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Comparison of Field Measurements of CH_4 Emission from Rice Cultivation in Nanjing, China and in Texas, USA①

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ABSTRACT

Field measurements of methane emission from rice paddies were made in Nanjing, China and in Texas, USA, respectively. Soil temperature at approximately 10 cm depth of the flooded soils was automatically recorded. Aboveground biomass of rice crop was measured approximately every 10 days in Nanjing and every other week in Texas. Seasonal variation of soil temperature in Nanjing was quite wide with a magnitude of 15.3°C and that in Texas was narrow with a magnitude of 2.9°C. Analysis of methane emission fluxes against soil temperature and rice biomass production demonstrated that the seasonal course of methane emission in Nanjing was mostly attributed to soil temperature changes, while that in Texas was mainly related to rice biomass production. We concluded that under the permanent flooding condition, the seasonal trend of methane emission would be determined by the soil temperature where there was a wide variation of soil temperature, and the seasonal trend would be mainly determined by rice biomass production if there are no additional organic matter inputs and the variation of soil temperature over the rice growing season is small.

Key words: CH_4 emission, Rice paddies, Rice biomass production, Soil temperature

1. Introduction

Methane emission rates from rice paddies generally show a high temporal variability, but this seasonal pattern exhibits spatial variability between sites in the United States (Sass et al., 1992, Huang et al., 1997), Italy (Holzapfel–Pschorn and Seiler, 1986, Schütz et al., 1989), and China (Wang et al., 1993). Holzapfel–Pschorn and Seiler (1986) reported a close relationship between the mean values of CH_4 emission rates and soil temperatures throughout the rice vegetative period from an Italian rice field. Chen and Wang (1993) reported that methane emissions from a Chinese rice paddy were correlated with air temperature only on sunny days when cloudiness was less than 3 / 10 (cloud coverage of 30%). However, the seasonal course of CH_4 emission observed by several authors from the United States (Cicerone et al., 1983,

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Sass et al., 1990, 1992), Italy (Schütz et al., 1990a), Indonesia (Nugroho et al., 1996) and Japan (Yagi et al., 1996) cannot be directly attributed to temperature changes, although the diel patterns were correlated with diel temperature changes (Schütz et al., 1990b, Sass et al., 1991, Zheng et al., 1999). Nevertheless, a very strong dependence of daily methane emission on rice above-ground biomass was observed over an entire rice growing season in Texas (USA) (Sass et al., 1990, Huang et al., 1997), and hence the seasonal course of methane emission from rice fields in this particular location was thought to be rice biomass production dependent (Huang et al., 1997).

By comparing the magnitude of air temperature variations between the sites of Beaumont in Texas (USA) and Vercelli (Italy), we suggested that the seasonal response of methane emission to soil temperature is dependent on the magnitude of temperature variation rather than the temperature itself (Huang et al., 1998). In Beaumont, methane emission measurements were generally made during the period from late May / early June to August. The variation of monthly air temperature is only some 1.3°C during this period. In consonance with this small variation in temperature, seasonal pattern of methane emission was not found to be temperature dependent (Sass et al., 1990, 1992; Huang et al., 1997). In contrast with the Beaumont case, the air temperature in Vercelli, where methane emission was reported to be temperature related (Holzapfel-Pschorn and Seiler, 1986), varied from 17.5°C in the early season (mid May) up to 24.1°C in the heading-flowering period (mid August) and dropped to 20°C at harvest (mid September), approximately a 6.6°C in difference between the maximum and the minimum during the methane observation periods.

To further investigate the factors that influence seasonal variations of methane emission from rice paddies, field experiments were conducted in Beaumont, Texas (USA) and in Nanjing, Jiangsu Province (China) where the air temperature varies widely over the rice growing season (Domröd and Peng, 1988). We made simultaneous measurements of soil temperature, rice biomass production and methane fluxes from the two experiments with the same methods. The objective of this paper is to identify the factors regulating the seasonal pattern of CH_4 emission from rice paddies in the sites of Nanjing, China and Texas, USA, and hence to help developing a better understanding of what drives the spatial variability in seasonal pattern of CH_4 emission from rice paddies.

2. Experiments and measurements

One field experiment was performed during the 1997 rice growing season in the Texas A & M University Agricultural Research and Extension Center near Beaumont, Texas, USA. The other field experiment was conducted during the 1999 rice growing season in the county of Jiangning near Nanjing of Jiangsu Province, China. A *japonica* cultivar named Lemont was planted in the Texas experiment. The rice crop was drill-planted with rows spaced 20 cm apart on April 18. The duration from planting to maturity was approximately 120 days. Permanent flooding was initiated on May 28 and the field remained flooded for about 11-12 weeks before being drained in preparation for harvest. A *japonica* cultivar named ♯9516 was planted in the Nanjing experiment. The rice crop was planted in a seedling bed on May 14. The duration from planting to maturity was approximately 160 days. The transplanting date was June 21. Permanent flooding was initiated 3 days before transplanting and field remained flooded until one week before harvest. A regular fertilization in these experiments was performed according to the local agricultural practice. Nitrogen fertilization as urea (total of 190 kg N / ha) was applied as needed at planting (35%), just before permanent flooding (35%)

and at panicle differentiation (30%) in the Texas experiment. Chemical fertilizer (total of 300 kg N / ha) was applied at transplanting (56%), elongation (28%) and booting (16%) in the Nanjing experiment. No additional organic matter was incorporated into the soil during these experiments. More detailed information of experimental sites, climate, soil, rice phenological development and fertilization is given in Table 1.

Table 1. Basic information of climate, soil, rice phenological development and fertilization at the experimental sites in Nanjing, China and in Texas, USA

Items	Experimental site	
	Jiangning, Nanjing (China)	Beaumont, Texas (USA)
Latitude, Longitude	31°52′N, 118°50′E	29°57′N, 94°30′W
Observation Period	June ~ October	May ~ August
Climate During the Observation Period		
Mean air temperature (°C)	24.0	26.7
Range of monthly T_{air} (°C)	16.9 ~ 28.0	24.0 ~ 28.3
Total rainfall (mm)	606	581
Mean solar radiation (Einstein / m^2 / d)	36.8	40.4
Soil		
Classification	Hydromorphic	Bernard–Morey
Organic carbon (g / kg)	17.5	11.1
Sand % (mean ± SD)	4.2 ± 0.8	23.8 ± 1.0
Silt % (mean ± SD)	45.1 ± 0.8	41.8 ± 1.0
Clay % (mean ± SD)	50.7 ± 1.9	34.5 ± 0.7
Rice Phenological Development		
Planting	May 14, 1999	April 18, 1997
Emergence	May 17, 1999	April 28, 1997
Heading	September 5, 1999	July 17, 1997
Maturity	October 20, 1999	August 20, 1997
Fertilization (kg / ha)		
N	300	190
P_2O_5	40	56
K_2O	40	56

In these two field experiments, boardwalks to randomly selected methane measurement sites were installed from border levees to reduce soil disturbance during flux measurements. Permanently installed aluminum flux collars near the boardwalks ensured reproducible placement of gas–collecting chambers during successive methane emission measurements. Three and two replicates were applied at the Texas site and the Nanjing site, respectively. During the permanent flooding period, methane measurements from rice fields were taken approximately twice weekly in both experiments, by taking samples of the headspace gas of an open–bottom chamber. The cross–sectional area of the chamber used at the Beaumont site and the Nanjing site was 0.397 (0.63 × 0.63) m^2 and 0.25 (0.5 × 0.5) m^2, respectively. The chamber was equipped with a circulating fan to ensure complete gas mixing and wrapped with a layer of sponge and aluminum foil to minimize temperature changes during the period of sampling. While taking gas sampling, the chamber was placed over the vegetation with the rim of the chamber below the water surface and fitted into a groove in the permanent collar. Methane mixing ratios were obtained by gas chromatography (Shimadzu) with a flame ionization detector. The emission was determined from the slope of the mixing ratio change in the five samples (50 cm^3 and 60 cm^3 in Texas site and in Nanjing site, respectively) taken over a 20–min sampling period. Sample sets that did not yield a linear regression value of r^2 greater than 0.90 were rejected. Rates of methane emission were determined from an average of three replicates in Texas site and an average of two replicates in Nanjing site. Water depth and air temperature inside chamber were recorded with each set of emission measurements.

Soil temperature at approximately 10–cm depth in the flooded soils was automatically recorded through the Optic StowAway Temperature Loggers (Onset Computer Corporation, USA) with one–hour and two–hour intervals in the Texas site and the Nanjing site, respectively. Aboveground biomass was measured every other week in the Texas site and approximately every ten days in the Nanjing site. The plants were cleaned with water and then oven dried to a constant weight at approximately 90°C.

3. Results and discussion

3.1 *Seasonal trends of methane emission, soil temperature and rice biomass production*

Methane fluxes in both sites increased steadily during the early 35–day period (Fig. 1a). The emission rates were very similar between these two, ranging from 0 to 8.5 mg $m^{-2}h^{-1}$. The slow increment of methane emission in the early season is recognized to be associated with a relative high and slowly decreasing soil potential (Eh) for the Texas site. Evidence from a Texas field measurement (Lewis, 1996) shows that the Eh in top 10 cm depth of soil did not reach a critical value of −150 mv for methane production (Wang et al., 1993).

After the 35–day period, the emission trends became distinguishable. Emissions at the Nanjing site no longer increased considerably, but three peaks of methane flux were observed around 35, 50 and 80 days after transplanting, respectively (Fig. 1a). The highest emission occurred in 50 days after transplanting with a rate of 10.6 mg $m^{-2}h^{-1}$. Unlike the seasonal course at the Nanjing site, emissions at the Texas site showed an increasing trend until around 10 days after heading (Figs. 1a and 1c). The methane flux reached a maximum value of 21.9 mg $m^{-2}h^{-1}$. Another emission peak was observed around 10 days before heading with a rate of 18.8 mg $m^{-2}h^{-1}$. Over a 40–day period from 35 to 75 days after transplanting / flooding when the observation in the Texas site stopped, average methane emissions were, respectively, 7.3 and 16.3 mg $m^{-2}h^{-1}$ for the Nanjing site and the Texas site, approximately a 2.2–fold difference.

Soil temperature at the Nanjing site varied by 15.3°C, ranging from 13.6°C in harvest to 28.9°C in early August (Fig. 1b) with a seasonal average value of 24.5°C. It is noteworthy that the periodic variations in soil temperature (Fig. 1b) were accompanied by the variations in methane emission (Fig. 1a) over the season. During the early 40–day period, soil temperature increased sharply from some 21.5 to 28.9°C, with a 7.4°C difference (Fig. 1b). Simultaneously, methane fluxes increased to peak emission of 8.6 mg $m^{-2}h^{-1}$ (Fig. 1a). The second peak in methane emission appeared between 45 and 70 days after transplanting when soil temperature ranged from 27.1 to 22.5°C, with a 4.6°C difference (Fig. 1b). The emission rates ranged from 12.7 to 5.1 mg $m^{-2}h^{-1}$, with a 7.6 mg $m^{-2}h^{-1}$ difference (Fig. 1a). During the period between 75 and 95 days after transplanting, soil temperature varied from 26.0 to 19.0°C, with a 7.0°C difference (Fig. 1b). The relevant methane flux ranged from 7.1 to 1.5 mg $m^{-2}h^{-1}$, with a 5.6 mg $m^{-2}h^{-1}$ difference (Fig. 1a). In contrast with the wide variation of soil temperature at the Nanjing site, the seasonal change of soil temperature at the Texas site was very small

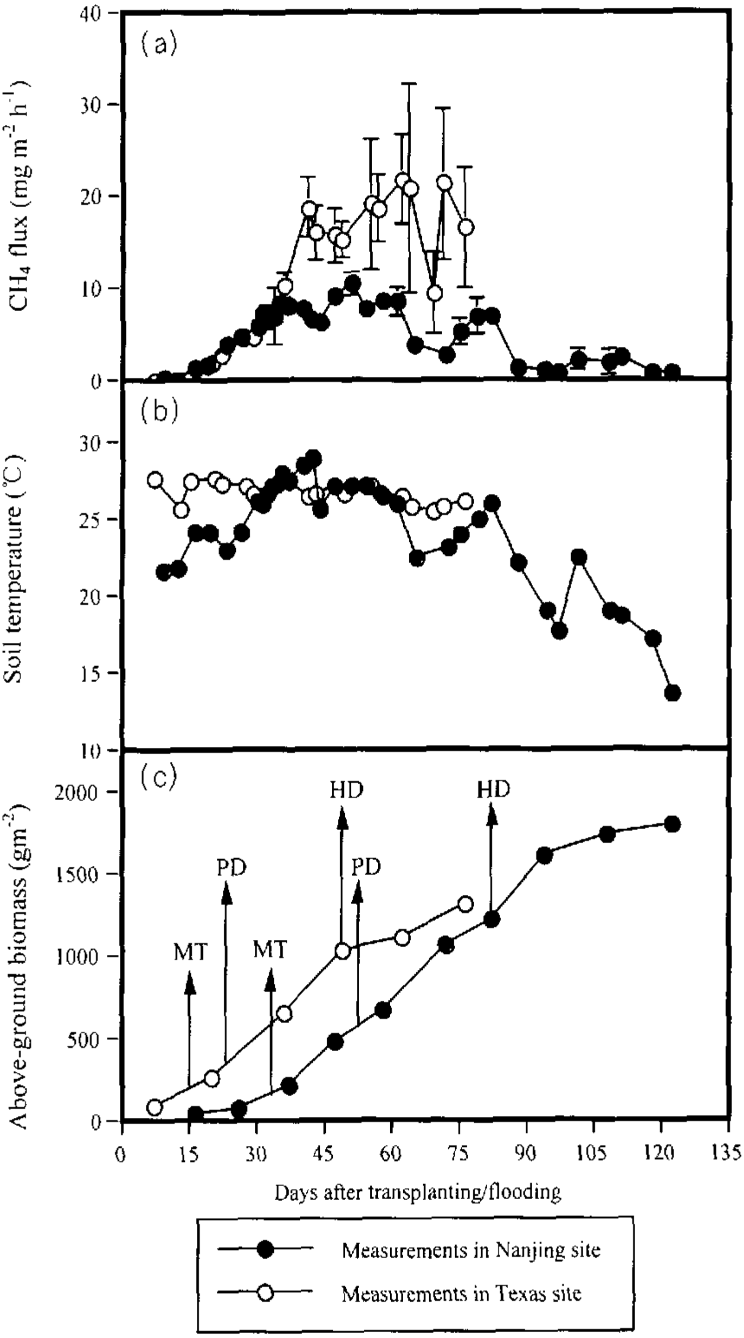

Fig. 1. Comparison of seasonal trends of CH_4 emission (a), soil temperature (b) and rice biomass production (c) between experimental sites in Nanjing, China and in Texas, USA. The vertical bars in (a) are standard deviation from 3 (Texas site) and 2 (Nanjing site) sampling replicates. MT, PD and HD represent the phenological development stages of maximum tillering, panicle differentiation and heading, respectively.

(Fig. 1b). The magnitude of the variation is some 2.9°C, ranging from 25.2°C to 28.1°C with a seasonal average value of 26.7°C. No clear relationship between soil temperature and methane emission was found in this case, suggesting that the changes in soil temperature are too small to affect the seasonal course of methane emission in this site.

Rice growth in biomass increment and phenological development at the Texas site were faster than that at the Nanjing site (Fig. 1c). The experiment at the Nanjing site showed an increase in rice biomass as rice growth and development proceeded (Fig. 1c), while the methane emissions varied independently (Fig. 1a). Thus, there is no clear evidence that the seasonal trend of methane emission is dependent on the rice biomass production from this specific case. Compared with the results obtained at the Nanjing site, the course of methane emission at the Texas site (Fig. 1a) was similar to that of rice biomass (Fig. 1c), which is consistent with our previous measurements (Huang et al., 1997).

Seasonal average of methane flux was 4.1 at the Nanjing site and 10.3 mg $m^{-2}h^{-1}$ at the Texas site, respectively. It is noteworthy that the soil at the Texas site is more sandy than that at the Nanjing site (Table 1). In addition to the difference in sand fraction, seasonal average of soil temperature at the Texas site was some 2.2°C higher than that at the Nanjing site (Table 2). In light of our previous studies from 1989 to 1992 rice growing seasons, methane emission was positively correlated with soil sand percentage (Sass et al., 1994). The integration of higher sand percentage and higher soil temperature may contribute to the higher methane emission at the Texas site. We did not find significant difference in plant height and plant density between these two sites, but the grain yield and the aboveground biomass at the Texas site were lower than that at the Nanjing site (Table 2).

Table 2. Comparison of CH_4 emission, soil temperature and rice crop production between experimental sites in Nanjing, China and in Texas, USA

Items	Experimental site	
	Jiangning, Nanjing (China)	Beaumont, Texas (USA)
CH_4 emission		
Seasonal average (mg $m^{-2}h^{-1}$)	4.1	10.3
Range of flux (mg $m^{-2}h^{-1}$)	0.18~10.57	0~21.90
Seasonal total (g m^{-2})	12.11	18.75
Daily soil temperature (°C)		
Seasonal average	24.5	26.7
Range	13.6~28.9	25.2~28.1
Rice crop production		
Plant height at heading (cm)	103 ± 16	105 ± 3
Plant density at heading (m^{-2})	343 ± 20	332 ± 37
Grain yield (g m^{-2})	648.5 ± 138.7	583.1 ± 27.1
Aboveground biomass (g m^{-2})	1593.2 ± 37.8	1302.1 ± 59.1

3.2 *Seasonal determination of methane emission*

It is fairly clear that methane emission at the Nanjing site was dependent on soil temperature (Figs. 1a and 1b). Assuming that the influence of temperature on the emission can be quantitatively expressed through a temperature coefficient (Q_{10}), a nonlinear relationship between methane flux and soil temperature was proposed as

$$F_T = F_o \times Q_{10}^{(T-10)/10} .$$

where F_T and F_O represent the methane flux (mg $m^{-2}h^{-1}$) under the soil temperature of T and 10°C, respectively. The measurements of methane emissions and soil temperature at the Nanjing site were used to determine the parameters of F_O and Q_{10} by employing a nonlinear method (SYSTAT, 1989) to the above equation. The values of F_O and Q_{10} were evaluated as 0.345 (mg $m^{-2}h^{-1}$) and 6.06. This relationship yields a correlation coefficient (r^2) of 0.741 ($n = 33$, $p < 0.001$).

Figure 2 shows the equation fit and the field measurements. Solid circles and open circles represent the data sets obtained during rice vegetative and reproductive periods, respectively, suggesting that the seasonal variation of methane emission at the Nanjing site is mainly determined by the temperature over the entire growing season. However, the Q_{10} value in this case is much different from those reported by Khalil et al. (1991), by Schütz et al. (1989) and by Zheng et al. (1998). Field measurements from Sichuan province (China) by Khalil et al. (1991) suggest the temperature coefficient for methane emission has a value of 2, while a temperature coefficient of 4 was reported by Schütz et al. (1989) from the field measurements in Vercelli of Italy. Based on the field measurements with regular drainage events in the suburban of Suzhou City, Jiangsu Province (China), Zheng et al. (1998) reported that the CH_4 emission rate was exponentially correlated with the soil temperature at approximately 4 cm depth. The Q_{10} would reach a value of 15 according to their exponential function of CH_4 emission rate against the soil temperature. A possible reason for the enormous difference in reported Q_{10} values might be the site–specific response of methanogens to temperature. The Q_{10} values may also reflect temperature limitations to fermentation. A further investigation on the relationship between methane emission and soil temperature would be required to evaluate the impact of temperature on the emission.

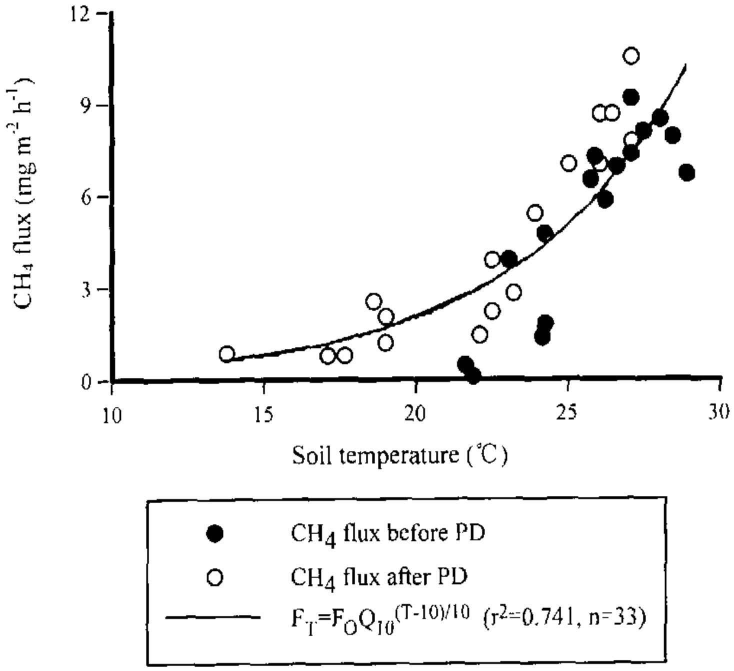

Fig. 2. Nonlinear dependence of methane flux on soil temperature in Nanjing, China, 1999.

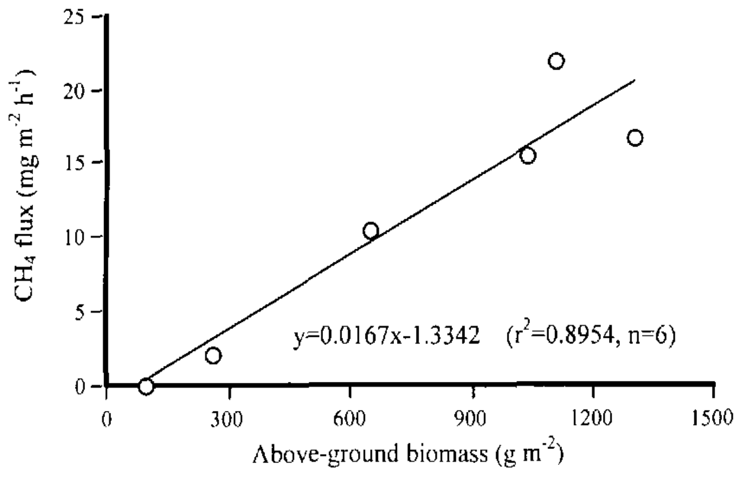

Fig. 3. Correlation of methane flux with rice biomass production in Texas, USA, 1997.

Our previous measurements in Texas suggested that the rice plant is a very strong controller of methane emission and that the contribution of rice biomass production to methane emission is controlled not only by the size but also by the age dependent morphology of the plant (Huang et al., 1997). When the methane flux from the Texas experiment was correlated with the available data sets of rice above–ground biomass (Fig. 3), there was a linear relationship (r^2 = 0.895, n= 6, p< 0.01). The dependence of seasonal methane emission on rice biomass production is further supported by this case.

The fact that the seasonal course of methane emission from rice paddies is dependent on soil temperature for the Nanjing site (Fig. 2) and on rice biomass for the Texas site (Fig. 3) opens the question of why the factors regulating the seasonal pattern of CH$_4$ emission from these two sites are different. Theoretically speaking, processes involved in biochemical and microbial activities must be associated with temperature. Thus, it is not surprising that the seasonal trend of methane emission at the Nanjing site is attributed to the wide variation of soil temperature. When the seasonal fluctuation of soil temperature is large, the seasonal variation of methane emission becomes more dependent on the temperature. In this case, the contribution of rice biomass production to the seasonal variation of methane emission became obscure. In contrast with the Nanjing case, the seasonal variation of soil temperature was very small in the Texas case (Table 2) and the values from 25.2 to 28.1°C are close to the optima for most microbial activities. Thus, the temperature does not limit the methane production and emission. The rice plants, on the other hand, release organic substances into the rhizosphere by root exudation and biomass litter to provide methanogenic substrates (Schütz et al., 1991). When the soil temperature does not significantly affect the microbial activities, the supply of methanogenic substrates becomes dominant, and hence the seasonal variation of methane emission in Texas site was mainly modulated by rice biomass production when there were no additional organic matter inputs.

4. Conclusion

Analysis of field measurements in Nanjing (China) and in Texas (USA) demonstrates that under the conditions of permanent flooding and without additional organic matter inputs, the seasonal trend of methane emission from rice cultivation is mainly attributed to the soil temperature where a wide variation of soil temperature is exhibited, while the seasonal trend is most likely to be modulated by rice biomass production when the variation of soil temperature is small over the rice growing season.

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中国南京与美国德克萨斯稻田甲烷排放的比较

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摘 要

稻田甲烷排放试验分别在南京与德克萨斯水稻生长季实施，观测期内测定甲烷排放通量、土壤温度和水稻生物量。结果表明：南京稻田土壤温度的季节性变幅为15.3°C，甲烷排放通量与土壤温度成非线性正相关而与水稻生物量无关；德克萨斯稻田土壤温度的季节性变幅为的2.9°C，甲烷排放通量与土壤温度无关而与水稻生物量成线性正相关。由此得出结论：在持续淹水和无外源有机碳施加的条件下，土壤温度变幅大的地区驱动稻田甲烷排放季节性变化的关键因子为土壤温度，土壤温度变幅小的地区其关键驱动因子则为水稻的生长量。

关键词：甲烷排放，稻田，水稻生物量，土壤温度