Research Article

Contribution of Ebullition to Methane and Carbon Dioxide Emission from Water between Plant Rows in a Tropical Rice Paddy Field

Shujiro Komiya,¹ Kosuke Noborio,² Kentaro Katano,³ Tiwa Pakoktom,⁴ Meechai Siangliw,⁵ and Theerayut Toojinda⁵

¹Graduate School of Agriculture, Meiji University, Kawasaki, Kanagawa 214-8571, Japan

²School of Agriculture, Meiji University, Kawasaki, Kanagawa 214-8571, Japan

³Formerly Graduate School of Agriculture, Meiji University, Kawasaki, Kanagawa 214-8571, Japan

⁴Department of Agronomy, Kasetsart University, Kamphaeng Saen, Nakhon Pathom 73140, Thailand

⁵Rice Gene Discovery Unit, National Center for Genetic Engineering and Biotechnology (BIOTEC),

National Science and Technology Development Agency, Kasetsart University, Kamphaeng Saen, Nakhon Pathom 73140, Thailand

Correspondence should be addressed to Kosuke Noborio; noboriok@meiji.ac.jp

Received 12 October 2015; Revised 9 December 2015; Accepted 9 December 2015

Academic Editor: Weixin Ding

Copyright © 2015 Shujiro Komiya et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Although bubble ebullition through water in rice paddy fields dominates direct methane (CH_4) emissions from paddy soil to the atmosphere in tropical regions, the temporal changes and regulating factors of this ebullition are poorly understood. Bubbles in a submerged paddy soil also contain high concentrations of carbon dioxide (CO_2), implying that CO_2 ebullition may occur in addition to CH_4 ebullition. We investigated the dynamics of CH_4 and CO_2 ebullition in tropical rice paddy fields using an automated closed chamber installed between rice plants. Abrupt increases in CH_4 concentrations occurred by bubble ebullition. The CO_2 concentration in the chamber air suddenly increased at the same time, which indicated that CO_2 ebullition was also occurring. The CH_4 and CO_2 emissions by bubble ebullition were correlated with falling atmospheric pressure and increasing soil surface temperature. The relative contribution of CH_4 and CO_2 ebullitions to the daily total emissions was 95–97% and 13–35%, respectively.

1. Introduction

Understanding the dynamics of methane (CH_4) and carbon dioxide (CO_2) fluxes in rice paddy fields is crucial for improving the accuracy of estimating CH_4 and CO_2 emissions from global rice paddy fields. In particular, flooded rice paddies are considered to be a major source of anthropogenic CH_4 . Methane emissions from rice paddies in tropical Asian countries account for 90% of global annual CH_4 emissions from rice paddies [1, 2].

Methane produced in an anaerobic-flooded paddy soil is mainly transported to the atmosphere through the aerenchyma of rice plants [3–5]. Such emissions through the aerenchyma are estimated to account for 48–85% of net CH_4 emissions throughout the rice-cropping season [5]. In

addition, CO_2 exchange in paddy fields mainly results from photosynthesis and respiration of rice plants, as well as soil microbial respiration.

Also, some of the CH_4 and CO_2 produced in rice field soil is directly emitted to the atmosphere through paddy water. In one study, when rice straw was applied to a paddy field, CH_4 emissions via bubble ebullition from the soil accounted for 35–62% of total CH_4 emissions [6]. However, research on the direct CH_4 and CO_2 exchanges between paddy soil and the atmosphere, via paddy water, is limited and so further studies are required on these emissions, as has been noted by other researchers [7, 8].

Methane in paddy soil is transported to the atmosphere through paddy water by two pathways: (1) diffusion between soil and atmosphere and (2) bubble ebullition [9]. Methane

emission by bubble ebullition is considered to be greater than that by diffusion from paddy water [6]. The bubbles usually contain a high concentration of CH_4 ranging between 1 and 82% (v/v) [10, 11] and comprise most of the total CH_4 pool in flooded paddy soil [12]. Bubble production and ebullition are enhanced by applied organic materials during the initial plant growth period [6, 13, 14] and by organic substances originating from rice roots during later growth stages [6, 12, 14]. Although the variation of CH_4 bubble ebullition during the cultivation period has been studied previously, the factors controlling the diurnal changes in CH_4 ebullition remain unclear [15].

Methane ebullition from submerged peatlands, which are similar to flooded paddy soil in that they contain many bubbles, is controlled by atmospheric pressure, soil temperature, and water table level [16–19]. Falling atmospheric pressure has been shown to be the most important contributor to CH_4 bubbling in peatlands [18, 19]. A study in rice paddy fields in Thailand also suggested that CH_4 ebullitions occurred when atmospheric pressure dropped, but further research is needed to clarify this [20].

In contrast, CO_2 exchange through paddy water is the result of photosynthesis of aquatic plants and respiration of both the plants and the soil microorganisms [21]. Emission due to soil respiration is suppressed by paddy water during flood irrigation [21, 22], but the CO_2 concentration in soil bubbles is between 2.2 and 13.0% (v/v) [11, 23], which suggests that bubble ebullition will release both CH_4 and CO_2 from paddy soil into the atmosphere.

Therefore, in this paper, we examined the dynamics of both CH_4 and CO_2 ebullition in tropical rice paddy fields in Thailand using an automatically closing chamber method.

2. Materials and Methods

Gas field measurements were conducted on September 20th and 21st, 2014, in a rice field of Kasetsart University, Kamphaeng Saen campus (14°00'33"N, 99°59'03"E) located in Nakhon Pathom Province, Thailand. The soil had a clay texture (65.7% clay, 23.30% silt, and 11.0% sand) with a dry bulk density of 1.69 g m^{-3} . The soil was sampled on September 17 and had a pH of 6.0 (1:1 for soil: water), 4.32% organic matter, 1.81% total carbon, and 1.85% total nitrogen. Seedlings of the rice variety "Homcholasit" were transplanted on June 30 at $18 \times 30 \text{ cm}$ spacing with 4–5 seedlings per hill, after the soil had been plowed on June 17 and 26 when weeds and rice plants that had grown during the fallow period were plowed into the soil. The rice plants headed on September 22 and were harvested on October 28. The paddy field was continuously flooded from June 17 until harvest, with flooding water depth maintained at 2–20 cm. During the gas measurement period, the water depth slowly decreased from 5.5 to 4 cm because there was no precipitation or irrigation.

The CH_4 and CO_2 fluxes were measured using the automatic closed chamber method. A customized-bottomless polycarbonate chamber ($50 \times 20 \text{ cm}$ at the base and 40 cm height, Green Blue Corp., Tokyo, Japan) was placed between the rows of rice plants on August 8; the base part was inserted 4.5 cm deep into the paddy soil (Figure 1). The lid of

the chamber was automatically closed for 10 min every 1 h by a pneumatic piston, with the lid kept open for the rest of the time. A small electric fan was installed on the upper sidewall inside the chamber and was kept running throughout the experiment to uniformly mix the air within the chamber. The chamber headspace air was circulated at 500 mL min^{-1} (using a diaphragm pump; TD-4X2N, Brailsford Co., Rye, NY, USA) between the chamber and a 250 mL buffer tank placed in a shed located approximately 4 m away from the chamber to minimize the high frequency noise. A loop line was installed between the buffer tank and a wavelength-scanned cavity ring-down spectroscopy CH_4/CO_2 analyzer (G2201-i, Picarro Inc., Santa Clara, CA, USA). Air in the buffer tank was withdrawn to the analyzer at a flow rate of $\sim 25 \text{ mL min}^{-1}$ using another diaphragm pump (UN84.4 ANDC-B, KNF Neuberger Inc., NJ, USA) and then returned to the loop line. Concentrations of CH_4 and CO_2 were analyzed at approximately 3.6 s intervals by the gas analyzer. The sampled air was dried before entering the gas analyzer using a reflux method with a membrane dryer (SWG-A01-06, Asahi Glass Engineering Co., Chiba, Japan) so that the water vapor concentration in the air was kept $< 0.1\%$. Based on the internal volumes of the buffer tank and connecting tube and the flow rate the air inside the chamber was calculated to first reach the gas analyzer 2 min after closing the chamber lid. The measurements of CH_4 and CO_2 concentrations in the chamber air stopped when the chamber lid opened meaning that a measurement cycle of gas flux measurements lasted 8 min every hour.

Temporal changes in CH_4 concentration in the chamber during a measurement cycle were categorized into either a sudden increase (Figures 2(a), 2(c), and 2(e)) or a slow-constant increase (Figures 2(c) and 2(e)). Emission by bubble ebullition events was defined as a sudden increase in concentration ($\Delta C/\Delta t$) of $\geq 0.29 \text{ ppm min}^{-1}$, whereas emission by diffusion was defined as a slow-constant increase ($\Delta C/\Delta t$) of $< 0.29 \text{ ppm min}^{-1}$.

Changes in CO_2 concentration in the chamber showed either an episodic increase accompanied by CH_4 ebullition events (Figures 2(b) and 2(f)), a steady increase (Figure 2(d)), or a decrease by plant uptake (Figure 2(f)). CO_2 emission by bubble ebullition was defined as episodic CO_2 concentration increases accompanied by CH_4 ebullition, whereas emission by diffusion was defined as a constant CO_2 increase. The CO_2 uptake by photosynthetically active aquatic plants was defined by a decrease in CO_2 concentration (Figure 2(f)) observed during the daytime on both days.

Since CH_4 and CO_2 concentrations in the chamber often changed episodically with time due to bubble ebullition events (Figures 2(a), 2(b), 2(c), 2(e), and 2(f)), CH_4 and CO_2 fluxes were calculated for each single flux event and then summed proportionately for the time of each event to give a total flux for each 8 min measurement period. The start of each flux event was determined as the intersection between tangent lines at the inflection point of the time series of CH_4 or CO_2 concentrations (Figure 2). The end of each event was the time just before the start of the next flux event or the end of the 8 min measurement period (Figure 2). The gas flux

FIGURE 1: Schematic diagram of an automatic closed chamber placed between the rows of rice plants.

F ($\text{mg m}^{-2} \text{h}^{-1}$) was calculated using temporal changes in gas concentrations as [24]

$$F = \frac{V}{A} \left[\frac{dC(t)}{dt} \right]_{t=0}, \quad (1)$$

where V is the headspace volume within the chamber (m^3), A is the water-surface area covered by the chamber (m^2), t is elapsed time (h), and $C(t)$ is temporal changes in gas concentration (mg m^{-3}) expressed as

$$C(t) = C_{\max} - (C_{\max} - C_0) \exp(-kt), \quad (2)$$

where $C_{\max}$ is the maximum gas concentration (mg m^{-3}), C_0 is the initial gas concentration (mg m^{-3}), and k is a rate constant. The values of $C_{\max}$, C_0 , and k were iteratively obtained using the data of observed gas concentration versus time. Substituting (2) at $t = 0$ into (1) means that the gas flux F ($\text{mg m}^{-2} \text{h}^{-1}$) can be calculated as [24]

$$F = \frac{V}{A} k (C_{\max} - C_0). \quad (3)$$

Atmospheric pressure and air temperature were measured with a barometer (MPXAZ6115A and MPXV7007DP, Freescale Inc., TX, USA) and a thermometer (HMP45A, Vaisala Inc., Helsinki, Finland), respectively. Water depth in the rice field was measured with a water level sensor (eTape Continuous Fluid Level Sensor, Milone Technologies Inc., NJ, USA). Soil surface temperature was measured with a type T thermocouple.

Bubbles in soil were collected directly with a syringe by disturbing the topsoil at 3 p.m. local time on September 20. The CH_4 and CO_2 concentrations in the bubbles were measured using the CH_4/CO_2 gas analyzer after the sampled air was diluted 101 times with high-purity nitrogen gas.

3. Results and Discussion

3.1. CH_4 Emission. Episodic and rapid increases in CH_4 concentration were identified in 21 out of the 46 measurements (Figures 2(a), 2(c), and 2(e)). These sudden increases in

CH_4 concentration are likely to be from bubbles released from the soil to the atmosphere because the CH_4 concentration in topsoil bubbles was as high as 63.73% v/v. In the other 25 measurements, the CH_4 concentration in the chamber air increased gradually with time ($\Delta\text{CH}_4/\Delta t < 0.29 \text{ ppm min}^{-1}$) during the closure period, indicating that CH_4 was released from the water surface to the atmosphere by molecular diffusion. The CH_4 fluxes at the water surface fluctuated between 0.7 and $218.7 \text{ mg m}^{-2} \text{h}^{-1}$ on the observation days, which are similar to previously reported values of -0.6 – $192.0 \text{ mg m}^{-2} \text{h}^{-1}$ [25].

The large CH_4 emissions via bubble ebullition mainly occurred between 10:00 a.m. and 5:00 p.m. local time (Figure 3(a)). During this period, atmospheric pressure markedly decreased and reached a minimum value (Figure 3(b)). A night-time CH_4 ebullition event also occurred at 2:50 a.m. local time on September 21 (Figures 2(c), 3(a), and 3(b)), once again when air pressure decreased. There was a significant negative linear correlation between atmospheric pressure and $\log_{10}$ - CH_4 emission by bubble ebullition (Figure 4; $r = -0.77$, $p < 0.001$). These results suggesting that decreases in atmospheric pressure triggered the CH_4 ebullitions in the tropical rice paddy field are supported by the findings of Tokida et al. [18, 19] who reported that decreases in atmospheric pressure triggered CH_4 ebullitions in peatlands.

In peatlands, air pressure reduction expands bubble volume and thereby enhances bubble buoyancy which causes the bubbles to rise to the water surface [16]. Reduced air pressure also increases the CH_4 concentration of gas bubbles by degassing dissolved CH_4 in soil solution [16, 26, 27]. These factors probably caused the higher CH_4 emissions via ebullition that were found in the current study. Moreover, the higher CH_4 ebullition emissions in the daytime, compared with nighttime, are probably due to larger decreases in daytime atmospheric pressure which would increase the volume of the bubbles and the CH_4 concentration.

Rising soil temperature also increases the buoyancy and CH_4 concentration of bubbles as barometric pressure decreases [17, 27]. In the current study, soil surface temperature increased from around 6:30 a.m. and reached

FIGURE 2: Examples of the changes in CH_4 , CO_2 concentrations (7-point running average) in the closed chamber measured at 2:50 p.m. on September 20 ((a), (b)), at 2:50 a.m. on September 21 ((c), (d)), and at 4:50 p.m. on September 21 ((e), (f)). The solid line denotes the best fitting line for each emission/uptake. The white circle with black edge indicates the event starting point. The dashed lines denote the tangent lines at the local maximum or minimum points for CH_4 , CO_2 emission/uptake rates, before respective increase or decrease events.

TABLE 1: Cumulative CH₄ emissions and relative contribution of bubble ebullition and diffusion processes to total emissions.

Date	CH ₄ ebullition (mg m ⁻² d ⁻¹)	Via CH ₄ ebullition (%)	CH ₄ diffusion (mg m ⁻² d ⁻¹)	Via CH ₄ diffusion (%)	Total CH ₄ emission (mg m ⁻² d ⁻¹)
Sep. 20	617.4	95.3	30.3	4.7	647.7
Sep. 21	546.2	96.3	20.9	3.7	567.1

FIGURE 3: Temporal changes on September 20 and 21 in CH₄ and CO₂ fluxes measured with the automatic closed chamber method (a) and atmospheric pressure and soil surface temperature (b).

a maximum value at 3:00–3:30 p.m. on each day (Figure 3(b)). This period approximately corresponded to that when CH₄ ebullition events frequently occurred. The positive and significant correlation between soil surface temperature and log₁₀-CH₄ emission via bubble ebullition ($r = 0.66$; $p < 0.005$; Figure 4(b)) indicates that the increase in soil surface temperature contributed to CH₄ ebullitions in the daytime. Ebullition events occurred at 8:50 a.m. on both days and at 9:50 a.m. on September 21, even though atmospheric pressure did not fall between 6:30 a.m. and 10:00 a.m. on either day. These ebullitions indicate that the rising soil temperature principally triggered the release of bubbles at those times. Rising soil temperature also has a role in enhancing methanogenic activities, leading to increases in CH₄ production in soil [28]. Therefore such increased biological activities might have also increased the CH₄ concentration in the bubbles.

CH₄ emission via bubble ebullition (546–617 mg m⁻² d⁻¹) contributed 95–96% of total daily CH₄ emission (567–647 mg m⁻² d⁻¹) through flooded water (Table 1). These CH₄ ebullitions mainly occurred in the daytime and were associated with falling atmospheric pressure and increasing soil temperature, as discussed above (Figures 3(a) and 3(b)). In contrast, CH₄ emission by diffusion (21–30 mg m⁻² d⁻¹) accounted for only 3.7–4.7% of total daily CH₄ emission from flooded water (Table 1). The CH₄ emissions by diffusion were mostly observed at nighttime when soil temperature decreased (Figures 3(a) and 3(b)). Therefore, these results clearly show that CH₄ emission in rice paddy fields is predominant by daytime ebullition from flooded water with much lower CH₄ emissions at nighttime by diffusion.

3.2. CO₂ Emission. Episodic increases in CO₂ concentration were found in 14 of the 21 measurements when CH₄ ebullition events occurred. During these 14 chamber closure periods, the CO₂ concentration in the chamber air increased abruptly (Figures 2(b) and 2(f)) at about the same time as CH₄ concentration increased (Figures 2(a) and 2(e)). These similar patterns indicate that CO₂ was released to the atmosphere in the bubbles along with the CH₄. In the other 7 measurements, there was a steady increase in CO₂ concentration but no episodic increase, as shown in Figure 2(d), while CH₄ concentration abruptly increased (Figure 2(c)). This suggests these bubbles did not contain much CO₂.

CO₂ uptake via the photosynthetic activities of the aquatic plants was also observed in these measurements. In the other 25 measurements, there was a transfer of CO₂ from flooded water to the atmosphere by diffusion, likely due to the gradient in CO₂ concentration at the interface between the flooded water and the atmosphere and also due to respiration of the aquatic plants [21]. The values of CO₂ fluxes ranged between -120.4 and 196.2 mg m⁻² h⁻¹ which are within the previously reported range of -285.1 to 459.4 mg m⁻² h⁻¹ [29].

On September 20, most of the CO₂ fluxes were outgoing emissions due to bubble ebullitions. The highest CO₂ emission (196.2 mg m⁻² h⁻¹) occurred at 2:50 p.m. (Figures 2(d) and 3(a)), coinciding with a high CO₂ concentration in the bubbles of up to 11.74% (v/v). However, at 1:50 p.m., there was a negative (incoming) CO₂ flux, even though there was a CO₂ ebullition event. This overall negative flux must have been due to the fact that CO₂ uptake by photosynthesis of the aquatic plants exceeded emissions by bubble ebullition, as shown in Figure 2(f) for CO₂ transfer.

FIGURE 4: Relationship between CH_4 emission by bubble ebullition and change of atmospheric pressure (a) or soil surface temperature (b). Relationship between CO_2 emission by bubble ebullition and change of atmospheric pressure (c) or soil surface temperature (d). The change in atmospheric pressure was determined as the difference between the local maximum or minimum value and the value closest to the time when the CH_4 or CO_2 ebullition occurred.

During the daytime on September 21, the CO_2 fluxes mainly showed negative values even though CO_2 ebullition events were observed. Therefore, this indicates that CO_2 assimilation by the aquatic plants dominated CO_2 fluxes on that day.

The $\log_{10}$ - CO_2 emissions by bubble ebullitions, omitting measurements with evidence of absorption by plant photosynthesis, were significantly correlated to changes in atmospheric pressure ($r = -0.72$; $p < 0.05$; Figure 4(c)) and soil surface temperature ($r = 0.72$; $p < 0.05$; Figure 4(d)). This indicates that these two environmental factors control

CO_2 ebullition in addition to CH_4 ebullition. As previously discussed, these two triggered expanding bubble volume and degassing of gas dissolved in soil solution [16, 17]. In addition, the soil surface temperature was between 27 and 40°C during the measuring period which was optimal for respiratory soil microbes in the submerged paddy soil [28]. Therefore, all these factors probably enhanced CO_2 bubble ebullitions.

CO_2 emission by bubble ebullition, accounted for only 13–35% of total CO_2 emissions, compared with 65–87% from CO_2 diffusion (Table 2), indicating that CO_2 ebullition did not dominate CO_2 emissions from flooded water unlike CH_4

TABLE 2: Cumulative CO₂ emissions and relative contributions of bubble ebullition and diffusion processes to total emissions.

Date	CO ₂ ebullition (mg m ⁻² d ⁻¹)	Via CO ₂ ebullition (%)	CO ₂ diffusion (mg m ⁻² d ⁻¹)	Via CO ₂ diffusion (%)	Total CO ₂ emission (mg m ⁻² d ⁻¹)
Sep. 20	648.2	35.0	1203.8	65.0	1852.0
Sep. 21	159.7	13.3	1040.4	86.7	1200.1

ebullition. This is probably due to the fact that CO₂ uptake by aquatic plants would have exceeded CO₂ emission by bubble ebullition. Moreover, the very low concentration of CO₂ in the bubbles also contributed to lower CO₂ emission by bubble ebullition. The CO₂ emissions by diffusion mostly occurred at nighttime just like for CH₄. The nighttime CO₂ emissions by diffusion were mostly attributed to the gradient in CO₂ concentrations between the atmosphere and the flooded water and also to CO₂ respiration by small aquatic plants [21].

4. Conclusions

Our study found that daytime CH₄ ebullition events in tropical rice paddy fields occurred due to falling atmospheric pressure and increasing soil surface temperature. At nighttime, the drop in atmospheric pressure predominately triggered the CH₄ ebullition because soil temperature was low compared with that in the daytime. The fact that CH₄ and CO₂ concentrations in the chamber air increased abruptly when bubbles were released suggests that bubble ebullition events caused not only CH₄ emission but also CO₂ emission. The CO₂ ebullition events were also controlled by decreases in air pressure and increases in soil temperature. Therefore, diurnal changes in atmospheric pressure and soil temperature play major roles in regulating CH₄ and CO₂ ebullitions in tropical rice paddy fields.

We also found that CH₄ emission was predominant due to daytime ebullition, whereas only a small proportion of CO₂ emissions was due to daytime ebullition. The low CO₂ ebullition throughout the day was due to CO₂ photosynthesis and respiration by aquatic plants, meaning that CO₂ emission was mainly by diffusion between flooded water and the atmosphere.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

This research was partly supported by Grant-in-Aid for Scientific Research (A) (25252044, PI: K. Noborio), a JSPS Fellowship (DC1, 12J10924, for S. Komiya) by the Japan Society for the Promotion of Science, and a Program for Establishing Strategic Research Foundations in Private Universities (S0901028, PI: K. Noborio) by MEXT of Japan. The authors are grateful to Dr. Jonaliza Siangliw (BIOTEC) and Ms. Rungthip Kohkhoo for their support at our experimental

field, to Dr. Fumiyoshi Kondo (National Institute for Environmental Studies), Dr. Takeshi Tokida, and Dr. Seiichiro Yone-mura (National Institute for Agro-Environmental Sciences) for their valuable comments, to Dr. Iain McTaggart (Meiji University) for reviewing a draft, to Dr. Masaru Mizoguchi (University of Tokyo) for making the water level sensor, to Mr. Ryoji Taniyama (Takumi Technical Laboratory Inc., Japan) for assisting with data analysis, to Mr. Ryo Higuchi for making the sensors, and to Mr. Shinsuke Aoki, Mr. Naoto Sato, and Mr. Ryuta Honda for analyzing soil samples. Experimental information and data are available on request to K. Noborio.

References

- [1] X. Yan, H. Akiyama, K. Yagi, and H. Akimoto, "Global estimations of the inventory and mitigation potential of methane emissions from rice cultivation conducted using the 2006 Intergovernmental Panel on Climate Change guidelines," *Global Biogeochemical Cycles*, vol. 23, no. 2, Article ID GB2002, 2009.
- [2] IPCC, *Climate Change 2013: The Physical Science Basis, Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, New York, NY, USA, 2013.
- [3] I. Nouchi, S. Mariko, and K. Aoki, "Mechanism of methane transport from the rhizosphere to the atmosphere through rice plants," *Plant Physiology*, vol. 94, no. 1, pp. 59–66, 1990.
- [4] K. Butterbach-Bahl, H. Papen, and H. Rennenberg, "Impact of gas transport through rice cultivars on methane emission from rice paddy fields," *Plant, Cell and Environment*, vol. 20, no. 9, pp. 1175–1183, 1997.
- [5] R. Wassmann and M. S. Aulakh, "The role of rice plants in regulating mechanisms of methane emissions," *Biology and Fertility of Soils*, vol. 31, no. 1, pp. 20–29, 2000.
- [6] R. Wassmann, H. U. Neue, M. C. Alberto et al., "Fluxes and pools of methane in wetland rice soils with varying organic inputs," *Environmental Monitoring and Assessment*, vol. 42, no. 1-2, pp. 163–173, 1996.
- [7] Y. Usui, M. I. M. Mowjood, and T. Kasubuchi, "Absorption and emission of CO₂ by ponded water of a paddy field," *Soil Science and Plant Nutrition*, vol. 49, no. 6, pp. 853–857, 2003.
- [8] S. M. Green, "Ebullition of methane from rice paddies: the importance of furthering understanding," *Plant and Soil*, vol. 370, no. 1-2, pp. 31–34, 2013.
- [9] H. Schütz, W. Seiler, and R. Conrad, "Processes involved in formation and emission of methane in rice paddies," *Biogeochemistry*, vol. 7, no. 1, pp. 33–53, 1989.
- [10] M. Uzaki, H. Mizutani, and E. Wada, "Carbon isotope composition of CH₄ from rice paddies in Japan," *Biogeochemistry*, vol. 13, no. 2, pp. 159–175, 1991.
- [11] F. Rothfuss and R. Conrad, "Effect of gas bubbles on the diffusive flux of methane in anoxic paddy soil," *Limnology and Oceanography*, vol. 43, no. 7, pp. 1511–1518, 1998.

- [12] T. Tokida, W. Cheng, M. Adachi et al., "The contribution of entrapped gas bubbles to the soil methane pool and their role in methane emission from rice paddy soil in free-air [CO₂] enrichment and soil warming experiments," *Plant and Soil*, vol. 364, no. 1-2, pp. 131-143, 2013.
- [13] H. A. C. D. van der Gon and H. U. Neue, "Influence of organic matter incorporation on the methane emission from a wetland rice field," *Global Biogeochemical Cycles*, vol. 9, no. 1, pp. 11-22, 1995.
- [14] A. Watanabe and M. Kimura, "Methane production and its fate in paddy fields. VIII. Seasonal variations in the amount of methane retained in soil," *Soil Science and Plant Nutrition*, vol. 41, no. 2, pp. 225-233, 1995.
- [15] H. U. Neue, "Fluxes of methane from rice fields and potential for mitigation," *Soil Use and Management*, vol. 13, supplement 4, pp. 258-267, 1997.
- [16] E. J. Fechner-Levy and H. F. Hemond, "Trapped methane volume and potential effects on methane ebullition in a northern peatland," *Limnology and Oceanography*, vol. 41, no. 7, pp. 1375-1383, 1996.
- [17] E. Kellner, A. J. Baird, M. Oosterwoud, K. Harrison, and J. M. Waddington, "Effect temperature and atmospheric pressure on methane (CH₄) ebullition from near-surface peats," *Geophysical Research Letters*, vol. 33, no. 18, Article ID L18405, pp. 1-5, 2006.
- [18] T. Tokida, T. Miyazaki, and M. Mizoguchi, "Ebullition of methane from peat with falling atmospheric pressure," *Geophysical Research Letters*, vol. 32, no. 13, pp. 1-4, 2005.
- [19] T. Tokida, T. Miyazaki, M. Mizoguchi et al., "Falling atmospheric pressure as a trigger for methane ebullition from peatland," *Global Biogeochemical Cycles*, vol. 21, no. 2, pp. 1-8, 2007.
- [20] S. Komiya, K. Noborio, Y. Shoji, T. Yazaki, and T. Toojinda, "Measuring CH₄ flux in a rice paddy field in Thailand using relaxed eddy accumulation (REA) method," *Journal of the Japanese Society of Soil Physics*, vol. 128, pp. 23-31, 2014 (Japanese).
- [21] H. Koizumi, T. Kibe, S. Mariko et al., "Effect of free-air CO₂ enrichment (FACE) on CO₂ exchange at the flood-water surface in a rice paddy field," *New Phytologist*, vol. 150, no. 2, pp. 231-239, 2001.
- [22] S. Nishimura, S. Yonemura, K. Minamikawa, and K. Yagi, "Seasonal and diurnal variations in net carbon dioxide flux throughout the year from soil in paddy field," *Journal of Geophysical Research G: Biogeosciences*, vol. 120, no. 1, pp. 63-76, 2015.
- [23] W. Cheng, K. Yagi, H. Xu, H. Sakai, and K. Kobayashi, "Influence of elevated concentrations of atmospheric CO₂ on CH₄ and CO₂ entrapped in rice-paddy soil," *Chemical Geology*, vol. 218, no. 1-2, pp. 15-24, 2005.
- [24] W. Z. De Mello and M. E. Hines, "Application of static and dynamic enclosures for determining dimethyl sulfide and carbonyl sulfide exchange in *Sphagnum* peatlands: implications for the magnitude and direction of flux," *Journal of Geophysical Research*, vol. 99, no. 7, pp. 14-607, 1994.
- [25] B. H. Byrnes, E. R. Austin, and B. K. Tays, "Methane emissions from flooded rice soils and plants under controlled conditions," *Soil Biology and Biochemistry*, vol. 27, no. 3, pp. 331-339, 1995.
- [26] A. J. Baird, C. W. Beckwith, S. Waldron, and J. M. Waddington, "Ebullition of methane-containing gas bubbles from near-surface *Sphagnum* peat," *Geophysical Research Letters*, vol. 31, no. 21, pp. 2-5, 2004.
- [27] T. Tokida, T. Miyazaki, and M. Mizoguchi, "Physical controls on ebullition losses of methane from peatlands," in *Carbon Cycling in Northern Peatlands*, A. J. Baird, L. R. Belyea, X. Comas et al., Eds., pp. 219-228, AGU, Washington, DC, USA, 2009.
- [28] H. Yao and R. Conrad, "Effect of temperature on reduction of iron and production of carbon dioxide and methane in anoxic wetland rice soils," *Biology and Fertility of Soils*, vol. 32, no. 2, pp. 135-141, 2000.
- [29] Y. Liu, K.-Y. Wan, Y. Tao et al., "Carbon dioxide flux from rice paddy soils in central china: effects of intermittent flooding and draining cycles," *PLoS ONE*, vol. 8, no. 2, Article ID e56562, 2013.