Dynamic Emission of CH$_4$ from a Rice-Duck Farming Ecosystem

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ABSTRACT

Global climatic change induced by emissions of greenhouse gases from human activities is an issue of increasing international environmental concerns, and agricultural practices and managements are the important contributors for such emissions. This study investigated dynamic emission of methane (CH$_4$) from a paddy field in a rice-duck farming ecosystem. Three different cultivation treatments, namely the organic fertilizer + duck (OF+D), chemical fertilizer + duck (CF+D), and chemical fertilizer (Control) treatments, were employed in this study. Experimental data showed that hourly variations of CH$_4$ emission from the paddy field during the day were somewhat positively correlated ($R^2 = 0.7$ for the OF + D treatment and $R^2 = 0.6$ for the CF+D treatment) to the hourly changes in air temperatures in addition to the influences of the duck activities. The rate of CH$_4$ emission for the CF+D treatment was higher than that of the Control treatment at the tillering stage, whereas the opposite was true at the heading stage. In contrary, the rate of CH$_4$ emission for the OF + D treatment was always higher than that of the Control treatment regardless the tillering or heading stage. Our study revealed that the rate of CH$_4$ emission depended not only on air temperature but also on the rice growth stage. A 6.7% decrease in CH$_4$ emission and in global warming potential (GWP) was observed for the CF+D treatment as compared to the Control treatment. This study suggested that although the impacts of duckling on the emission of CH$_4$ depended on the rice growth stage and air temperature regime, the introduction of ducks into the rice farming system in general mitigated the overall CH$_4$ emission and thereby the GWP.

Keywords: Methane Emission, Global Warming Potential, Rice-Duck Farming

1. Introduction

Global warming, resulted from the elevated concentrations of greenhouse gases in the atmosphere, has emerged as the most prominent global environment issue. While many gases have been examined, only three of them, namely carbon dioxide (CO$_2$), methane (CH$_4$), and nitrous oxide (N$_2$O), were identified to have significant global warming potential (GWP) [1]. These gases have strong infrared absorption capacity and trap part of the thermal radiation from earth’s surface. Methane is an important greenhouse gas and has approximately 25 times more infrared absorption capacity or GWP than that of CO$_2$ on a molecule basis [2,3]. It has been reported that the atmospheric concentration of CH$_4$ increased from 1.50 to 1.72 ppm during the last decades [4,5] and contributed 5% toward the enhanced global warming [6].

Methane is produced naturally in soils through the microbial processes. Under the anaerobic conditions, a type of soil organisms or methanogens can transform some of the soil organic matter into CH$_4$ through the following two pathways: 1) CH$_3$COOH $\rightarrow$ CH$_4$ + CO$_2$; and 2) CO$_2$ +4H$_2$ $\rightarrow$ CH$_4$ + 2H$_2$O) [7,8]. Meanwhile, methane can also be oxidized by another type of soil organisms or methanotrophs into CO$_2$. Therefore, soil CH$_4$ emission into the atmosphere is a net result of CH$_4$ production and CH$_4$ oxidation [9,10]. In addition, soil temperature regime and organic carbon content are the major environmental factors affecting the emission of CH$_4$ into the atmosphere.

Although the dominant source of anthropogenic CO$_2$ is from fossil fuel burning, various agricultural activities in general and wetland rice agricultural practices in particular are the major sources of CH$_4$ emissions [11-14]. This source has increased in recent years due to the expansion of rice cultivation in Southeast Asia [15,16]. The amount of CH$_4$ emission from paddy fields is estimated to be 10% - 20% of the total CH$_4$ emission [17,18].
Therefore, a need exists to understand which agricultural farming systems have the greatest potential to mitigate CH\textsubscript{4} emission contributing to global warming. To develop an improved conservation technology for mitigation of CH\textsubscript{4} emission with multiple benefits in economy, environmental protection, food security, and agricultural sustainability, an old farming system, i.e., the rice-duck farming system, has been re-examined for this purpose in recent years, especially in South China [19-21].

The system of rice cultivation associated with duck raises is known as an integrated rice-duck farming system. This system is a form of organic farming that yields two crops simultaneously, one for rice as the main crop and the other for ducks as the subsidiary crop, using the same natural resources. Integrated the rice-duck farming is known to have numerous economical, environmental, and ecological benefits. Ducks control weeds and insects effectively in the paddy field. Ducks eat weed seeds, tender weeds, insects and crabs, and thus keep the paddy field pest free. They also improve microclimate environment in rice canopy and thereby indirectly mitigating the outbreak of some rice diseases. Due to the frequent movement, ducks improve the physical structure of the paddy soil that enhances the root growth and ultimately produce more yields. The rice-duck system can also reduce the costs of the weeding, insecticides, and chemical fertilizers, and therefore the higher net returns could be achieved. The rice-duck farming has a long history and is also a major complex planting and breeding model of paddy fields in South China [21].

Several studies have been devoted to investigating the emissions of greenhouse gases in the rice-duck farming system in recent years. Kumaraswamy \textit{et al.} [22] demonstrated that the amount of CH\textsubscript{4} emission declined from the rice-duck farming system due to the increase in dissolved oxygen (DO) concentration, resulting from the frequent movement of ducks. Huang \textit{et al.} [16] characterized the emission of CH\textsubscript{4} from a wetland rice-duck ecosystem in the subtropical region of China. These authors found that the diurnal variations of CH\textsubscript{4} emission were highly correlated to diurnal variations of paddy field temperature, whereas the seasonal variations of CH\textsubscript{4} emission were primarily dependent on the rice growth stages and planting periods (\textit{i.e.}, early and late rice). These studies have provided good insights into the impacts of the rice-duck farming system upon the emission of CH\textsubscript{4} into the atmosphere. However, the role of ducks in regulation of CH\textsubscript{4} emissions from the paddy fields into the atmosphere under varying soil conditions, planting and breeding models, and fertilizer cultivation treatments is still poorly understood.

The purpose of this study was to investigate the dynamic emission of CH\textsubscript{4} from a rice-duck farming ecosystem and its impacts upon the GWP. Our specific motivations were to: 1) estimate the hourly variations of CH\textsubscript{4} emission from the paddy field in a rice-duck farming ecosystem under conditions with varying rice growth stages and fertilizer application treatments; 2) evaluate the monthly variations of CH\textsubscript{4} emission from the paddy field under the same conditions as stated in 1); and 3) assess the cumulative emission of CH\textsubscript{4} into the atmosphere and its impacts upon the GWP for conditions with and without the rice-duck farming systems. Additionally, the introduction of ducks into rice field upon CH\textsubscript{4} emission also was evaluated.

2. Materials and Methods

Study Site and Experimental Design

The experiment was conducted at the Ning-Xi Research and Educational Station located about 40 km east campus of South China Agricultural University, Guangzhou City, China. This station has a subtropical climate with an average annual rainfall of 1.8 m and a mean annual temperature of 22°C. The paddy field soil in the station is developed from the Latosol and has pH 6.0 with an organic matter content of 29.35 g·kg\textsuperscript{-1}, a total nitrogen (N) of 0.07 g·kg\textsuperscript{-1}, a total phosphorus (P) of 0.21 g·kg\textsuperscript{-1}, an available P of 0.03 g·kg\textsuperscript{-1}, a total potassium (K) of 13.54 g·kg\textsuperscript{-1}, and an available K of 0.07 g·kg\textsuperscript{-1}.

The rice species used in this study was \textit{Sheng Ba Xi Miao}, which was provided by South China Agricultural University, Guangzhou City, China. The following three cultivation treatments each with duplicated experimental plots were chosen for the experiment: 1) organic fertilizer + duck (OF + D); 2) chemical fertilizer + duck (CF + D); and chemical fertilizer (Control), which resulted in the total of six experimental plots. Each experimental plot had an area of 666 m\textsuperscript{2} and was separated from each other by inserting the plastic barriers into a soil depth of 0.3 m around the plot boundaries to prevent water and air exchanges between the plots. These plots were randomly distributed in the study site. The organic fertilizer used was the dried chicken manure at the application amount of 3750 kg·ha\textsuperscript{-1} which contains about 51% of organic matter, 3.26% of N, 3.08% of P\textsubscript{2}O\textsubscript{5}, and 1.7% of K\textsubscript{2}O, whereas the chemical fertilizer used was the compound fertilizer (Compound Fertilizer Inc., Academy of Agriculture of Guangdong, China) with the application amounts of 100, 90, and 90 kg·ha\textsuperscript{-1}, respectively, for N, P, and K.

The pesticide used was Masha with "Antai" brand that was purchased from the Antai Limited Inc., Guangxi Zhuang Autonomous Region, China.

The experimental plots in the paddy field was tilled, fertilized, and planted, respectively, on April 1, 5, and 6, 2004. To prevent the ducks from escaping, the plots were contained by the nylon-net with a height of 0.5 m. After
10 days of rice transplanting, an average of 25 ducklings with the ages ranged from 10 to 15 days were introduced into each experimental plot. The flooding depth in the plots during the rice-duck experimental period was kept at 0.06 to 0.08 m through periodically irrigation. The ducks were retrieved and transferred to other places after the heading stage of the rice growth.

A gas chamber (Figure 1(a)) was installed in each experimental plot for collection of CH$_4$ gas, which was modified from Sass et al. [17] and Mishra et al. [9]. This chamber was made of Perspex sheets with a size of $0.5 \times 0.6$ m and a height of 0.9 m and the joints were sealed with silicon grease to prevent the leakage of the gases. The chamber was placed on an aluminum alloy base with an inner size of $0.5 \times 0.6$ m and a height of 0.2 m (Figure 1(b)). This base was jacketed with a water channel of water to make the gas chamber airtight. The base was inserted into the soil to a depth of 0.1 to 0.15 m, which made the air holes (for gas exchange) on the base 0.05 to 0.10 m below the soil surface.

To ensure a minimum disturbance to the soil inside the chamber during sampling, a bridge was built between the paddy field ridge and the chamber. The gas samples were collected from the chamber at the intervals of 0, 10, 20, and 30 minutes using a 120 ml airtight syringe and closed with a three-switch valve. Mixing of the gas inside the chamber was accomplished at the time of sampling by turning on the electrical fan installed on the top of the chamber. The gas samples were collected every other day before May 3, 2004 and once a week after this date. The flooding depth in the paddy field during the day at the tillering stage of the rice growth under three different cultivation treatments are shown in Figure 2. This figure shows that the rates of CH$_4$ emission increased from 8 to 14 h and then decreased from 14 to 16 h for all of the three treatments. For example, the rate of CH$_4$ emission was about 38 mg·m$^{-2}·h^{-1}$ at 8 h, about 49 mg·m$^{-2}·h^{-1}$ at 14 h, and about 39 mg·m$^{-2}·h^{-1}$ at 16 h for the OF + D treatment. We attributed such hourly variations in CH$_4$ emission primarily to the hourly changes of air and soil temperatures. The typical hourly changes of air temperatures at the experimental site from April to July have the following pattern: increasing from early morning to early afternoon and decreasing from early afternoon to next morning. Figure 3 shows a similar hourly variation pattern in air temperature as compared to that of the CH$_4$ emission. These air temperatures were obtained from the same experimental period and site. Air temperature has a profound impact on respiration and transpiration of the rice and thereby affecting the emission of CH$_4$. Figure 4 plots the correlations between the air temperature and the CH$_4$ emission rate among the three treatments. Based on the correlation coefficients ($R^2$) and $p$ values, the dependence of CH$_4$ emission rate upon air temperature was in the following order (from good to poor): OF + D > CF + D > Control. Results suggested that air temperature had discernible impacts on CH$_4$ emission in the rice-duck farming system.

The influence of soil temperature on CH$_4$ production and emission has been investigated by Khan et al. [24], Kumaraswamy et al. [25], Yang and Chang [26], and Huang et al. [16]. These authors demonstrate that the rate
of CH₄ production increased with soil temperature from 15 to 40°C and a significant positively correlation exists between CH₄ emission and soil temperature, which can be characterized by Arrhenius equation. Variations in soil temperature can affect the physiological functions of rice such as oxygen diffusivity, root exudation, and root oxidation [27,28] as well as stimulate the activities of methanogenic and methanotrophic microorganisms in the rice rhizosphere [29], which could exert a substantial influence on CH₄ emission. It has been reported that rice roots can uptake the dissolved methane and transport through the aerating tissues of the rice and final emit into the atmosphere through respiration and transpiration [30]. In addition, the duck activities during the day may also affect the hourly variations of CH₄ emission from the paddy field. Ducks are the hot-susceptibility animals and they always seek for foods when the temperature is cooler in the early morning and late afternoon and rest on the ridges of the paddy field or any shed areas when the temperature is warmer at noon [20]. The frequent movement of the ducks in the early morning and late afternoon brought more DO into the surface water of the paddy field, expedited the oxidation of CH₄, and thereby reduced the rate of CH₄ emission at those time periods.

In general, the rates of CH₄ emission among the three cultivation treatments during the tillering stage of the rice growth were in the following order: OF + D > CF + D > Control. The maximum rates of CH₄ emission were about 48, 32, and 27 mg·m⁻²·h⁻¹, respectively, for the OF + D, CF + D, and Control at 14 h. In other words, the maximum rates of CH₄ emission increased 78% and 19%, respectively, for the OF + D and CF + D treatment as compared to that of the Control treatment during the tillering stage of the rice growth. A 58% (i.e., 78% - 19%) increase in the maximum rate of CH₄ emission for the OF + D treatment against that for the CF + D treatment as compared to that of the Control treatment during the tillering stage of the rice growth. A 58% (i.e., 78% - 19%) increase in the maximum rate of CH₄ emission for the OF + D treatment against that for the CF + D treatment occurred probably because there was more carbon sources available from organic fertilizer for methanogens to produce CH₄. It is also very interesting to learn that a 19% increase in the maximum rate of CH₄ emission for the CF + D treatment occurred as compared to that of the Control treatment at this rice growth stage. We attributed this phenomenon to frequent activities of the ducks that physically accelerated the CH₄ emission from the paddy field.

Similar hourly variations in CH₄ emission from the
paddy field during the day for the same cultivation treatments were obtained at the heading stage of the rice growth (Figure 5). That is, the rates of CH₄ emission increased from the morning to the early afternoon and decreased from the early afternoon to late afternoon. As stated above, this process was primarily driven by hourly variations of soil and air temperatures. The hourly temperature variations and CH₄ emissions are a cause-and-effect phenomenon. As the temperature varies, the rate of CH₄ emission changes accordingly.

Comparison of Figures 2 and 5 shows that the rates of the hourly CH₄ emission were higher at the tillering stage than at the heading stage for all of the three treatments. For instance, the rate of the hourly CH₄ emission for the OF + D treatment was about 42 mg·m⁻²·h⁻¹ at the tillering stage but was about 33 mg·m⁻²·h⁻¹ for the same treatment at the heading stage. The former was about 21% higher than the latter. A similar finding also was reported by Huang et al. [16] although no explanations have been provided by these authors. We speculated this occurred because more carbon sources were available for methanogens to produce CH₄ at the tillering stage (early time of rice growth) than at the heading stage (late time of rice growth). The more carbon sources were available, the higher rate of CH₄ emission occurred.

Comparison of the two rice growth stages further reveals that the rate of the hourly CH₄ emission for the CF + D treatment was higher than for the Control treatment at the tillering stage, whereas the opposite was true at the heading stage. In other words, the duck activities increased the rate of CH₄ emission during the tillering stage but decreased such a rate during the heading stage. Although the exact reasons for such a phenomenon remain unknown, a possible explanation is as follows. The role of the duck activities is two-fold: 1) it can accelerate the CH₄ emission into the atmosphere by physically stirring the water of the paddy field, and 2) it can expedite the CH₄ oxidation by physically increasing the DO concentration in the water of the paddy field, and thereby decrease the rate of CH₄ emission. At the tillering stage, the rate of CH₄ production was high presumably because there was more soil organic matter available in the paddy field. Under such a high rate of CH₄ production, the physical acceleration of CH₄ emission due to the duck activities seems to be more important than the oxidation of CH₄ through the physical increase of DO concentration due to the duck activities. Therefore, more CH₄ was emitted at the tillering stage. As time elapsed to the heading stage, the rate of CH₄ production was low because there was less soil organic matter available. Under such low rate of CH₄ production, the physical acceleration of CH₄ emission due to the duck activities seems to play a least important role than the oxidation of CH₄ through the physical increase of DO concentration due to the duck activities when the ducks grew bigger and became very strong at this stage. As a result, less CH₄ were emitted at the heading stage.

3.2. Monthly Emission of CH₄

Changes in monthly emission of CH₄ from the paddy field for the three cultivation treatments were shown in Figure 6. The rates of CH₄ emission increased dramatically in approximately the first month after the rice planting, decreased consecutively, and reached their minimums after three months. The maximum rates of CH₄ emission within the first month of the rice growth period were about 55, 37, and 26 mg·m⁻²·h⁻¹, respectively, for the OF + D, CF + D, and Control treatments. It is apparent that more CH₄ were produced during the first month of the rice growth although the exact reasons remain to be investigated. Further investigation of Figure 4 disclosed that the rate of CH₄ emission was greater for the CF + D treatment than for the Control treatment before May 20 (the tillering stage), whereas the opposite was true after this date (the heading stage). This occurred due to the same reasons as in the case of hourly CH₄ variations for the tillering and heading stages.

Figure 5. Hourly variations of CH₄ emission rate at the heading stage.

Figure 6. Monthly variations of CH₄ emission rate.
No correlation existed between the monthly changes in air temperature and the monthly variations in the rate of \( \text{CH}_4 \) emission. The average monthly air temperatures were 22°C, 25°C, and 27°C, respectively, for April, May, and June at the experimental site, whereas the average monthly rates of \( \text{CH}_4 \) emission were about 18, 25, and 11 mg·m\(^{-2}\)·h\(^{-1}\), respectively, for April, May, and June at the same site. In other words, an increase in average monthly temperature did not necessarily increase in the average rate of monthly \( \text{CH}_4 \) emission. This occurred because the rate of \( \text{CH}_4 \) emission was more or less dependent on the rate of \( \text{CH}_4 \) production, which, in turn, was presumably controlled by the soil organic matter content. As time elapsed, the rate of \( \text{CH}_4 \) production decreased due to the reduction of soil organic matter content in the paddy field. As a result, the rate of \( \text{CH}_4 \) emission decreased although the air temperature increased with time.

Cumulative emission of \( \text{CH}_4 \) (the amount of total \( \text{CH}_4 \) emission at a give experimental period) for the three cultivation treatments is given in Figure 7. The overall emissions of \( \text{CH}_4 \) from the paddy field were 62,810, 38,583, and 41,375 mg·m\(^{-2}\), respectively, for the OF + D, CF + D, and Control treatments at the end of the experiment. It is apparent that a 6.7% of \( \text{CH}_4 \) emission reduction was obtained for CF + D treatment as compared to that of the Control treatment. Results imply that although the impacts of duckling on the emissions of \( \text{CH}_4 \) depended on the rice growth stages, the introduction of ducks into the rice farming system normally mitigated the emission of \( \text{CH}_4 \) into the atmosphere.

### 3.3. Impacts on Global Warming Potential

Global warming potential is a measure of how much a given mass of greenhouse gas is estimated to contribute to global warming. It is an index defined as the cumulative radiative forcing between the present and a chosen later time horizon caused by a unit mass of gas emitted now [30]. The GWP can be used to compare the effectiveness of each greenhouse gas to trap heat in the atmosphere relative to CO\(_2\). A GWP is calculated over a specific time interval and the value of this must be stated whenever a GWP is quoted or else the value is meaningless.

The GWP is based on a number of factors, including the radiative efficiency (heat-absorbing ability) of each gas relative to that of CO\(_2\) as well as the decay rate of each gas (the amount removed from the atmosphere over a given number of years) relative to that of CO\(_2\). The GWP value for \( \text{CH}_4 \) is 62 based on a 20-year time horizon and is 23 based on a 100-year time horizon when the GWP value for CO\(_2\) is taken as 1 [30].

Impacts of \( \text{CH}_4 \) emission on the GWP from the rice-duck farming ecosystem under three different cultivation treatments used in this study are shown in Table 1. The GWP based on the 20- or 100-year time horizon was high for the OF + D treatment, low for the CF + D treatment, and with the Control treatment in between. A 6.7% decrease in GWP based on the 20- or 100-year time horizon was observed for the CF + D treatment as compared to that of the Control treatment. A statistical analysis with F-test demonstrates such a percentage decrease was within a 1 percent level of significance (i.e., \( \alpha = 0.01 \)). Results demonstrate that the introduction of ducks into a rice farming system reduced the emission of \( \text{CH}_4 \) into the atmosphere as compared to that of the Control treatment. A statistical analysis with F-test demonstrates such a percentage decrease was within a 1 percent level of significance (i.e., \( \alpha = 0.01 \)). Results demonstrate that the introduction of ducks into a rice farming system reduced the emission of \( \text{CH}_4 \) into the atmosphere as compared to that of the conventional rice farming system (i.e., the Control treatment) in South China. Table 1 further reveals that the GWP with the use of organic fertilizer was 65% higher than with the use of chemical fertilizer in the rice-duck farming system. It is apparent that the use of organic fertilizer would enhance the GWP through the increase of \( \text{CH}_4 \) emission.

### Table 1. Impacts of \( \text{CH}_4 \) emission from the rice-duck forming ecosystem on the global warming potential (GWP).

| Treatment          | Average hourly \( \text{CH}_4 \) emission (mg·m\(^{-2}\)·h\(^{-1}\)) | Cumulative \( \text{CH}_4 \) emission (mg·m\(^{-2}\)) | GWP based on 20 years | GWP based on 100 years |
|--------------------|---------------------------------------------------------------|-------------------------------------------------|----------------------|------------------------|
| Organic fertilizer + duck (OF + D) | 26.32                                                        | 63,810.48                                       | 3956249.76           | 1467641.04             |
| Chemical fertilizer + duck (CF + D) | 15.91                                                        | 38,583.98                                       | 2392206.76           | 887431.54              |
| Chemical fertilizer (Control) | 17.06                                                        | 41,375.88                                       | 2565304.56           | 951645.24              |

*The GWP values based on 20- and 100-year time horizons are calculated by multiplying the cumulative \( \text{CH}_4 \) emissions with 62 and 23, respectively; **The values among different treatments are statistically different at \( \alpha = 0.01 \) through F-test.*
However, the use of chemical fertilizer can increase the rate of N₂O emission into the atmosphere in rice agriculture [14]. Therefore, further study is warranted to compare the GWP induced from the emission of CH₄ due to the use of organic fertilizers and from the emission of N₂O due to the use of chemical fertilizers in the rice-duck farming system.

4. Summary
Experiments were conducted to investigate the dynamic emission of CH₄ from a paddy field under the rice-duck farming system. Three different cultivation treatments, namely the organic fertilizer + duck (OF + D), chemical fertilizer + duck (CF + D), and chemical fertilizer (Control) treatments, were selected in this study. Our study showed that hourly variations of CH₄ emission from the paddy field during the day were positively correlated to the hourly changes in air temperatures in addition to the influences of the duck activities. The rate of CH₄ emission for the CF + D treatment was higher than for the Control treatment at the tilling stage, whereas the opposite was true at the heading stage. Our study revealed that the rate of CH₄ emission depended not only on temperature but also on the rice growth stage. A 6.7% reduction in CH₄ emission as well as in GWP was observed for the CF + D treatment as compared to the Control treatment for the entire experimental period. This study suggested that although the impacts of ducking on the emission of CH₄ depend on rice growth stage and air temperature regime, the introduction of ducking into the rice farming system in general mitigated the overall CH₄ emission and thereby the GWP.

Although the use of organic fertilizers enhanced the GWP through the increase of CH₄ emission, the use of chemical fertilizers would also enhance the GWP through the increase of N₂O emission. Therefore, further study is warranted to compare the GWP from the emission of CH₄ due to the use of organic fertilizers with the GWP from the emission of N₂O due to the use of chemical fertilizers in the rice-duck farming system. Additionally, soil organic matter should also be measured for a better characterization of CH₄ emission from the rice-duck farming system.

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