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# Comparison of greenhouse gas emissions from rice paddy fields under different nitrogen fertilization loads in Chongming Island, Eastern China

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## HIGHLIGHTS

- In Chongming Island, Shanghai, GHG emissions were measured under different nitrogen fertilizer rates from the paddy.
- Low nitrogen fertilizer application reduced $CH_4$ and $N_2O$ emissions.
- The study showed that 210 kg N/ha was the suitable fertilizer application rate.

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## ABSTRACT

Rice is one of the major crops of southern China and Southeast Asia. Rice paddies are one of the largest agricultural greenhouse gas (GHG) sources in this region because of the application of large quantities of nitrogen (N) fertilizers to the plants. In particular, the production of methane ($CH_4$) is a concern. Investigating a reasonable amount of fertilizers to apply to plants is essential to maintaining high yields while reducing GHG emissions. In this study, three levels of fertilizer application [high (300 kg N/ha), moderate (210 kg N/ha), and low (150 kg N/ha)] were designed to examine the effects of variation in N fertilizer application rate on carbon dioxide ($CO_2$), methane ($CH_4$), and nitrous oxide ($N_2O$) emissions from the paddy fields in Chongming Island, Shanghai, China. The high level (300 kg N/ha) represented the typical practice adopted by the local farmers in the area. Maximum amounts of $CH_4$ and $N_2O$ fluxes were observed upon high-level fertilizer application in the plots. Cumulative $N_2O$ emissions of 23.09, 40.10, and 71.08 mg $N_2O/m^2$ were observed over the growing season in 2011 under the low-, moderate-, and high-level applications plots, respectively. The field data also indicated that soil temperatures at 5 and 10 cm soil depths significantly affected soil respiration; the relationship between *Rs* and soil temperature in this study could be described by an exponential model. Our study showed that reducing the high rate of fertilizer application is a feasible way of attenuating the global-warming potential while maintaining the optimum yield for the studied paddy fields.

## 1. Introduction

Global warming is caused by the emission of greenhouse gases (GHG), such as methane ($CH_4$), nitrous oxide ($N_2O$), and carbon dioxide ($CO_2$), etc. Within 100 years, the global warming potentials of $CH_4$ and $N_2O$ are expected to become 21 and 310 times that of $CO_2$ (IPCC, 1995), respectively. Today, GHG levels continue to increase not only because the anthropogenic emissions, but also because the longer lifetime which caused by the decreases in the amount and stability of atmospheric [$OH^·$] (Montzka et al., 2011). The energy consumption, industrial pollution, poor agriculture and deforestation management practices of humans have directly and indirectly increased the atmospheric concentrations of several GHGs, especially those of $CO_2$, $CH_4$, and $N_2O$ (Houghton et al., 1996). Thus, mitigating the agricultural emissions of these GHGs by altering human activities is a very important endeavor.

On global scale, agricultural activities accounted for an estimated 5.1–6.1 Gt $CO_2$-eq/yr of emissions in 2005 (10%–12% of the total anthropogenic GHG emissions) and a nearly 17% increase in $CH_4$ and $N_2O$

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emissions from 1990 to 2005 (IPCC, 2007). The GHG inventory for agriculture was 819 Mt $CO_2$-eq and accounted for 11% of the total GHGs in China. Emission from rice paddy and agricultural land uses was 374 Mt $CO_2$-eq, accounting for 45.7%. (P.R.-China, 2013).

Rice, an important food in many parts of the world, is a semi-aquatic species and mostly grows under flooded low-land conditions in paddies (Kögel-Knabner et al., 2010). Induced by periodic short-term flooded cycles over long periods of time, paddy fields have special soil characteristics, such as soil redox potential, different bacterial communities, anaerobic status, etc. (Kögel-Knabner et al., 2010; Lüdemann et al., 2000; Yao et al., 1999). The soil environment of redox gradients, microbes, and limited $O_2$ microhabitats significantly affects the biogeochemical processes [carbon cycle and nitrogen (N) dynamics] that occur in flooded paddy fields. Recent research on rice paddy fields has mostly focused on water management, microbial communities and GHG emissions (Fuller and Qin, 2009; Hama et al., 2011; Hou et al., 2012; Ke and Lu, 2012; Tago et al., 2011; Tyagi et al., 2010; van Groenigen et al., 2011). Rice producers employ multiple cropping management practices, e.g., tillage and fertilizers. The effects of tillage and fertilizer on the carbon stock of soil have recently been reported (Ahmad et al., 2009; Baggs et al., 2003; Huang et al., 2006; Morell et al., 2011; W. Zhang et al., 2007).

Modification of farming management practices such as tillage, fertilization, straw residue, and water management, is an effective way of mitigating GHG emissions. Direct-seeding mulch-based cropping (DMC) systems present a tillage method that has noticeably increased in application over the last decades.

A previous study showed that DMC use in rainfed fields (rice, wheat, maize) in Latin America results in maximized productivity and stable or unstable carbon protection (Scopel et al., 2004). Carbon and N contents as well as denitrification activity in the soil increase significantly under DMC systems mainly because the microbial community and chemical processes in soil are closely correlated with soil tillage management (Baudoin et al., 2009). The DMC system may increase carbon stocks in soil and emissions (Chapuis-Lardy et al., 2009; Metay et al., 2007; Six et al., 2002).

Rice contributes about 43.7% of the total national grain production in China (irri.org, from International Rice Research Institute). Paddy-rice yields per hectare have greatly increased with the application of high levels of fertilizer, especially N fertilizers (ICAM, 2012; Peng et al., 2002b). Approximately, 30% of the N fertilizer produced worldwide is consumed by China with low fertilizer use efficiency (Peng et al., 2002a). Fertilization management significantly affects GHG emissions from paddy fields. According to Kahrl's estimation, N fertilizer reduction can lead to GHG emission reductions (Kahrl et al., 2010), and $N_2O$ emission rate is also affected by fertilizer types. Appropriate N fertilizer application rates can help increase biomass production and decrease GHG emissions (Snyder et al., 2009). It was observed that seasonal $N_2O$ emissions generally increase with fertilizer input during the rice-growing season (Zou et al., 2008).

Numerous countries have taken effective actions to reduce GHG emissions. Agricultural management practices contribute significantly to GHG emissions. China is a developing country with rapid economic growth in conjunction with increasing of GHG emissions. Few studies have addressed the nature of GHG emissions from DMC. This study aims to estimate the GHG emissions of DMC-paddy fields under different doses of applied N fertilizer in a typical rice field in Chongming Island, Shanghai, China and explore mitigation measures.

## 2. Materials and methods

### 2.1. Experimental site

The experiment was carried out in a paddy field of Dadong Village, Chongming Island, Shanghai, China (31.61°N, 121.62°E) from 2010 to 2011. Chongming Island, the third largest island in China, is located in the Yangtze River estuary. The fields used for the experiment had been cultivated with rice and broad bean (*Vicia faba* Linn.) rotation over the last 5 years and had been managed routinely according to local planting traditions. The soil organic carbon, total N content, and soil bulk density before planting were 15.65 g/kg, 1.28 g/kg, and 1.4 g/$cm^3$, respectively. The paddy fields were fertilized with 300 kg N/ha, a typical practice in Chongming Island. The rate was much higher than the crop demand for N. In East Asia, the estimated average N application rate is 155 kg N/ha (F. Zhang et al., 2007).

The rice paddy plots used in this experiment measured 5 m × 15 m with three replicates separated by plastic film and a high ridge. Each plot has three measurement points. Paddy was treated with a urea dosage of 150 (low), 210 (moderate), or 300 (high) kg N/ha. The rice seeds were directly planted and flooded after 2 weeks. The fertilization stages included (1) basal fertilizer application during the transplanting stage and (2) top dressing fertilizer application during the tillering stage (before flooding and 2 weeks after flooding, with 2/3 and 1/3 of the designated fertilizer treatment, respectively).

### 2.2. Observed data

#### 2.2.1. $CH_4$ and $N_2O$ emission flux

After planting and fertilization, the dark static chamber/GC method was used to detect the GHG flux between 9:00 am and 12:00 am every 2 weeks from June 9 to November 10 in 2011. The static chamber was a gas collector box made of PVC plastic plate with a standard size of 50 cm × 50 cm × 75 cm. Five hills of rice seedlings were covered in each chamber. Each sampling was subdivided five times in 10 min intervals. A fan was used to mix the gases in the chamber, which were then drawn off by a syringe and transferred into a 100 mL gas-sampling bag made of aluminum foil. $CO_2$, $CH_4$, and $N_2O$ were simultaneously detected by a GC system configured by the Institute of Atmospheric Physics, Chinese Academy of Sciences (Wang et al., 2010; Zheng et al., 2008) in laboratory. The increase of GHG concentration in the static chamber was calculated by linear regression. Fluxes were calculated from the following formula (Davidson et al., 2002; Huang, 2003).

$$F = \frac{dC}{dt} \times \frac{mPV}{ART} = H \times \frac{dC}{dt} \times \frac{mP}{RT}. \qquad (1)$$

Here, $\frac{dC}{dt}$ is acquired by the linear regression equation. The value $m$ is the molecular weight of trace gas, $P$ indicates the atmospheric pressure ($P = 1.013 \times 10^5$ Pa), $R$ is the gas constant ($R = 8.314$ J/mol/K), and $T$ is the air temperature in the chamber. $V$, $H$, and $A$ are the volume, height, and area of the static chamber, respectively.

#### 2.2.2. Soil $CO_2$ emission flux

The soil $CO_2$ flux was measured in 3 points per each plot from June 9 to December 23 in 2011 using the static chamber method. However, no rice seedlings were covered in these sampling chambers.

Soil respiration ($Rs$) in the paddy field was calculated, along with the GHG flux. An exponential model was fitted with the soil temperature to obtain the following formula.

$$Rs = \alpha e^{\beta T} \qquad (2)$$

where $\alpha$ and $\beta$ are two different constants and $T$ is the soil temperature.

$T$ was measured adjacent to each static chamber ring at the time of flux measurement. The temperature was measured at 5 and 10 cm below the surface of the paddy soil.

$Q_{10}$ values (the coefficient for the exponential relationship between soil respiration and temperature) were calculated by equation 3. (Boone et al., 1998; Davidson et al., 2002; Lloyd and Taylor, 1994)

$$Q_{10} = e^{10\beta} \qquad (3)$$

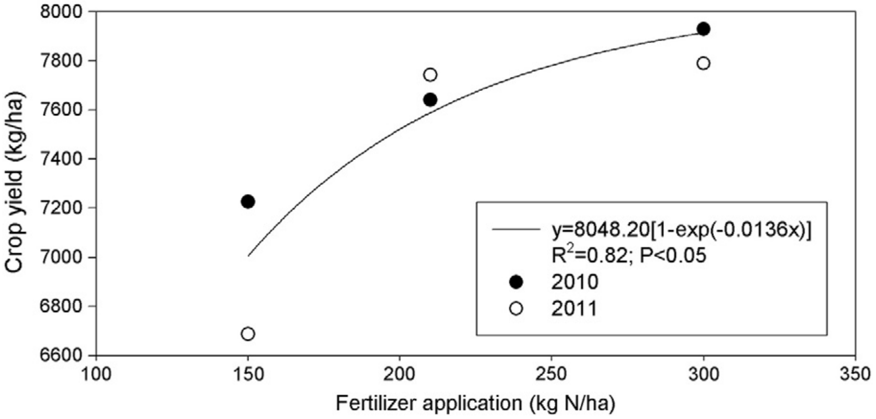

**Fig. 1.** Relationship between rice yield and fertilizer application during 2010–2011.

Meteorological data, such as daily temperature and precipitation, were collected from Shanghai's Meteorological Bureau.

### 2.3. Global warming potential (GWP)

GWP is an indicator that compares the contributions of GHGs to the atmospheric temperature. IPCC (Houghton et al., 1996, 2001) factors were used to calculate GWP in $CO_2$-equivalents per hectare per growing season over a 100-year time scale to estimate the potential of $CO_2$, $CH_4$, and $N_2O$ in the following equation.

$$\begin{aligned} GWP = {} & CH_4 \text{emission (emission from rice field)} \times 21 \\ & + N_2O \text{ emission (emission from rice field)} \times 310 \\ & + CO_2 \text{emission (emission from fertilizer production)}. \end{aligned} \tag{4}$$

### 2.4. GHG emissions/crop yield ratio

Agriculture and fertilizer production both emit GHGs. The crop yield increases because of fertilizer management practices in the field. The GHG emissions/crop yield ratio is an index of the $CO_2$-eq emission per unit yield.

$$Ratio = \frac{\sum CO_2-eq}{Y} \tag{5}$$

where Y indicates the rice yield and $\Sigma CO_2$-eq is the sum of $CO_2$-eq emissions from the paddy field and fertilizer production.

### 2.5. Statistical analysis of data

Data in the figures (Figs. 3, 4 and 5) are presented as average values with standard deviations. Sigma Plot 10.0 and Sigma Stat 3.5 were used for statistical analyses. The data were subjected to one-way ANOVA and differences among treatments were tested by the Kruskal–Wallis one-way ANOVA by ranks.

## 3. Results

### 3.1. Crop yields under different fertilizer loads

Crop yields under low, moderate, and high fertilizer loads ranged from 7224.83 kg/ha to 7928.13 kg/ha in 2010 and from 6688.27 kg/ha to 7788.20 kg/ha in 2011. The maximum crop yields were obtained under high fertilizer application. The relationship between crop yields and fertilizer application rates could be characterized by nonlinear regression ($P < 0.05$, $R^2 = 0.82$, Fig. 1), and increases in fertilizer use did not show a corresponding increase in the rate of crop yield.

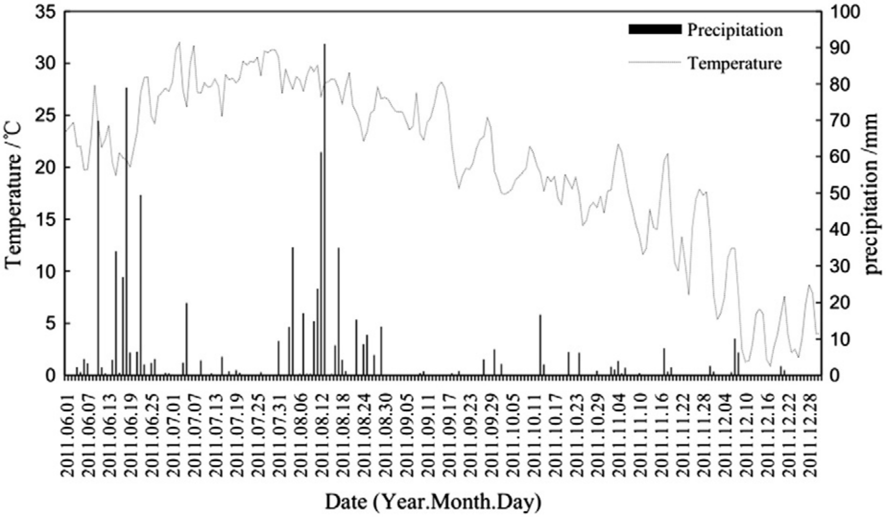

**Fig. 2.** Variations of daily air temperature and precipitation from June 1 to December 31 in 2011.

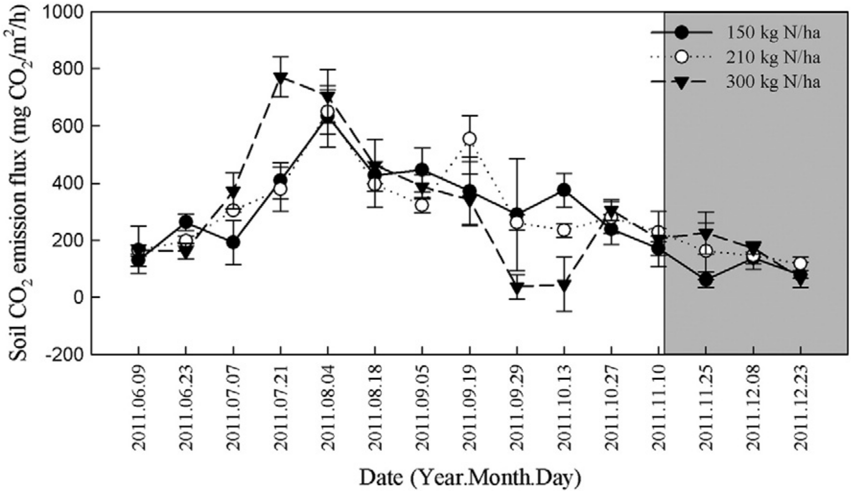

**Fig. 3.** Soil $CO_2$ emission fluxes for different fertilizer applications. The blank area was measured during the rice growing season and the shadow area was sampled after rice harvested.

### 3.2. Air and soil temperature

As shown in Fig. 2, during the rice-growing season (June 1 to November 13) in 2011, the daily minimum/maximum air temperatures respectively ranged from 11.6 °C to 32 °C, and the average and accumulated temperatures were 23.75 °C, and 3942.6 °C, respectively. Daily precipitation ranged from 0 mm to 91 mm and the cumulative precipitation was 774.6 mm during the rice-growing season.

From June 1 to December 31, 2011, the air temperature varied from 0.9 °C to 32 °C and decreased with some peaks as winter approached; the amount of precipitation during this period totaled 810.1 mm.

### 3.3. Soil $CO_2$ emission

Soil $CO_2$ emissions were measured during the rice-growing season and after harvest in 2011 with the dark chamber method. The measured $CO_2$ fluxes should consist of soil microbial heterotrophic respiration and crop root respiration. As shown in Fig. 3, the soil $CO_2$ emission grew rapidly with increasing air temperature. After rice flowering, the $CO_2$ flux began to decrease. The $CO_2$ flux fell to minimal levels after rice harvest. Fertilization showed limited effects on $CO_2$ emission. At low, moderate, and high fertilizer loads, $CO_2$ fluxes ranging from 62.13 mg $CO_2/m^2/h$ to 634.00 mg $CO_2/m^2/h$, 117.37 mg $CO_2/m^2/h$ to 349.01 mg $CO_2/m^2/h$, and 36.72 mg $CO_2/m^2/h$ to 770.82 mg $CO_2/m^2/h$ were respectively observed with averages of 281.90, 293.18, and 294.94 mg $CO_2/m^2/h$, respectively.

During the rice-growing season, the cumulative $CO_2$ emission fluxes observed under low, moderate, and high fertilizer loads were 1311.21, 1318.81, and 1314.44 g $CO_2/m^2$, respectively (Table 1). No statistical differences were observed ($P = 0.977$).

### 3.4. $CH_4$ emission

The $CH_4$ emission flux in all treatments increased gradually in the early stage of crop growth, and peaked on November 10 before harvest. After the harvest, the fluxes went down. At low fertilizer application, $CH_4$ fluxes ranged from −0.71 μg $CH_4/m^2/h$ to 331.80 μg $CH_4/m^2/h$; at moderate fertilizer application, $CH_4$ fluxes ranged from −11.30 μg $CH_4/m^2/h$ to 364.30 μg $CH_4/m^2/h$; finally, at high fertilizer application, $CH_4$ fluxes ranged from 20.10 μg $CH_4/m^2/h$ to 407.50 μg $CH_4/m^2/h$. The average $CH_4$ fluxes observed under low, moderate, and high fertilizer application were 112.89, 113.79, and 124.83 μg $CH_4/m^2/h$, respectively.

During the rice-growing season, the cumulative $CH_4$ emission fluxes observed under low, moderate, and high fertilizer application were 0.55, 0.54, and 0.58 g $CH_4/m^2$, respectively (Table 1); no statistical difference was observed among treatments ($P = 0.966$ on ANOVA analysis).

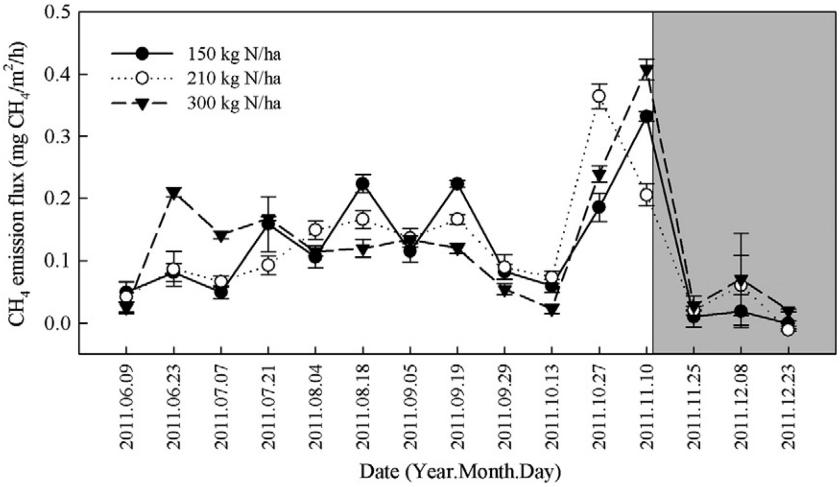

**Fig. 4.** $CH_4$ emission fluxes for different fertilizer applications. The blank area was measured during the rice growing season and the shadow area was sampled after rice harvested.

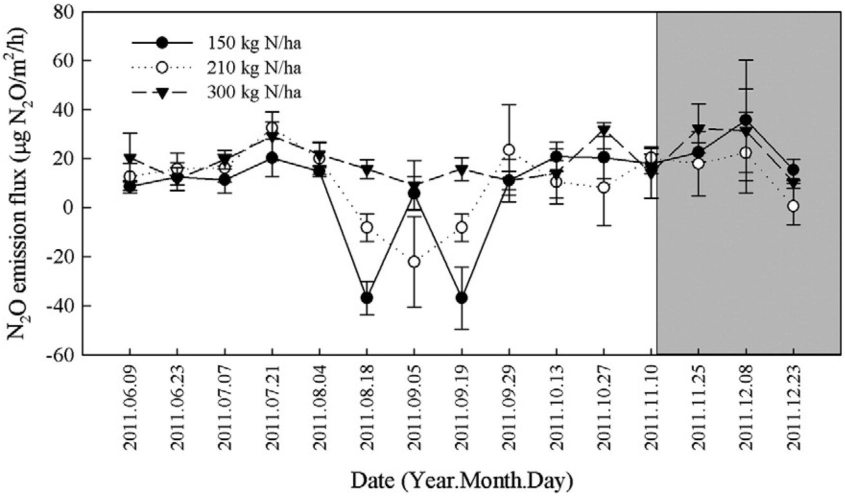

**Fig. 5.** $N_2O$ emission fluxes for different fertilizer applications. The blank area was measured during the rice growing season and the shadow area was sampled after rice harvested.

### 3.5. $N_2O$ emission

The measured $N_2O$ fluxes were marginally low around zero (Fig. 5). Higher fertilizer applications led to higher $N_2O$ emission trends. During the rice-growing season, $N_2O$ fluxes observed under low, moderate, and high fertilizer application varied from $-36.83$ μg $N_2O/m^2/h$ to 20.80 μg $N_2O/m^2/h$, from $-22.14$ μg $N_2O/m^2/h$ to 32.55 μg $N_2O/m^2/h$, and from 9.12 μg $N_2O/m^2/h$ to 31.95 μg $N_2O/m^2/h$, respectively. The cumulative $N_2O$ emission fluxes obtained under low, moderate, and high fertilizer application were 23.09, 40.10, and 71.08 mg $N_2O/m^2$, respectively (Table 1).

### 3.6. GWP and consumption of paddy

The measured GHG emissions patterns and the calculated GWPs of different fertilizer levels were shown in Table 2. The GWPs observed under low, moderate, and high fertilizer application were 427.68, 574.49 and 822.63 kg $CO_2$-eq/h, respectively. The GWP from low N fertilizer application was lower than the other applications. The results indicated that the contributions of $CO_2$, $CH_4$ and $N_2O$ to GWP were in the order of $N_2O < CH_4 < CO_2$ under low fertilizer application, and $CH_4 < N_2O < CO_2$ under moderate and high fertilizer application. In this study, the ratio of GWP to crop yields, which includes GHG emissions from the paddy field and $CO_2$-eq from fertilizer production, varied from 0.064 to 0.106 under low, moderate, and high fertilizer application (Table 3). The GHG emissions/crop yield ratio of the high fertilizer treatment was the highest than those of the low and moderate treatments.

### 3.7. The effect of soil temperature on GHG emissions

The effect of soil temperature (at 5 and 10 cm depths) on GHG emissions fluxes and *Rs* were shown in Figs. 6 and 7. $CH_4$ and $N_2O$ emissions had no relationship with soil temperature remarkably. Soil temperature significantly influences $CO_2$ emissions by inducing the acceleration of soil organic carbon decomposition, root respiration, and microbe respiration.

Measurements of *Rs* made in this study indicated that *Rs* increases due to the temperature. *Rs* in the paddy field ranged from 36.72 mg $CO_2/m^2/h$ to 770.82 mg $CO_2/m^2/h$. Temperature varied from 4.5 °C to 31.6 °C at 5 cm depth and from 5.3 °C to 29.0 °C at 10 cm depth. An exponential model can be used to explain the relationship between *Rs* and temperature ($Rs = 85.23e^{0.054T}$ at 5 cm depth and $Rs = 65.66e^{0.070T}$ at 10 cm depth). $Q_{10}$ values of 1.72 and 2.01 at 5 and 10 cm soil depths, respectively, were also obtained.

**Table 1**
Cumulative of GHG emissions from different fertilizer applications during rice growing season (June 1 to November 13, 2011).

| Treatment | $CO_2$ (g $CO_2/m^2$) | $CH_4$ (g $CH_4/m^2$) | $N_2O$ (mg $N_2O/m^2$) |
|---|---|---|---|
| 150 kg N/ha | 1311.21 | 0.55 | 23.09 |
| 210 kg N/ha | 1318.81 | 0.54 | 40.10 |
| 300 kg N/ha | 1314.44 | 0.58 | 71.08 |

## 4. Discussion

In 2005, GHG emissions from the agricultural sector accounted for 10.97% of all GHG emissions in China (P.R.-China, 2013). Agriculture can potentially play an important role in reducing the net GHG emissions and has substantial potential for absorbing or emitting GHGs through various land uses, tillage, fertilization, and other soil management practices.

### 4.1. Soil $CO_2$ emissions under different fertilizer loads

The soil $CO_2$ flux from agricultural ecosystems is the result of anaerobic degradation of organic matter, aerobic heterotrophic *Rs*, etc. Fertilizer application may affect soil properties and rice root growth to influence the release of $CO_2$ emission. Iqbal et al. (2009) reported that $CO_2$ fluxes from row increased with increasing N fertilizer use because of increased root activity and microbial respiration, but no significant differences among different fertilization were observed from inter-row and bare soil in paddy fields. And a study conducted in Moody County, South Dakota, USA, revealed that N fertilization has no effect on $CO_2$ fluxes (Lee et al., 2007). Furthermore, no significant difference in soil $CO_2$ fluxes from bare soil was observed among the low, moderate, and high fertilizer treatments in this study.

Temperature (Bond-Lamberty and Thomson, 2010; Raich and Schlesinger, 1992) and soil moisture are important factors that influence the soil $CO_2$ flux. In this study, soil $CO_2$ emissions from paddy fields were significantly related to air temperature and poorly related to soil moisture because the soil temperature is dominated by the air

**Table 2**
GWP (kg $CO_2$-eq/ha/season) of different fertilizer applications during rice growing season (June 1 to November 13, 2011).

| Treatment | $CH_4$ | $N_2O$ | $CO_2^a$ | GWP |
|---|---|---|---|---|
| 150 kg N/ha | 116.10 | 71.58 | 240 | 427.68 |
| 210 kg N/ha | 114.17 | 124.32 | 336 | 574.49 |
| 300 kg N/ha | 122.29 | 220.34 | 480 | 822.63 |

Note: $CO_2^a$ is the consumption of urea production which calculated using index (1.6 t $CO_2$/t N) (Kongshaug, 1998).

**Table 3**
GHG emissions/crop yield ratio of different fertilizer treatments in paddy during rice growing season.

| Treatment | Rice yields (kg/ha) | $CO_2$-eq (kg $CO_2$/ha) | Ratio |
|---|---|---|---|
| 150 kg N/ha | 6688.27 | 427.68 | 0.064 |
| 210 kg N/ha | 7742.00 | 574.49 | 0.074 |
| 300 kg N/ha | 7788.20 | 822.63 | 0.106 |

temperature and the soil was saturated with moisture during the rice-growing season. Respiration fluxes increased with increasing air temperature and decreased with decreasing air temperature.

Dynamic changes in *Rs* and temperature could be explained by the exponential model in Fig. 7. The temperature coefficient ($Q_{10}$) is an important index that reveals the relationship between temperature and *Rs* (Coyne and Kelley, 1975). Ren et al. (2007) measured temperature during fallow periods using the eddy covariance method and found $Q_{10}$ values of *Rs* of 2.07–2.23 and 2.04–2.28 at 5 and 10 cm depths, respectively. Lu et al. (2012) and Zhu et al. (2005) measured *Rs* using the closed static-chamber method during the rice-growing period and revealed $Q_{10}$ values of *Rs* of 2.96 and 1.70. Spatial *Rs* variations in China affected the T pattern. For example, $Q_{10}$ values in cropland range from 1.28 to 4.75, and the average $Q_{10}$ is 1.99 (Zheng et al., 2009). In this study, $Q_{10}$ values in paddy fields were mostly consistent with other studies during the fallow periods (1.72 at 5 cm and 2.01 at 10 cm depths).

### *4.2. $CH_4$ emissions under different fertilizer loads*

The mechanism of $CH_4$ production, aerenchyma in rice as a gas-exchange medium, number of productive tillers/m$^2$, root mass, and microbial activity influence the $CH_4$ flux (Shao and Li, 1997). $CH_4$ production easily occurs in highly reduced and anoxic environments. Plants may influence $CH_4$ emissions from submerged soil. For example, more than 90% of the $CH_4$ emissions in paddy fields are emitted by plant-mediated activities (Holzapfel-Pschorn et al., 1986).

In temperate paddy fields investigated in this study, seasonal $CH_4$ emission variations did not closely correlate with temperature as observed before by Schütz et al. (1990). The air temperature in Shanghai during the rice-growing season varied from 11.6 °C to 32 °C in 2011 and was not a limiting factor for $CH_4$ emission (Das and Adhya, 2012; Kögel-Knabner et al., 2010; Rui et al., 2011).

$CH_4$ fluxes increased after tillage (June 09, 2011) and reached maximum levels before harvest. The increase in $CH_4$ fluxes is probably related to the processes induced by the growth of rice plants. $CH_4$ fluxes decreased and were maintained at low levels after the harvest probably because of (1) the absence of plant-medium transport, (2) lower temperature, and (3) the absence of an anaerobic environment because the paddy field was not flooded.

The effects of different types and amounts of fertilizer on $CH_4$ emissions vary: compared with N salts, addition of compost and NPK fertilizers significantly improves methanotrophic activity (Jugnia et al., 2012). Wang et al. (1992) showed that fertilization application enhances $CH_4$ emissions likely because fertilizers increase soil pH and Eh. Nitrogen source was a key co-factor affecting $CH_4$ emissions being interlinked with $NH_4^+$ oxidation and affecting $CH_4$ oxidation (Chowdhury and Dick, 2013). In our study, $CH_4$ emissions observed under high fertilizer loading were higher than those observed under low and moderate fertilizer loadings. However, no significant difference among treatments was observed (Fig. 4, Table 1).

### *4.3. $N_2O$ emission from different fertilizer applications*

Denitrification occurs not only in upland fields but also in wetland fields. Paddy fields are wetland fields that are important sources of $N_2O$ emissions. Many factors affect $N_2O$ emissions, such as water management (Hou et al., 2012; Yang et al., 2011), fertilizer application (Cai et al., 1997; Zou et al., 2008), land use (Yang et al., 2003), straw mulching (Xing et al., 2009), and tillage (Ahmad et al., 2009; Baggs et al., 2003).

Most $N_2O$ emission responses in the paddy field have a positive relationship with fertilizer application (Hou et al., 2012; Liao and Yan, 2011; Liu et al., 2012). Hou et al. observed that high $N_2O$ emissions result from high fertilizer levels. N fertilizer application may increase $N_2O$ emissions by 5–6 times at 200 kg N/ha and by 10–14 times at 270 kg N/ha. The most suitable rate of N fertilizer application is 200 kg N/ha because this rate exerts the lowest global warming potential (Ma et al., 2007).

### *4.4. Consumption of fertilizer*

Chemical fertilizer production requires a significant amount of energy and generates high levels of GHGs as a by-product (Wood and Cowie, 2004). Fertilizer production consumes approximately 1.2% of the world's energy and is responsible for approximately 1.2% of the total

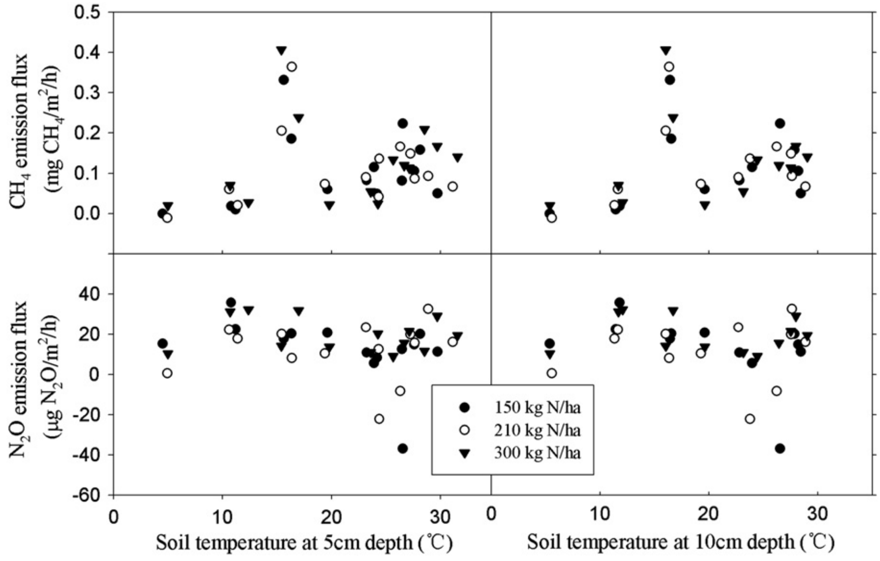

**Fig. 6.** The effect of soil temperature on $CH_4$ and $N_2O$ emission fluxes.

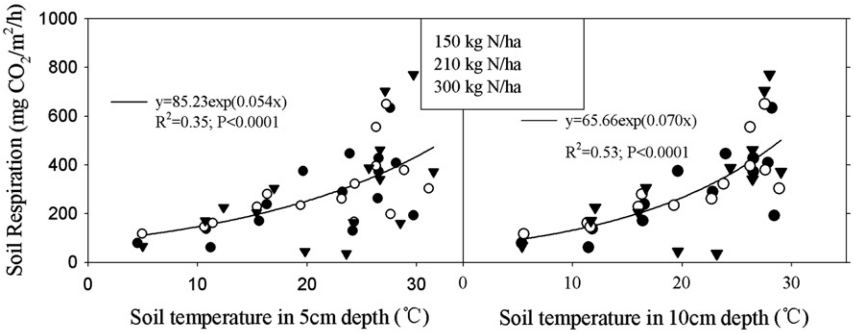

**Fig. 7.** The relationships between soil respiration ($Rs$, mg $CO_2/m^2/h$) and soil temperature at 5 cm and 10cn depth. The dynamic curves were fitted from exponential equation. ($Rs = \alpha e^{\beta T} = 85.23e^{0.054T}$, $Q_{10} = e^{10\beta} = e^{10 \times 0.054} = 1.72$ at 5 cm depth; $Rs = \alpha e^{\beta T} = 65.66e^{0.070T}$, $Q_{10} = e^{10\beta} = e^{10 \times 0.070} = 2.01$ at 10 cm depth).

GHG emissions worldwide; the GHG emissions from urea production is 1.6 t $CO_2$/t N (Kongshaug, 1998). Thus, a decrease in fertilizer usage in croplands will not only reduce GHG emissions but also contribute to food security.

Inputs and farming management practices used in agriculture, such as chemical addition and tillage, can increase crop yields. However, the overall energy consumption in agriculture has increased rapidly, and this increase has generated more GHG emissions. The efficient use of fertilizers can enhance crop production. Qiao et al. (2012) reported that increasing N fertilizer application is crucial for grain yield improvement and found a maximum N application rate of 232–257 kg N/ha, as deduced from a yield-fertilizer rate curve. In our study, the rice yields obtained under low fertilizer loading were lower than those obtained under moderate and high fertilizer loadings; no significant difference in yields between moderate and high fertilizer loading were observed. Because the increased fertilization application did not cause same increased trend of rice yields, a lower GHG emissions/crop yield ratio and optimum yield was observed under moderate fertilizer application.

## 5. Conclusions

GHG emissions from large paddy fields and excessive fertilizer application can significantly contribute to global warming. Managing fertilizer application is one of the more feasible ways of limiting GHG emissions from paddy areas. Low fertilizer application results in low energy consumption, which can contribute to the reduction of GHGs and lessen global warming. Based on the results of this study, a fertilizer application rate of 210 kg N/ha in paddy fields is recommended for the benefit of both the environment and the security of food.

## Conflict of interest

All authors have no conflict of interest including any financial personal or other relationships with other people or organizations within three years of beginning the submitted work that could inappropriately influence, or be perceived to influence, their working in this manuscript.

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