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RESEARCH ARTICLE

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Characteristics of CO_2, CH_4 and N_2O emissions from winter-fallowed paddy fields in hilly areas of South China

Abstract With closed static chamber and modified gas chromatograph (HP5890II), the *in situ* measurements were made on the CO_2, CH_4 and N_2O emissions from winter-fallowed paddy fields in the hilly areas of South China. Gas samples were taken simultaneously from the fields with and without rice stubble. The results showed that both of the fields had the peak value of CO_2 flux in the later afternoon. In the fields with and without rice stubble, the CH_4 flux was positive in the day time while negative in the night, and the N_2O flux in the day time was 1.79 and 1.58 times as much as that in the night, respectively. The diurnal average CO_2 flux in the plot with rice residue was significantly higher than that of bare plot ($P < 0.05$). Correlation analysis demonstrated that CO_2 flux in the winter-fallowed paddy fields had significant correlations with soil temperature at a depth of 5 cm, above-ground temperature and air temperature, suggesting that temperature was the main factor affecting CO_2 emission from rice fields after harvesting. During the observation time (from November 10, 2003 to January 18, 2004), the average CO_2, CH_4 and N_2O fluxes in the field with rice residue were (180.69 ± 21.21) mg/m$^2 \cdot$h, (-0.04 ± 0.01) and (21.26 ± 19.31) μg/m$^2 \cdot$h, respectively. Compared with bare fields, the CO_2 flux in the field with rice residue was 13.06% higher, CH_4 absorption increased by 50%, while N_2O flux was 60.75% lower. It was concluded that the winter-fallowed paddy field in hilly areas of South China was the source of atmospheric CO_2 and N_2O, and the sink of atmospheric CH_4.

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1 Introduction

The increase in atmospheric greenhouse gases concentration is the main factor leading to global warming, and CO_2, CH_4 and N_2O are of great importance. Rice farming is now believed to be the primary anthropogenic source of CH_4 (Jacobson, 2005), and annual global CH_4 emissions from paddy fields were estimated to be 20–40 Tg (Wang, 2001), accounting for 8%–13% of the total emission (ICPP, 1992). Another greenhouse gas N_2O is also involved in rice farming, which was reduced to N_2 under anaerobic conditions, but anaerobic-aerobic circle favors the formation of N_2O (Granli and Bockman, 1994). Nevertheless, almost all experimental treatments in previous studies were focused on the rice-growing period. Research concerning CO_2 emission measurement *in situ* and synchronic identification of CO_2, CH_4, N_2O in paddy field were lacking (Kahlil et al., 1990; Wang and Wang, 2003; Zou et al., 2003), especially in fallow paddy field in winter (Xu and Cai, 2004). Some studies indicated that fallow paddy field was likely to be the sink of CH_4 (Thurlow et al., 1995; Singh et al., 1998). From most of the researchers, the estimated annual N_2O emission in fact was only the flux of the dry land soil over the world (Bouwman, 1994; Houghton et al., 1992). According to Xu and Hong (1999), the fallow fields in tropical and sub-tropical regions of the Northern Hemisphere were the potential sources of N_2O emission in terms of N_2O-N, which was about 0.75 Tg all year around. Based on the experiment platform Heshan Hilly Land Interdisciplinary Experimental Station, the uniform experimental program from branch central of CERN (Chinese Ecosystem Research Network) atmosphere department, and field measurements were conducted. This research is part of the greenhouse gases flux measurement above the ground of agroforestry ecosystem in northern China. Agroforestry ecosystem has an important role in land-use in northern China, hence the greenhouse gas emission measurement in the fallow paddy field can progressively improve our understanding about the variation of greenhouse gases in agroforestry ecosystem.

2 Materials and methods

2.1 Site description

The selected paddy field is a part of the agro-forestry ecosystem in Heshan Hilly Land Interdisciplinary Experimental Station, CAS (Chinese Academy of Sciences) (112°54′ E, 22°41′ N), which is located in the central part of Guangdong Province, 80 km away from Guangzhou City. The site is characterized by a lower subtropical monsoon climate, with a mean annual temperature of 21.7°C, July mean temperature 28.7°C (absolute maximum 37.5°C), accumulated temperature above 10°C of 7 597.2°C, a mean precipitation of 1 700 mm, annual total evaporation of 1 600 mm. The soil type is locally described as crimson soil (namely Latosol reddish soil).

2.2 Experimental design and statistical analysis

The experimental paddy field was divided into plots with and without rice stubbles, and each treatment had three duplicates randomly. Proper measures were taken to ensure that the soil and environmental conditions in the chamber were equal to those in the whole field. The seedlings of later-cropping rice were planted in the field with stubbles of 3–4 cm in height left after harvest in the previous growing season. Bare plots received the same fertilization and water management as the plots with stubbles, fallowing in the previous growing season. Generally the sample gas was collected from 9:00 to 12:00 (Kessavalou et al., 1998; Zou et al., 2003). This sampling time was based on the diurnal pattern of gas emission, assuming that this pattern remained the same in a day. Gas collection in our experiment was undertaken from 9:00 to 12:00, lasting about 69 days from November 10, 2003 to January 17, 2004. The measurement of daily variation was also conducted on sunny days at 2-h intervals in the daytime and at 3-h intervals in the nighttime during November, 2003.

Details of the method applied were available in Wang and Wang (2003). The sample gas was collected in a closed static chamber (50 cm × 50 cm × 50 cm) made from stainless steel, using a heat-a giant sheet outside the chamber in order to avoid the temperature increment inside the chamber under sunshine, which would reduce an influence on the observation. The chamber placed on a steel base that was inserted into the soil 5 cm deep. A silicon tube with a three-way stopcock small fan, a thermometer and a gas collector was internally installed to each chamber for gas sampling. 100 mL gas samples collected from the chamber headspace at 0, 10, 20 and 30 min, respectively, were analyzed in the laboratory with a modified gas chromatography in which an electron capture detector (ECD) for N_2O analysis and a flame ionization detector (FID) for CH_4 and CO_2 analysis. Columns were packed with Porpak Q 80/100 mesh. FI- and EC-detectors were heated to reach temperatures of 150°C and 330°C, respectively. The column temperature was held at 55°C. High-pure nitrogen (30 mL/min) was used as carrier gas for both FI- and EC-detectors. Air was added to the nitrogen carrier gas flow (400 mL/min) before the detectors increased the sensitivity. Flux of gases emission was calculated through making a linear regression of the four gases concentrations.

2.3 Flux calculation

The greenhouse gas emission flux, namely the change of the gas quantity over the soil per hour per unit area was calculated using the following equation

$$F = \frac{\Delta m}{A \cdot \Delta t} = \frac{\rho \cdot V \cdot \Delta C}{A \cdot \Delta t} = \rho \cdot h \cdot \frac{\Delta c}{\Delta t}$$

where F is the gas emission flux (mg/m^2·h); ρ is the gas density in the standard condition ($CH_4 = 0.716$ kg/m^3); Δc (ppm) and Δm (mg) are the mixed gas concentration and the gas mass in the chamber during a given period (Δt), respectively; h (m), V (m^3) and A (m^2) are the height, volume and bottom area of the chamber, respectively. When F is negative, F indicates that the gases of experimented system were taken up from the atmosphere, and when positive, it means that the gases emitted into the atmosphere.

2.4 Temperature measurement

The soil temperature at 5 cm deep, soil surface temperature and the air temperature in the chambers were measured with portable thermometer JM624 (ranging from −30°C to 50°C at 0.1°C intervals, with 0.5°C accuracy) respectively at beginning and the end of the sampling time. Then the two temperatures were averaged.

3 Results and analysis

3.1 Dynamic variation of CO_2 emission from fallow paddy field in winter

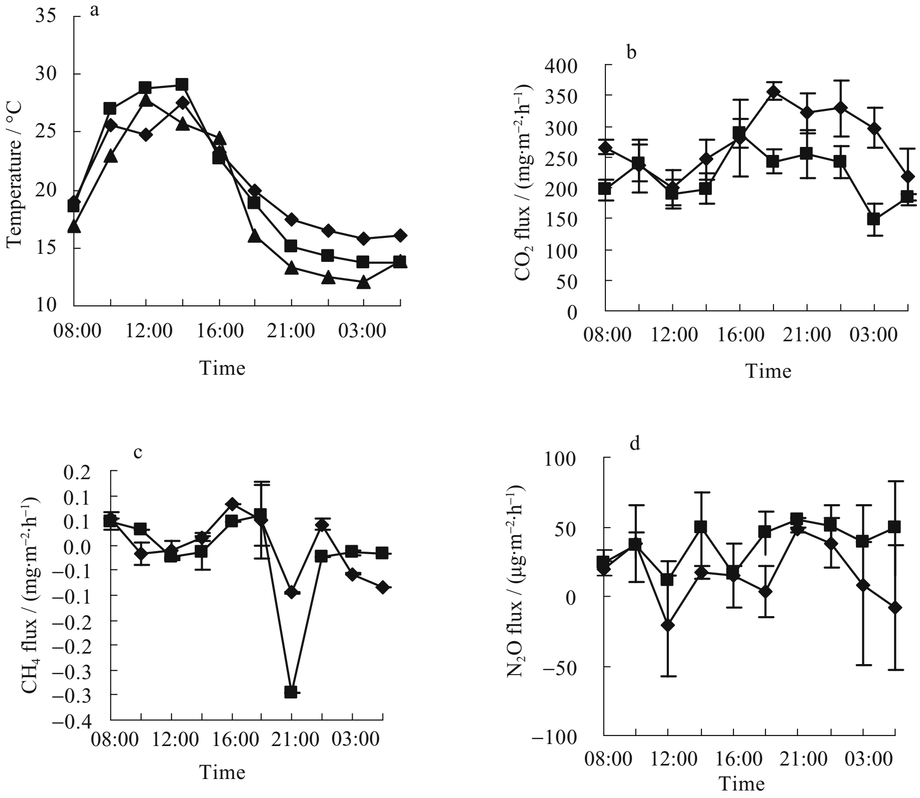
The diurnal dynamic variation of the soil temperature, soil surface temperature and air temperature are shown in Fig. 1(a). In the morning, air temperature increased as solar radiation increased with time prolonging. Compared with the air temperature, soil temperature and surface temperature were relatively higher and lagged behind air temperature. Air temperature reached the peak at 12:00, but soil temperature and surface temperature had their peak values at 14:00. Air temperature was relatively lower when surface temperature was close to 30°C. Soil temperature, surface temperature and air temperature decreased significantly after 18:00 in the afternoon and maintained below 15°C till the next morning.

The mean daily CO_2 emission from the field plot with residue stubbles and from the bare plot were 274.96 ± 16.20 and 218.27 ± 13.23 mg/m^2·h, respectively. CO_2 emission flux of the field with residue stubbles increased after 12:00 and reached the maximum around 18:00, but that of the bare plot had the peak value approximately at 16:00 and declined subsequently at night (Fig. 1(b)). It could be concluded that the mean daily CO_2 emission from the field with stubble was much higher than that from the bare plot ($P < 0.05$) and neither daily CO_2 emission from the plot with residue stubbles nor that from the bare plot had the significant correlation with soil temperature, surface temperature and air temperature.

The temperature variation during measurement is shown in Table 1. Soil temperature, surface temperature and air temperature rose gradually after harvest in November and reached 25.65°C, 26.98°C and 23°C respectively at the end of November, but all temperatures went down later. Temperature maintained 15°C except for lower temperatures in a short period and went up after December 22. At the same time, CO_2 emission flux from plot with residue stubbles went down from 340.63 mg/m^2·h after harvest to the minimum 39.71 mg/m^2·h in the middle of December. Afterward, CO_2 emission flux increased with temperature increment. Both temperature and CO_2 emission flux had obvious fluctuation since January 8 (Table 1). The correlation analysis indicated that CO_2 emission flux of the plot with residue was significantly positively correlated with soil temperature, surface temperature and air temperature, which implied that dynamic variation of the CO_2 emission in fallow paddy field was mainly attributed to the variation of the temperature. Paddy field with residue was the source of CO_2 emission.

3.2 Dynamic variation of CH_4 emission from fallow paddy field

From Fig. 1(c), it can be seen that CH_4 emissions from the plot with residue and the bare plot were positive in the daytime but negative in the nighttime immediately after harvest (November 24) and fallow fields were able to absorb little CH_4. During the measurement, CH_4 emission from the field with residue and the bare plot were both negative, which means that fallow rice field was capable of absorbing CH_4 in winter (Table 1). CH_4 fluxes of the plot with residue and the bare plot were −0.04 ± 0.01 and −0.02 ± 0.01 mg/m^2·h, respectively. The results and correlation analysis reflected that CH_4 emission from the rice field with residue was 50% higher than that from the bare plot, both diurnal variation of CH_4 emission and total CH_4 emission during the measurement had no significant relation with the soil temperature, aboveground temperature and air temperature.



Note: —◆— stands for plot with rice residue and soil temperature at a depth of 5 cm; —■— for bare plot and aboveground temperature; and —▲— for air temperature

Fig. 1 Diurnal variations of temperature and greenhouse gas fluxes in fallow paddy fields in winter (8:00–18:00, detecting per 2 h; 8:00–6:00, detecting per 3 h)

Table 1 Dynamic variations of temperature and greenhouse gas fluxes in fallow paddy field in winter

Date (year-month-day)	Temperature /°C			CO_2 flux /$(mg \cdot m^{-2} \cdot h^{-1})$		CH_4 flux /$(mg \cdot m^{-2} \cdot h^{-1})$		N_2O flux /$(\mu g \cdot m^{-2} \cdot h^{-1})$	
	Soil temperature	Aboveground temperature	Air temperature	Plot with rice residue	Bare plot	Plot with rice residue	Bare plot	Plot with rice residue	Bare plot
2003-11-10	17.05	16.58	14.53	340.63	232.60	–0.07	0.04	–23.76	–0.54
2003-11-13	14.95	15.23	16.93	297.44	164.48	0.04	–0.01	26.18	65.63
2003-11-17	20.60	20.75	22.68	310.28	269.79	–	–0.03	41.05	33.31
2003-11-21	20.88	21.20	22.93	243.04	194.59	–0.03	0.06	19.54	57.83
2003-11-24	25.65	26.98	23.00	235.43	239.99	–0.02	0.03	38.23	36.50
2003-12-01	15.90	16.68	14.95	232.08	122.95	–0.03	–0.02	62.64	21.91
2003-12-04	15.18	14.05	16.23	136.59	187.32	–0.04	–0.02	3.48	35.65
2003-12-08	14.50	14.30	13.60	65.09	114.35	–0.06	–0.02	–28.66	3.93
2003-12-11	14.58	13.50	14.20	89.81	45.11	0.00	0.05	16.08	–21.93
2003-12-17	13.53	14.85	13.58	39.71	91.39	0.03	–	–25.37	12.32
2003-12-20	10.33	10.20	10.80	–	–	–0.14	0.02	–	14.02
2003-12-22	10.23	10.73	13.80	106.16	77.88	–0.02	0.02	19.17	13.52
2003-12-25	11.85	12.20	13.23	163.63	112.47	–0.12	–0.07	6.92	30.08
2004-01-02	13.08	12.15	13.80	174.39	120.86	–0.07	0.01	147.09	–
2004-01-05	15.48	15.13	16.25	230.22	220.09	–0.01	–0.06	89.25	169.06
2004-01-08	17.13	17.13	18.83	208.25	225.78	–	–0.07	–	218.51
2004-01-13	12.65	13.88	12.48	88.43	117.54	0.00	0.00	144.93	168.11
2004-01-15	16.48	16.23	16.53	211.09	212.96	–0.04	–0.15	39.42	197.81
2004-01-17	11.83	13.43	11.80	80.21	126.56	–0.08	–0.10	–214.77	–80.58

3.3 Dynamic variation of N_2O emission from fallow paddy field in winter

N_2O emission from the rice field with residue was slightly lower than that from the bare plot on November 24 (Fig. 1(d)). N_2O emission in the daytime was slightly higher than that in the nighttime. N_2O emission fluxes from the paddy field with residue and the bare plot in daytime were 1.79 times and 1.58 times higher than those in nighttime. N_2O emission from both paddy field with residue and bare plot had obvious fluctuation in over-wintering period except from November 10 to December 25 (Table 1). During the whole measurement, the mean N_2O emissions from the paddy field with residue and the bare plot were 21.26 ± 19.31 and 54.17 ± 19.06 $\mu g/m^2 \cdot h$, respectively, and the former was 60.75% lower than the latter. Soil temperature, surface temperature and air temperature had no effect on the diurnal change of N_2O emission and total N_2O emission over the whole measurement period.

4 Discussion

4.1 Characteristics of CO_2, CH_4 and N_2O emission from fallow paddy field in winter

It is considered that CO_2 emission is mostly from organic (soil organic, litter and dead root) decomposition and root respiration (Bowden et al., 1993). Since there are no rice plants left in fallow paddy field in winter, root respiration could be ignored. CO_2 emission from the paddy field with residue was higher than that from the bare field, which might be associated with higher litter amount and residues after harvest. Based on the results from Lower Liaohe River Plain by Xie et al. (2004), the finding of CO_2 emission in this paper was a bit higher, which might be a result of relatively higher temperature in winter in South China. Mean CO_2 emissions from the rice field with residue and the bare field were both higher during the entire measurement period; therefore, the fallow paddy field in winter was well recognized as one of CO_2 emission sources. And the paddy field was a crucial CH_4 emission source (IPCC, 1992), and the CH_4 emission from flooding rice field during a year was higher than that from the drained rice field (Cai et al., 2005). The flooding rice field was propitious for CH_4 continuous emission because of the abiotic condition under flooding (Cai et al., 2003). While the drained paddy field or fallow paddy field had already been proven to be the CH_4 emission sink by Thurlow et al. (1995) and Singh et al. (1998), and the capacity of CH_4 absorption depended on the soil temperature and moisture. According to our study, it was concluded that, after harvest, not only the field with residues but also the bare field showed negative CH_4 emission and positive CH_4 absorption, namely, the fallow paddy field was the sink of CH_4. CH_4 emission without rice plants mainly resulted from transmethylation process and CO_2 reduction by obligative anaerobic microorganisms under the anaerobic condition (Hou et al., 2000). For there was no rice plants left in paddy field after harvest.

It was unfavorable for producing CH_4 after paddy field was drained when soil temperature was relatively lower, owing to the lower activities of microbes. Whether it was CH_4 emission or absorption was related to the sum of CH_4 production and CH_4 oxidation (Wang et al., 1998), and CH_4 oxidation depended on the soil aeration condition. It was expected that soil water content would fall down because of stronger light density and seasonal drought. Yang and Chang (1998) pointed out that CH_4 was hardly produced when soil water content went down to 23%. CH_4 absorption had no significant correlation with soil temperature, and CH_4 uptake started immediately after harvest possibly due to soil water deficit.

A great amount of soil N_2O came from nitrification and denitrification processes, the oxidative status of soil in winter was different from that under flooding situation as a result of higher accumulation of organic carbon and nitrate in winter (Xu and Hong, 1999), which did favor the organic decomposition and the following nitrification. Feng and Yin (1995) proved that nitrifying and denitrifying bacteria played an essential role in producing N_2O when soil water content ranged from 45% to 75% of maximum field capacity already.

Higher soil water content could increase N_2O emission because it promoted denitrification. In fact, N fertilizer, soil water content, oxygen concentration, organic matter and solubility of N_2O in water and so on, all had effects on N_2O emission (Blackmer et al., 1982; Yang and Chang, 1997). Paddy field with residue as well as bare plot kept low N_2O emission during the measurement after rice was harvested, but N_2O emission ascended drastically after middle-December. According to the simulation experiment by Byrnes et al. (1993), NO_3^- content at the beginning of winter was 30–50 times as high as that after fallow for two or three months, which might be associated with accumulated NO_3^- content after harvest and stimulated N_2O transformation and emission sequentially. The occurrence of sudden, strong N_2O pulses emission in the later period had nothing to do with the draining after harvest. It is widely accepted that soil water content has crucial effects on N_2O emission. Generally speaking, rice field with residue had better aeration status, so the N_2O emission was lower.

4.2 Factors influencing CO_2, CH_4 and N_2O emission from fallow paddy field in winter

There was no significant correlation between daily mean CO_2 emission and temperature (including soil temperature at the depth of 5 cm, surface temperature and air temperature), which reflected that temperature was not a key factor that influences the diurnal variation. Not only CO_2 flux emitted from soil respiration but also soil porosity, CO_2 concentration gradient among soil-plant-atmosphere system and wind speed can affect the CO_2 emission rate (Li et al., 2002; Nakadai et al., 2002). The CO_2 emission flux was positively correlated to temperature; thereby temperature played a decisive role in CO_2 seasonal variation from soil, for higher temperature may lead to higher decomposition rate, the activity of microorganism and emission rate. The CO_2 emission not from rice plants was significantly correlated with temperature as showed by Zou et al. (2003) as well, which was independent of tillage (non-tillage and tillage) (Wan and Lin, 2004). However, unlike CO_2 emission, neither daily CH_4 emission nor total CH_4 emission during the measurement was significantly correlated with temperature in hilly land in South China. Temperature alone could not account for dynamic change of CH_4 emission and seasonal variation of CH_4 emission. Actually, soil drought resulting from temperature had an evident influence on CH_4 emission. As for N_2O emission, besides soil water content, temperature played an important role in N_2O emission. There was a significant correlation between N_2O emission and soil temperature, and air temperature (Zou et al., 2003). Our results suggested that temperature (including soil temperature, aboveground temperature and air temperature) had no correlation with N_2O emission. What really influences N_2O emission is the interaction of soil water content and aeration condition. Unfortunately, no measurement of soil water dynamic variation in our study was conducted, and further experiments are to be carried out in future.

5 Conclusion

The winter-fallowed paddy fields with and without residue both had the peak values of CO_2 flux in the late afternoon. In the fields with and without rice stubble, the CH_4 flux was positive in the day time while it was negative in the night, and the N_2O flux in the day time was 1.79 times and 1.58 times as much as that in the night, respectively. Compared with the bare field, diurnal average CO_2 flux in the field with rice stubble was significantly higher ($P<0.05$). However, CO_2 flux in the field with residue in terms of its total amount during the measurement was a little higher but with no significance. During the measurement, CO_2 flux changed with the temperature variation. Correlation analysis demonstrated that CO_2 flux in the winter-fallowed paddy fields had significant correlations with soil temperature at a depth of 5 cm, aboveground temperature and air temperature, suggesting that temperature was the main factor affecting CO_2 emission from the rice field after harvesting. It was concluded that the winter-fallowed paddy field was the source of atmospheric CO_2 and N_2O, and the sink of atmospheric CH_4, CO_2 and N_2O flux in the rice field with stubble was lower than that in the bare plot because of the better aeration condition. Hence autumn plowing is recommended after rice harvest, which might reduce CO_2 and N_2O emissions from the fallow paddy field in winter. It is necessary that the condition of greenhouse gas emission should be taken into account, for many economic crops are grown after later-cropping of rice in South China.

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