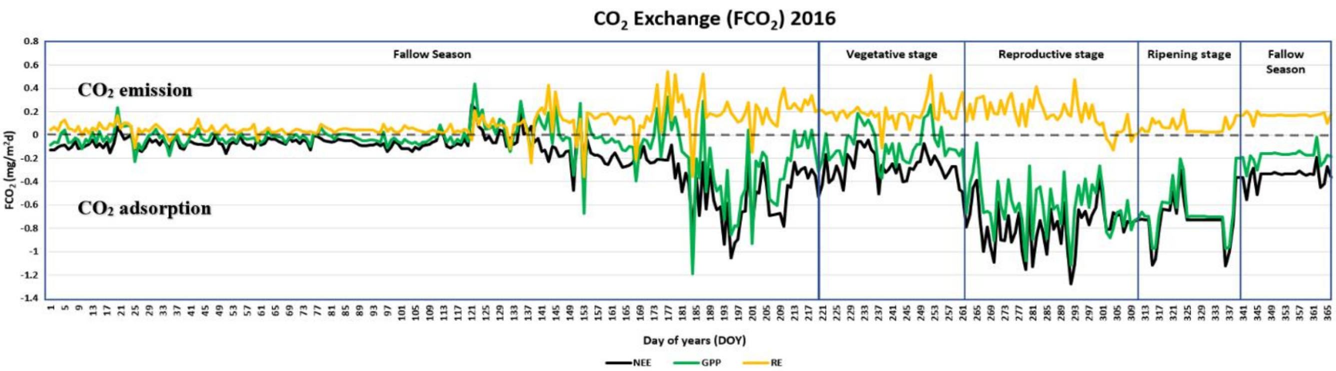

Figure 5. Daily Net ecosystem exchange (NEE, black line), Gross primary productivity (GPP, green line, and Ecosystem respiration (RE, yellow line) for the entire year. The cultivation period was from 221 DOY to 340 DOY.

NEE was highest during the reproductive stage at about -1.12 mg $CO_2/m^2/d$ (October 18, 2016). RE for the whole season was 44.72 mg $CO_2/m^2/d$, and highest during the reproductive stage at about 0.54 mg $CO_2/m^2/d$ (October 19, 2016). For the GPP, it was also highest during the reproductive stage and was -27.34 mg CO_2/m^2 for the entire growing season (see Table 1).

Table 1. The growing season CO_2 exchange, expressed in terms of NEE, RE, and GPP in 2016.

Year	Stage	NEE (mg CO_2/m^2)	RE (mg CO_2/m^2)	GPP (mg CO_2/m^2)
2016	Vegetative stage	-3.56 ±0.15	7.99 ±0.09	-4.43 ±0.22
	Reproductive stage	-30.48 ±0.21	8.68 ±0.13	-21.81 ±0.29
	Ripening stage	-18.57 ±0.21	2.13 ±0.06	-16.44 ±0.24
	Annual total	52.30 ±0.32	18.58 ±0.11	-33.70 ±0.38

Especially, when observed in the fallow season, CO_2 exchange was detected (even without rice cultivation), with a CO_2 uptake as high as -19.76 mg CO_2/m^2/season (see Fig. 5), averaging approximately 2.57 tons C/ha/season. Due to heavy rain in the fallow season. According to the rainfall and SWC data recorded in 2016, as shown in Fig. 3, this may induce weeds in the ecosystem and CO_2 exchange for plant growth. It was possibly the main cause of CO_2 uptake detected in the study area.

3.4 Seasonal variations of methane flux (FCH_4)

Unlike CO_2, only net CH_4 emission but not net uptake is commonly found in rice cultivation. The main greenhouse gas emitted from rice fields is methane (CH_4), which is caused by the decomposition of organic matter by microorganisms in the soil [8]. The amount of available organic matter and the activity of methanogens, along with environmental factors such as temperature and soil conditions, are all factors affecting the emissions of CH_4 [9].

The results of CH_4 emissions are provided in Fig. 6. It can be seen that the CH_4 emissions can be detected throughout the whole year, with an average rate of 0.06 $mgCH_4/m^2$. During the growing season, the emission rate was about 0.11 $mgCH_4/m^2$. According to the IPCC, the rice field CH_4 emissions baseline is 1.3 kg CH_4/ha/day. Based on the measurement results in this study, the CH_4 emissions calculated by the eddy covariance method for the whole year were approximately 1.37 kg CH_4/ha/day. This is therefore quite comparable to that provided by the IPCC. The measurement of the eddy covariance method during the fallow season can detect CH_4 emissions at an average rate of 0.46 kg CH_4/ha/day.

The emissions of CH_4 during the fallow season without the existence of rice plants may be explained by the occasional rain events, as shown in Fig. 3. For example, during a week after a rain event, around DOY 87, increased emissions as well as soil moisture were observed. Several rain events occurred before the growing season that were followed by increased CH_4 emissions.

The CH_4 flux peaked on 30th, October 2016 (DOY 304), and the upward trend was observed during the start of the rice growing season (see Fig. 7). The daily CH_4 flux reaches a peak of 0.0015 $mgCH_4/m^2/d$ at the end of the reproductive stage. Generally, the emissions of CH_4 during the vegetative stage and the ripening stage were lower than in the reproductive stage. It was noted that the period with the highest emission of CH_4 was at the end of the reproductive stage of rice fields. At that time, there was a very high rainfall. The presence of a large amount of water in rice fields could be the major factor causing the increased emission of CH_4, as reported previously [4].

It is well known that rice fields are one of the major sources of CH_4 emissions [2]. This is because flooded soil creates an anaerobic environment that favors CH_4 producing microbes. However, rice fields can also act as carbon sinks because they uptake atmospheric CO_2 through photosynthesis and can accumulate organic matter in the soil [10].

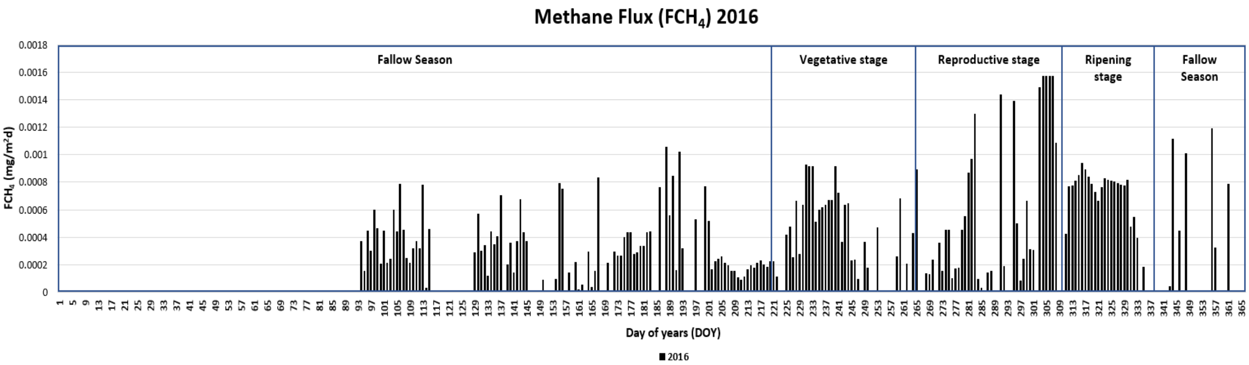

Figure 6. Variations of CH_4 flux throughout the annual on a diurnal in 2016.

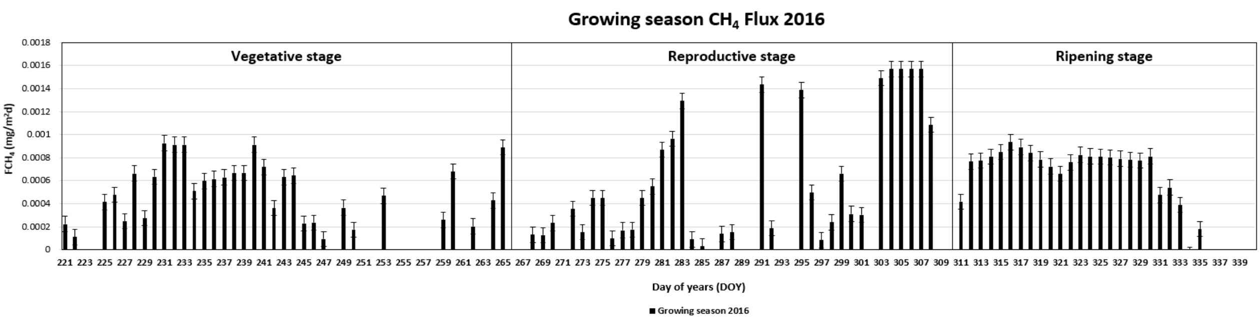

Figure 7. The daily CH_4 flux during the growing season of rice growth in 2016.

Comparing the daily dynamics of CO_2 and CH_4 fluxes, it was found that the pattern of fluxes was different. Fig. 8 shows that CO_2 uptake peaked around 12 p.m. because in the daytime, rice plants are able to absorb CO_2 through photosynthesis, while during the nighttime, CO_2 is released through respiration. On the other hand, CH_4 releases peaked around 2 p.m.

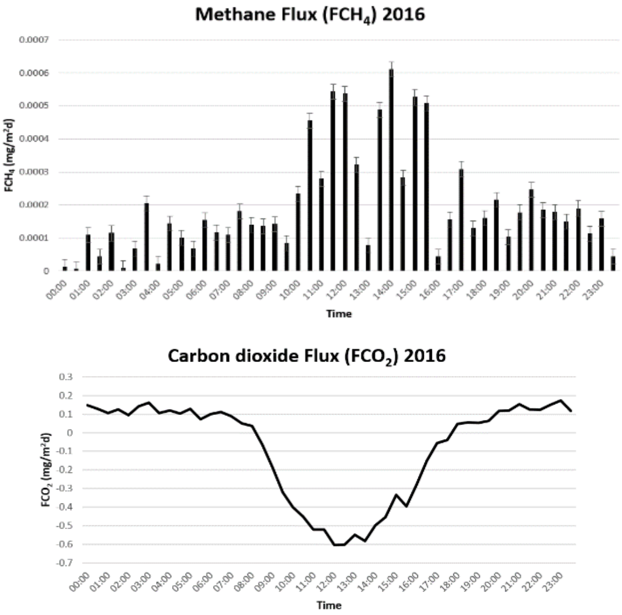

Figure 8. Comparison of CH_4 and CO_2 release periods in rice fields in 2016.

We found, however, no significant relationship between CH_4 and CO_2 fluxes (see Fig. 9). In fact, the correlation between CH_4 and CO_2 emissions in rice fields is complex and depends on factors such as air temperature, soil temperature, soil moisture, nutrient availability, and management practices. In general, when rice fields are flooded, methane emissions increase while CO_2 emissions decrease. This is because flooded soil creates an anaerobic environment that is favorable to the growth of CH_4 producing microorganisms. At the same time, it inhibits the activity of CO_2 consuming microorganisms [11]. On the other hand, when rice fields are drained, CO_2 emissions may increase due to the oxidation of soil organic matter, while methane emissions may be reduced due to the absence of anaerobic conditions [12].

4. Conclusions

This study presents the measurement results of CH_4 and CO_2 emissions from the rainfed rice field for the entire year 2016 by using the eddy covariance method. It was found that the majority of CH_4 was released during the rice-growing period. However, it was also found that CH_4 was also released throughout the year. Measured CH_4 emissions (1.37 kg CH_4/ha/d) were calculated for the whole year. This is comparable to baseline emissions by the IPCC (1.30 kg CH_4/ha/d). During the fallow period, an average emission rate of 0.46 kg CH_4/ha/day was estimated. On the other hand, it was found that this rainfed rice field acted as a net carbon sink, with an annual NEE of -72.60 mg CO_2/m^2. The highest CO_2 emissions were found in the reproductive stage. The majority of uptake was found during the rice growing season, with a NEE of -52.30 mg CO_2/m^2/season, equivalent to 5.89 tons C/ha/season. During the fallow season, the CO_2 uptake was detected at an average rate of -19.76 mg CO_2/m^2 or approximately 2.57 tons C/ha was detected. No relationship between CH_4 and CO_2 fluxes were found during both rice growing and fallow seasons.

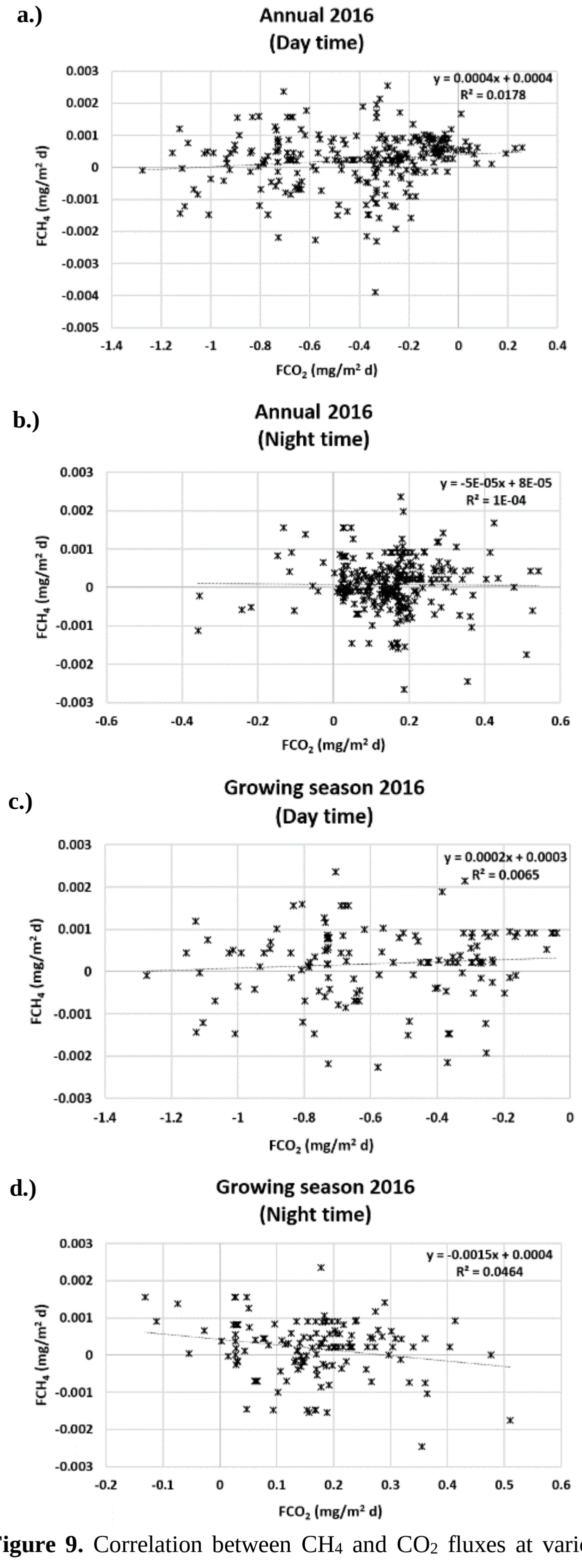

Figure 9. Correlation between CH_4 and CO_2 fluxes at various growth stages in rice fields; a.) Entire year (Day time), b.) Entire year (Night time), c.) Growing season (Day time), and d.) Growing season (Night time) in 2016.

Acknowledgments

This study was partly supported by the National Research Council of Thailand (NRCT) through the International Research Network (IRN) under the project of climate change mitigation by sustainable agriculture soil management in Thailand under climate change and tropical soil carbon research network, the

Joint Graduate School of Energy and Environment (JGSEE) at King Mongkut's University of Technology Thonburi (KMUTT), the Center of Excellence on Energy Technology and Environment (CEE), PERDO, Ministry of Higher Education, Science, Research and Innovation, and the Fundamental Fund and by Thailand Science Research and Innovation (TSRI) Basic Research Fund: Fiscal year 2022 under project number FRB650048/0164.

References

[1] Chidthaisong, A., Cha-un, N., Rossopa, B., Buddaboon, C., Kunuthai, C., Sriphirom, P., Towprayoon, S., Tokida, T., Padre, A. and Minamikawa, K. 2017. Evaluating the effects of alternate wetting and drying (AWD) on methane and nitrous oxide emissions from a paddy field in Thailand, *Soil Science and Plant Nutrition*, 64, 1-8.

[2] IPCC. 2007. *Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*. IPCC National Greenhouse Gas Inventories Program Technical Support Unit.

[3] Yagi, K., Sriphirom, P., Cha-un, N., Fusuwankaya, K., Chidthaisong, A., Damen, B. and Towprayoon, S. 2019. Potential and promisingness of technical options for mitigating greenhouse gas emissions from rice cultivation in Southeast Asian countries, *Soil Science and Plant Nutrition*, 66, 37-49, DOI: 10.1080/00380768.2019.1683890.

[4] Ge, H.-X., Zhang, H.-S., Zhang, H., Cai, X.-H., Song, Y. and Kang, L. 2018. The characteristics of methane flux from an irrigated rice farm in East China measured using the eddy covariance method, *Agricultural and Forest Meteorology*, 249, 228-238.

[5] Foken, T., Aubinet, M. and Leuning, R. 2012. The Eddy Covariance Method. In: Aubinet, M., Vesala, T. and Papale, D. (eds.): *Eddy Covariance: A Practical Guide to Measurement and Data Analysis* (pp. 1-19). Springer Netherlands.

[6] Chaichana, N., Bellingrath-Kimura, S.D., Komiya, S., Fujii, Y., Noborio, K., Dietrich, O. and Pakoktom, T. 2018. Comparison of closed chamber and Eddy covariance methods to improve the understanding of methane fluxes from rice paddy fields in Japan, *Atmosphere*, 9, 356, https://doi.org/10.3390/atmos9090356.

[7] Baldocchi, D. 2014. Measuring fluxes of trace gases and energy between ecosystems and the atmosphere - the state and future of the Eddy covariance method, *Global Change Biology*, 20(12), 3600-3609.

[8] Kumar, A., Bhatia, A., Sehgal, V.K., Tomer, R., Jain, N. and Pathak, H. 2001. Net ecosystem exchange of carbon dioxide in rice-spring wheat system of Northwestern Indo-Gangetic Plains, *Land*, 10, 701, Available online: https://doi.org/10.3390/land10070701.

[9] Minamikawa, K., Sakai, N. and Yagi, K. 2006. Methane emission from paddy fields and its mitigation options on a field scale, *Microbes and Environments*, 21, 135-147.

[10] Conrad, R. 2020. Methane production in soil environments-anaerobic biogeochemistry and microbial life between flooding and desiccation, *Microorganisms*, 8(6), 881, doi:10.3390/microorganisms8060881.

[11] Neue, H.U. 1993. Methane emission from rice fields: Wetland rice fields may make a major contribution to global warming, *BioScience*, 43(7), 466-474, Available online: https://doi.org/10.2307/1311906.

[12] Conrad, R. 2016. Methane emission from flooded soils - from microorganisms to the atmosphere, *Geophysical Research Abstracts*, Vol. 18, EGU2016-3230.