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Response of CH_4 emission of paddy fields to land management practices at a microcosmic cultivation scale in China

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Abstract: The terrestrial ecosystem may be either a source or a sink of CH_4 in rice paddies, depending, to a great extent, on the change of ecosystem types and land use patterns. CH_4 emission fluxes from paddy fields under 4 cultivation patterns (conventional plain culture of rice(T1), no-tillage and ridge culture of rice(T2), no-tillage and ridge culture of rice and wheat (T3), and rice-wheat rotation(T4)) were measured with the closed chamber technique in 1996 and 1998 in Chongqing, China. The results showed that differences existed in CH_4 emission from paddy fields under these land management practices. In 1996 and 1998, CH_4 emission was 71.48% and 78.82% (T2), 65.93% and 57.18% (T3), and 61.53% and 34.22% (T4) of that in T1 during the rice growing season. During the non-rice growing season, CH_4 emission from rice fields was 76.23% in T2 and 38.69% in T1. The accumulated annual CH_4 emission in T2, T3 and T4 in 1996 decreased by 33.53%, 63.30% and 65.73%, respectively, as compared with that in T1. In 1998, the accumulated annual CH_4 emission in T1, T2, T3 and T4 was 116.96 g/m^2, 68.44 g/m^2, 19.70 g/m^2 and 11.80 g/m^2, respectively. Changes in soil physical and chemical properties, in thermal and moisture conditions in the soil and in rice plant growth induced by different land use patterns were the dominant causes for the difference in CH_4 emission observed. The relative contribution of various influencing factors to CH_4 emission from paddy fields differed significantly under different land use patterns. However, the general trend was that chlorophyll content in rice leaves, air temperature and temperature at the 5 cm soil layer play a major role in CH_4 emission from paddy fields and the effects of illumination, relative humidity and water layer depth in the paddy field and CH_4 concentration in the crop canopy were relatively non-significant. Such conservative land use patterns as no-tillage and ridge culture of rice with or without rotation with wheat are thought to be beneficial to reducing CH_4 emission from paddy fields and are, therefore, recommended as a significant solution to the problems of global (climatic) change.

Keywords: land use pattern; microcosmic cultivation scale; fluxes of CH_4 emission; paddy field

Introduction

Direct measurement of CH_4 emission rate was first reported by Cicerone in 1981 (Cicerone, 1981). Since then researchers in China and other countries have made fairly thorough-going investigations to understand whether the terrestrial ecosystem is the source or the pool of atmospheric CH_4 (Cicerone, 1983; Seiler, 1984; Holzapfel-Pschorn, 1986; Schütz, 1989; Cai, 1993) and come to the conclusion that the terrestrial ecosystem can be both the source and the pool of atmospheric CH_4, depending on the changes in ecosystem types and land use patterns (Stewart, 1989; Steudler, 1989; Bronson, 1993; Amstel, 1994; Castro, 1994; Goulding, 1996; Bradford, 2001; Yue, 2004). For example, the wetland systems (paddy fields and swamps) are an important source of atmospheric CH_4 (Stewart, 1989; Amstel, 1994; Bradford, 2001), while non-wetland terrestrial systems present a more complicated picture: natural forest and grassland systems are a net pool of atmospheric CH_4 (Bronson, 1993; Goulding, 1996; Yue, 2004) and upland fields may be at once the source and the pool of atmospheric CH_4 (Steudler, 1989; Bronson, 1993; Castro, 1994). However, most of the researches have been focused on the effects of transformation among different land use patterns on terrestrial carbon and atmospheric CH_4, and less work has been done in the aspect of land use practice on a microcosmic cultivation scale. With more knowledge and better understanding of the strength of the effect of different land use patterns on carbon cycling in a region and of its mechanisms, study on the effect of land use practice on a microcosmic cultivation scale is now becoming a new orientation in the research of global changes and terrestrial C cycling and has attracted the attention of the researchers as a part of the research of climatic changes on a global scale with greenhouse effect as its primary concern.

Global CH_4 emission at present is estimated at about 600 $TgCH_4/a$, and the concentration of atmospheric CH_4 has been increasing at a rate of 5 ppb/a. CH_4 emission from paddy fields accounts for one third of the world total (IPCC, 2001; Cai, 2003a; Michael, 2004). In the next 30 years the area of land allotted to paddy rice cultivation will probably increase by 50 million hm^2 to meet the demand for food by the growing world population. This implies that large acreage of land will have to be transformed into paddy fields (Huang, 2002). Therefore, on a meso-micro scale, paddy fields, a non-persistent land use pattern, have become a leading contributor to the short-term global changes and C reserve changes in most regions of the world. Land use on the microcosmic cultivation scale is a direct reflection of the action of human activities on the soil. It influences many natural phenomena and ecological processes mainly through its cascade and accumulation effects, such as soil nutrients, soil structure and moisture-heat exchange between the soil and the adjacent air layer, which will further affect the structure and function of the terrestrial ecosystem and result in the change of C storage in the system (Campphell, 2000; Yang, 2003; Makoto, 2004). At a microcosmic cultivation scale, some elementary knowledge about CH_4 emission from paddy fields has been acquired through reasonable selection of typical regions, distribution of measurement spots and uninterrupted measurement in time under different climate and soil conditions (Kyuma, 1992; Cai, 1993; Min, 1993;

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Denier, 1996; Jacinthe, 2004). However, the mechanisms for the effects of the micro-environment and hydro-thermal conditions resulting from different use patterns of paddy fields on the production, oxidation and transport of CH_4 in paddy fields are inadequately understood. It is this problem that may serve as an effective starting point for the search for the regulation and improvement of climate changes at the level of microcosmic land use. The present study was, therefore, carried out to get a better understanding of the effects of the micro-environment and hydro-thermal conditions resulting from different use patterns of paddy fields on CH_4 emission and their possible underlying mechanisms so as to provide a theoretical basis for the construction of rational ecology-production patterns which will benefit the farmers and the ecological environment.

1 Material and methods

1.1 Site description

The experiment was conducted in the Experimental Farm of Southwest Agricultural University, Chongqing, China(106° 26′ E, 30° 26′ N; alt. 230 m), with a mean annual temperature of 18.3℃, an annual precipitation of 1105.4 mm, of which 70% occurs in the period from May to September, an annual sunshine duration of 1276.7 h, and an annual frost-free period of 334 d. The soil at the experimental site is gray brown purple Udic Cambisols developed from the purple parent material of Mesozoic J_2s(Table 1).

Table 1 Basic property of the soils

Treatment	pH	O.M., g/kg	Total N, g/kg	Available N, mg/kg	Available P, mg/kg	Available K, mg/kg
Treatment 1,T1*	7.14	34.56	1.87	146	8.4	161.8
Treatment 2,T2	7.06	36.27	1.98	146	8.3	139.9
Treatment 3,T3	6.80	40.63	2.31	177	22.6	123.6
Treatment 4,T4	6.62	32.53	1.75	134	20.0	118.7

Notes: * T1. conventional plain culture of rice; T2. ridge culture rice with no tillage; T3. ridge culture of rice and wheat with no tillage; T4. rice-wheat rotation without ridge making

1.2 Experiment treatments

Four cultivation patterns were practiced in the long-term observation experiment at fixed locations starting from 1990. Conventional plain culture of rice (Treatment 1, T1): the paddy soil was ploughed and harrowed three times each year before rice planting. After the harvest of the mid-season rice crop, the field was re-flooded with water in winter. No-tillage and ridge culture of rice (Treatment 2, T2): ridges were made with intervening furrows in the fields. The ridges were 25 cm wide at the top and the furrows were 30 cm wide and 35 cm deep. Each plot consisted of 5 ridges. The field was submerged with water after rice harvest without tillage. No-tillage and ridge culture of rice and wheat (Treatment 3, T3): no tillage was performed throughout the year. Ridges were made as in T2. Wheat was grown after the harvest of the rice crop. During the wheat-growing season, water table in the furrows was lowered and soakage irrigation was maintained. The field was re-flooded after wheat harvest for the cultivation of rice. Rice-wheat rotation (Treatment 4, T4): the conventional method plain culture used by local farmers was followed. The field was drained and ploughed after the harvest of the rice crop, and wheat was grown. After the harvest of the wheat crop, the field was flooded and ploughed and harrowed for rice cultivation. The treatment plots, with 20 m^2 each, were arranged randomly in the current experiment.

1.3 CH_4 sampling and measurement

CH_4 emission from the paddy field was measured at different growing periods with PMMA (polymethyl methacrylate) static closed chambers (0.51 m × 0.51 m × 0.51 m and 0.51 m × 0.51 m × 1.02 m). A small fan was installed inside the chamber, so that CH_4 concentration was uniformly distributed in it. As water seal, four immovable wooden seats were placed at each sampling site. After the chamber was placed above the foundation with the water seal, gas sample in the chamber was taken with a syringe piercing into the rubber plug on one side of it and quickly transferred to a vacuum finger flask. Sampling was made at 10 min intervals and 4 samples, with a volume of 17.5 ml each, were collected at each sampling site. In 1996 and 1998, sampling started from May, when rice seedlings had been transplanted, and was conducted twice a week during the rice growing season and once a week after rice harvest. CH_4 concentration in the sampling flasks was measured with a gas chromatograph with FID (GC-12A). Fluxes of CH_4 emission were estimated with the following equation:

$$F = \frac{MP}{RT} \times H \times dc/dt,$$

where M is CH_4 molecular weight, P is the atmospheric pressure at sampling, T is temperature in the sampling chamber, R is a constant, H is the virtual height of chamber, and dc/dt is the variability of CH_4 concentration with time.

1.4 Statistical treatments

Using the software SPSS11.0, multivariate statistical analysis and gray relevancy analysis were made with the data obtained to study the influences of the seven factors chosen on CH_4 emission flux from the paddy field. Based on the principles of gray relevancy analysis, fluxes of CH_4 emission from the paddy field and the seven influencing factors were regarded as a gray system. Let fluxes of CH_4 emission from the paddy field under conventional plain culture be the reference series X_0, and air temperature, temperature at 5 cm soil layer, illumination in the paddy field, relative humidity in the paddy field, chlorophyll content in rice leaves, depth of water layer in the paddy field and CH_4 concentration of crop canopy were comparison series, designated as $X_1, X_2, X_3, X_4, X_5, X_6$ and X_7, respectively. The relevancy degree(R_i) is estimated with the equation:

$$\xi_i(k) = \frac{\min_i \min_k \Delta_i(k) + \rho \cdot \max_i \max_k \Delta_i(k)}{\Delta_i(k) + \rho \cdot \max_i \max_k \Delta_i(k)},$$

$$R_i = \frac{1}{N}\sum_{k=1}^{N} \xi_i(k),$$

where $\xi_i(k)$ represents relevancy coefficient, R_i is the relevancy degree, $\Delta_i(k) = | X_0(k) - X_i(k) |$ absolute difference of the X_0 series and X_1 series at kth, $\min_i \min_k \Delta_i(k)$ is two-tier minimum difference, $\max_i \max_k \Delta_i(k)$ is the two-tier maximum difference, and ρ is resolution coefficient, ranging from 0 to 1(being 0.5 generally).

2 Results

2.1 Fluxes of CH_4 emission from the paddy field

Fig. 1 and 2 show that significant differences were observed in CH_4 emission fluxes during rice growing seasons between different land use patterns in 1996 and 1998. Flux of CH_4 emission was the greatest in T1 (conventional plain culture of rice) and the smallest in T4 (rice-wheat rotation) (Table 2). During the same season, flux of CH_4 emission in T2(no-tillage and ridge culture of rice) and T3 (no-tillage and ridge culture of rice followed by wheat) was between that of T1 and T4(Table 2). In 1996, fluxes of CH_4 emission during the rice-growing season in T2, T3 and T4 accounted only for 71.48%, 65.93% and 61.53%, respectively, of that in T1. Similarly, in 1998, CH_4 emission during the rice growing season in T1, T2 and T3 decreased by 21.18%, 42.82% and 65.78%, respectively, as compared with T1. During the non-rice growing season, the fields were drained for wheat cultivation after rice harvest in T3 and T4, thus exposing the soil to the air for a longer time. Under such circumstances, soil oxidation-reduction potential (Eh) was raised and some reducible substances were transformed to oxidized substances through a variety of oxidation processes. For instance, NH_4^+-N was transformed into NO_3^--N through nitrification, and manganese (Ⅱ) (Mn^{2+}) and iron (Ⅱ) (Fe^{2+}) were oxidized into manganese(Ⅳ)(Mn^{4+}) and iron (Ⅲ)(Fe^{3+}). As a result, instead of emitting CH_4, the soil consumed part of the atmospheric CH_4. Therefore, CH_4 emission was detected only in T1 and T2(Fig.3 and 4). In the current study, CH_4 emission flux in T2 was reduced by 6.39 mg/($m^2 \cdot h$) and 7.51 mg/($m^2 \cdot h$), respectively, in 1996 and 1998, as compared with T1, indicating that the response of CH_4 emission from paddy fields to the changes in land management practices at the microcosmic cultivation scale was quite conspicuous. It was especially true of the practices of no tillage and ridge culture of rice(T2) and rice-wheat rotation (T4).

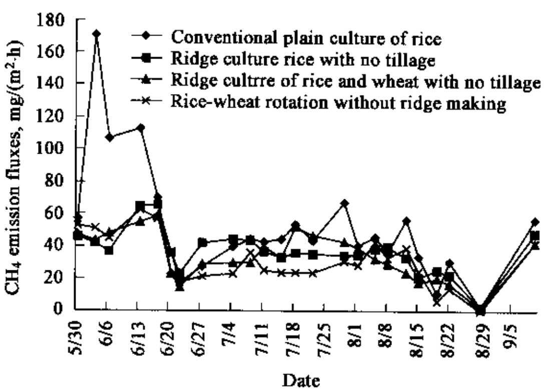

Fig. 1 Fluxes of CH_4 emissions from the rice growing seasons in 1996

Marked inter-annual variations were observed in fluxes of CH_4 emission from paddy fields in either the rice-growing season or in the non-rice growing season. Take for instance, CH_4 emission in T1 during the rice growing season averaged at 51.37 mg/($m^2 \cdot h$) with a maximum of 71.1 mg/($m^2 \cdot h$) in 1996. In contrast, the corresponding figures were 13.50 mg/($m^2 \cdot h$) and 45.03 mg/($m^2 \cdot h$) in 1998. This discrepancy was due to the fact that organic fertilizer was applied before rice planting in 1996 and that the date of rice sowing and harvesting was different in the 2 years, thus giving rise to differences in the influencing factors for CH_4 emission and in their strength caused by the practice of no-tillage and ridge culture. Another result meriting our attention was that the difference in CH_4 emission between T2 and T3 was slight in 1996 while it was quite considerable in 1998. This may probably attributed to the fact that the process of any melioration in micro-soil environment is normally slow and that hysteresis is characteristic of micro-soil environment changes. Therefore, long-term practice of no-tillage and ridge culture or rotation of paddy rice and upland crops will be more beneficial to reducing CH_4 emission from paddy fields.

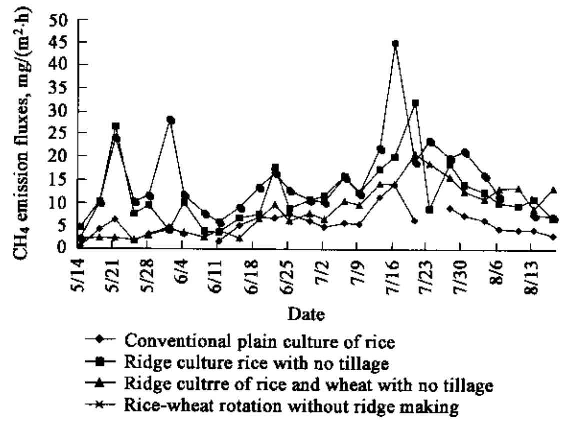

Fig.2 Fluxes of CH_4 emissions from the rice growing seasons in 1998

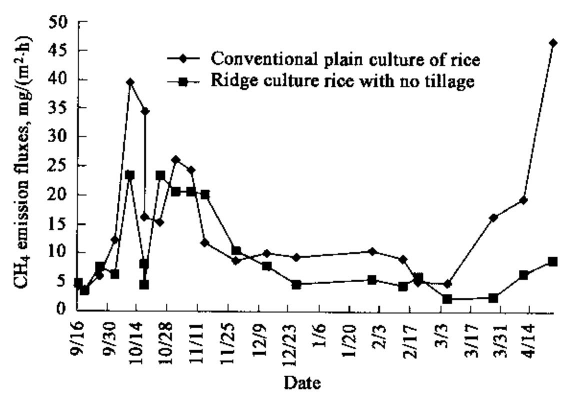

Fig.3 Fluxes of CH_4 emissions from the non-rice growing seasons in 1996

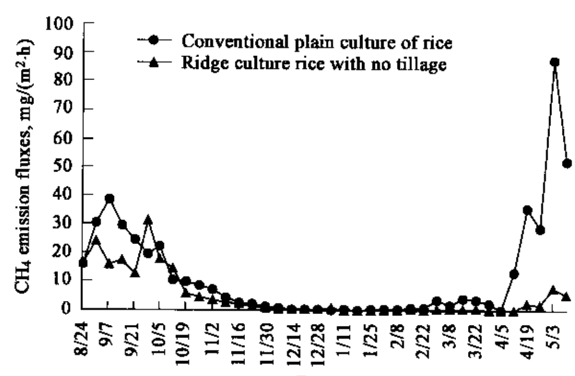

Fig.4 Fluxes of CH_4 emissions from the non-rice growing seasons in 1998

2.2 Annual accumulative flux of CH_4 emission from rice fields

Annual accumulative flux of CH_4 emission from paddy fields was significantly different under different tillage and cropping systems (Table 2). In the two studied years, CH_4 emission diminished progressively from T1 to T4, being 125.75, 89.90, 82.86 and 77.38 g/m^2, respectively, during the rice-growing season in 1996, and the difference among the treatments was considerably significant. The rice fields emanated 35.85 g/m^2, 42.89 g/m^2 and 48.37 g/m^2 less CH_4 annually in T2, T3 and T4 than in T1. Since there was little CH_4 emitted in such farming systems as T3 and T4 during non-rice growing seasons, CH_4 emission was detected only in T1 and T2, being 99.89 g/m^2 and 60.17 g/m^2, respectively. Thus the accumulative CH_4 emission for the year 1996—1997 was 150.07 g/m^2, 82.86 g/m^2 and 77.38 g/m^2, respectively, in T2, T3 and T4, a reduction of 33.53%, 63.30% and 65.73% as compared with T1. Field measurements made in 1998 presented a similar picture: during the rice growing seasons, CH_4 emission was the highest in T1 (34.45 g/m^2), followed in order by T2 (27.16 g/m^2), T3 (19.70 g/m^2) and T4 (11.80 g/m^2); during the non-rice growing seasons, CH_4 emission occurred only in T1 (78.20 g/m^2) and T2 (30.24 g/m^2). The accumulative CH_4 emission for the year 1998—1999 was 116.96 g/m^2, 68.44 g/m^2, 19.70 g/m^2 and 11.80 g/m^2, respectively, in T1, T2, T3 and T4. Thus, the annual accumulative CH_4 emission differed strikingly in different land use patterns and the annual accumulative CH_4 emission under the same land use patterns was also different in different years. For example, the annual accumulative CH_4 emission in T1 in 1998 was only 51.80% as mush as that in 1996. The underlying causes for such discrepancies are the same as what was discussed in the preceding text about the interannual variation for CH_4 emission flux in Section 2.1.

Table 2 CH_4 emission from paddy fields under the different land use patterns

Observation date	T1 *		T2		T3		T4	
	mg/(m^2·h)	g/m^2	mg/(m^2·h)	g/m^2	mg/(m^2·h)	g/m^2	mg/(m^2·h)	g/m^2
May 23, 1996—May 15, 1997	26.26	225.78	17.32	150.07		82.86		77.38
Rice growing season (May 23—Sept. 2)	51.37	125.75	36.72	89.90	33.87	82.86	31.61	77.38
Non-rice growing season (Sept. 2—May 15)	16.07	99.89	9.68	60.17				
May 14, 1998—May 10, 1999	13.50	116.96	7.90	68.44		19.70		11.80
Rice growing season (May 14—Aug. 17)	15.11	34.45	11.91	27.16	8.64	19.70	5.17	11.80
Non-rice growing seasons (Aug. 17—May 10)	12.25	78.20	4.74	30.24				

Note: * See note beneath Table 1

3 Discussion

The direction and the rate of the change in soil organic carbon content in the paddy fields depend on the changes in soil physical and chemical properties and biological process induced by changes in land use (Chan, 2001; Li, 2001; Silvana, 2002; Yang, 2004). CH_4 emission from the paddy field results from the interaction among the processes of CH_4 generation, oxidization, and transmission and release in the soil. Changes in the physical and chemical properties of the soil, in its hydrothermal regimes and in the conditions of rice plant growth conditions caused by different land management practices will influence the fluxes of CH_4 emission and its annual emission fluxes through their influence on any link of CH_4 emission from paddy fields. Examined from the perspective of SPAC (soil-plant-atmosphere continuum), with the exception of air temperature, all the other micro-soil environmental factors and biological processes, i. e. temperature at the 5 cm soil layer, illumination in the paddy field, relative humidity in the paddy field, chlorophyll content in rice leaves, depth of water layer in paddy field and CH_4 concentration under the plant canopy differed substantially with land management practices. For convenience in analysis, the corresponding observation values of these factors in the two years were averaged (Table 5—7) and the resulting data were subjected to multivariate analysis and gray relevancy analysis with CH_4 emission. It can be seen from Tables 5, 6 and 7 that the degree of contribution of each factor to CH_4 emission from the paddy field was strikingly different under different land management practices (Table 3), even the function sequence was different under the same land management practices (Table 4). However, the general trend was that chlorophyll content in rice leaves, air temperature and temperature at the 5 cm soil layer played a major role in CH_4 emission from the paddy field while the influences of illumination, relative humidity depth of water layer in paddy field and CH_4 concentration under the crop canopy were comparatively small.

3.1 Air temperature

Air temperature influences CH_4 emission from paddy field through its effect on the activity of CH_4-producing microbes in the soil. Fluxes of CH_4 emission rose with temperature indicated that organic matter was illimitably accommodated (Yang, 2001; Akira, 2004). Because the observation of air temperature was done synchronously in the plots of all treatments and the observation sites were close to one another, air temperature recorded was similar under different land management practices. In other words, the factor air temperature was independent of different land management practices. Nevertheless, as shown in Table 4, correlation of air temperature with fluxes of CH_4 emission from the paddy field was different under different land management practices. This result was in discrepancy with that determined by Schütz and Holzapfel-Pschorn *et al*. (Schütz, 1989), who found that an exponential relationship existed between CH_4 emission flux and air temperature, but was consistent with the results of Chen *et al*. (Chen, 1993a) obtained in their measurements in paddy fields in Southwest China. In sequencing of relevancy degree of the 7 factors estimated, air temperature was the first in T3, the second in T4 and T2 and the third in T1, suggesting that the influence of air temperature on CH_4 emission is important. The processes in which air temperature influences CH_4 emission flux are highly complicated, and sometimes they may contradict one another.

At present, the relationship between air temperature and CH_4 emission cannot be interpreted by a simple expression and further exploration will be needed.

Table 3 Fluxes of CH_4 emission from paddy fields and correlative matrix of their influencing factors($n = 15$)

Treatment	Factor	Fluxes of CH_4 emission	Air temp.	Temp. at 5 cm soil layer	Illumination in paddy field	Relative humidity in paddy field	Content of chlorophyll in rice leaves	Depth of water layer in paddy field	CH_4 conc. of crop canopy
T1**	CH_4 emission flux	1.000							
	Air temp.	-0.525*	1.000						
	Soil temp.	0.326	0.246	1.000					
	Illumination	-0.733*	0.759*	-0.208	1.000				
	RH	0.778*	-0.783*	-0.025	-0.694*	1.000			
	Chlorophyll	0.766*	-0.640*	0.264	-0.787*	0.727*	1.000		
	Depth of water layer	0.133	-0.202	-0.192	-0.272	0.160	0.404	1.000	
	CH_4 conc.	0.271	-0.277	0.100	-0.123	0.554*	0.243	0.160	1.000
T2	CH_4 emission flux	1.000							
	Air temp.	-0.135	1.000						
	Soil temp.	0.423	0.391	1.000					
	Illumination	-0.003	0.553*	0.273	1.000				
	RH	-0.016	-0.476	-0.008	0.422	1.000			
	Chlorophyll	0.179	-0.480	0.231	-0.431	0.732*	1.000		
	Depth of water layer	-0.310	-0.237	-0.255	-0.186	0.307	0.407	1.000	
	CH_4 conc.	0.449	-0.350	0.201	0.103	-0.256	-0.233	-0.115	1.000
T3	CH_4 emission flux	1.000							
	Air temp.	0.002	1.000						
	Soil temp.	-0.092	0.330	1.000					
	Illumination	-0.042	0.953*	0.261	1.000				
	RH	0.362	-0.787*	-0.341	-0.7468	1.000			
	Chlorophyll	0.525*	0.074	0.252	-0.036	0.106	1.000		
	Depth of water layer	0.378	-0.150	-0.344	-0.110	0.224	0.332	1.000	
	CH_4 conc.	-0.083	-0.0269	0.120	-0.099	0.140	0.130	-0.113	1.000
T4	CH_4 emission flux	1.000							
	Air temp.	0.019	1.000						
	Soil temp.	0.596*	0.452	1.000					
	Illumination	-0.220	0.850*	0.158	1.000				
	RH	0.162	-0.702*	-0.208	-0.777*	1.000			
	Chlorophyll	0.781*	0.128	0.531*	-0.179	0.188	1.000		
	Depth of water layer	0.482	0.019	0.154	-0.139	0.071	0.446	1.000	
	CH_4 conc.	0.492	0.149	0.438	0.316	-0.199	0.155	-0.082	1.000

Note: **See note beneath Table 1; * correlation $P < 0.05$

Table 4 Relevancy degree and sequence of influencing factors in relation to fluxes of CH_4 emission from paddy fields

Treatment	Factor	Air temp.	Temp. at 5 cm soil layer	Illumination in paddy fields	Relative humidity in paddy field	Content of chlorophyll in rice leaves	Depth of water layer in paddy field	CH_4 concentration of crop canopy
T1*	Relevancy degree	0.927	0.928	0.848	0.820	0.963	0.871	0.811
	Place	3	2	5	6	1	4	7
T2	Relevancy degree	0.941	0.938	0.815	0.848	0.957	0.894	0.755
	Place	2	3	6	5	1	4	7
T3	Relevancy degree	0.949	0.946	0.694	0.862	0.947	0.891	0.870
	Place	1	3	7	6	2	4	5
T4	Relevancy degree	0.968	0.974	0.751	0.830	0.962	0.931	0.864
	Place	2	1	7	6	3	4	5

Note: * See note beneath Table 1

3.2 Temperature at the 5 cm soil layer

The correlation of temperature at the 5 cm soil layer the flux of CH_4 emission from paddy fields varied with land use pattern. Temperature at the 5 cm soil layer was in significant positive correlation with CH_4 emission in T4($R = 0.596$, $n = 15$). It was also positively correlated with CH_4 emission in T1 and T2, though the correlation was non-significant statistically(R being 0.362 and 0.423, respectively). In contrast, in T3, the correlation was negative($R = -0.092$, $n = 15$). Such a confusing picture indicates that the relationship between temperature at the 5 cm soil layer and CH_4 emission is highly complicated. Tao *et al*.(Tao, 1995) noted that temperature at the 5 cm soil layer was significantly correlated with the seasonal variation in the flux of CH_4 emission from paddy fields. Chen *et al*. (Chen, 1993b) showed that the optimal temperature for the growth of methanotrophs was 40℃, but some 20% of them could survive at a temperature in the range of 40—70℃. It seems that temperature at the 5 cm soil layer is positively correlated with CH_4 generation in paddy fields, but this presumption is not sufficient to interpret the seasonal variation of CH_4 emission(Chen, 1993a; Cai, 1998; Inubushi, 2003). In sequencing of relevancy degree of the 7 factors with CH_4 emission from the fields, temperature at the 5 cm soil layer was the first, with the highest relevancy degree($R = 0.974$, $n = 15$). Soil temperature depended on the reallocation of solar radiation energy by the micro-topography at land surface and variations in soil thermal properties (Table 5). No-tillage and ridge culture (T2 and T3) exposed the soil to the air above the water surface and eliminated the reduction of solar energy by the water layer. As a result, compared with conventional plain culture (T1), T2 and T3 had smaller thermal capacity, higher heat conductivity and greater speed of warming up. Therefore, no-tillage and ridge culture accelerated the thermal transmission and exchange between soil and environment, promoted the multiphase movement of thermal flow in the soil and facilitated the movement of soil water, nutrients and air and the metabolism of microbes in the soil, thus eventually promoting the generation of CH_4.

Table 5 Temperature at the 5 cm soil layer under the different land use patterns

Observation time	8:00	11:00	14:00	17:00	20:00	23:00	Difference in temp.	Accumulated temp.
T1* temp., ℃	26.2	25.2	26.0	28.0	28.8	29.8	4.0	163.4
T2 temp., ℃	24.8	26.2	30.0	32.0	29.4	28.8	7.2	171.2
Water temp., ℃	26.0	26.0	31.4	32.2	31.4	28.2	6.2	175.2
Air temp., ℃	21.6	27.6	28.6	32.6	30.2	27.6	11.2	165.2

Note: * See note beneath Table 1

3.3 Illumination in the paddy field

The correlation of illumination in the paddy field with CH_4 emission was difficult to express with a single correlation coefficient or curve. Although their correlation was negative in the measurements in all the 4 treatments, the degree of correlation varied greatly, being significant statistically only in T1 ($R = -0.733^*$, $n = 15$). In T2, T3 and T4, the correlation coefficients were -0.003, -0.042 and -0.220, respectively. These results seemed to support the assumption of Kazuyuki *et al*. (Kazuyuki, 1994) and Axel and Ralf (Axel, 2003), who found in their measurements that emission of CH_4 through plants was higher in the shade than under strong illumination. But they appear to be opposite to the viewpoint of Min *et al*. (Min, 1993) and He *et al*. (He, 1993). The results from gray relevancy analysis on seven influencing factors in relation to CH_4 emission flux showed that the illumination in the paddy field with CH_4 emission varied with land use patterns. In T1 it took the 5th place, with a relevancy degree of 0.848 ($n = 15$). In paddy fields, solar radiation is intercepted by the vegetation layer and the water body before it reaches the soil surface. The loss of solar radiation in the plant canopy depends on the density of the rice seedlings transplanted and on the growth conditions of the crop. In our experiment, plant density in Treatment 2 was greater than in Treatment 1 and, accordingly, the relative illumination at the soil surface in T2 was lower than that at the water surface in T1 (Table 6). With stronger illumination, the metabolism of methanotrophs becomes more vigorous and they consume part of CH_4 that has been produced, thus lowering CH_4 emission fluxes. Diurnal variation in CH_4 emission was noticed in the experiment that CH_4 emission fluxes at night and in the morning were higher than at noon. So illumination in paddy fields played a more marked role in CH_4 emission from conventionally cultivated paddy fields than from no-tillage and ridge culture paddy fields.

Table 6 Relative illumination under the different types

Treatment	Observation time										
	8:00	9:00	10:00	11:00	12:00	13:00	15:00	16:00	17:00	18:00	19:00
T1* (water surface), %	8.0	11.0	14.3	20.0	15.1	10.9	28.8	32.8	26.7	16.2	21.3
T2 (soil surface), %	7.0	5.4	10.7	18.9	11.9	13.6	18.3	20.5	21.8	12.2	12.0

Note: * See note beneath Table 1

3.4 Relative humidity (RH) in paddy fields

The relationship between relative humidity in paddy fields and CH_4 emission varied with land management practice. The correlation coefficient was positive in T1, T3 and T4, being 0.778^*, 0.362 and 0.162 ($n = 15$), respectively, and negative in T2 ($R = -0.016$). Difference was also significant even among T1, T3 and T4, where the correlation was positive. This discrepancy in correlation might have arisen from abnormality in data estimation. Gray relevancy analysis of the 7 factors showed that relative humidity in paddy fields took the 6th place in all the treatments except T2, where it took the 5th place. Relative humidity in paddy fields, or the humidity in the crop canopy (about 1 m above the ground), reflects, to a certain extent, the rate of diffusion of soil vapor excrement to the atmosphere. Generally speaking, the higher the humidity is, the slower the vapor diffusion will be (Gulledge, 1998; Udo, 2001). That is why relative humidity can reflect the rate of diffusion of CH_4 to the atmosphere. Relative humidity in paddy fields was higher in T1 than in T2 owing to the fact that the radiation energy that the water surface obtained was more in T1 with its thicker water layer. In T2, in contrast, the greater soil surface that received solar radiation directly was more favorable to gas exchange between the soil and the atmosphere and unfavorable for the anaerobic generation of CH_4. Consequently, CH_4 emission was greater in T1 than in the other 3 treatments even with similar relative humidity.

3.5 Content of chlorophyll in rice leaves

A significant positive correlation existed between chlorophyll content in rice leaves and fluxes of CH_4 emission from paddy fields, though the correlation coefficient varied with land use pattern, being the highest in T4 ($R = 0.781^*$, $n = 15$), followed closely by T1 ($R = 0.766^*$, $n = 15$). Gray relevancy analysis showed that chlorophyll content in rice leaves played an important role in CH_4 emission from paddy fields and, the relevancy degree was different under different agronomic practices. The results were consistent with the measurements in many field experiments (Sass, 1997; Wassmann, 2000). The growth of rice plants exerts a strong effect on CH_4 emission from paddy fields, and it is estimated that 80% or more of field CH_4 is released into the atmosphere through the aerenchyma of the rice plants (Jia, 2003). In T1, chlorophyll content of rice leaves at the tillering stage of the plants was 3.15 mg/dm^2, being lower than that the other 3 treatments (Table 7). The content of chlorophyll in rice leaves can, reflect the state of photosynthesis and physiological metabolism of the rice plants. Higher chlorophyll content means more active physiological metabolism, accordingly, higher root activity and transpiration, thus benefiting CH_4 production and emission (Wei, 2000; Inubushi, 2003). In the present experiment, the first peak of CH_4 emission generally occurred 3—4 weeks after seedling transplanting, when the plants were at the stage of vigorous vegetative growth with prolific tillers and unimpeded channels for CH_4 release into the atmosphere. Chlorophyll content in rice leaves is the foundation and source of CH_4 emission from paddy fields under all land use patterns and is an important factor responsible for the seasonal variation in CH_4 emission from paddy fields.

Table 7 Content of chlorophyll in rice leaves under different land use patterns (mg/dm^2)

Treatment	Tillering stage	Jointing stage	Heading stage	Ripening stage
T1*	3.15	2.83	2.58	0.79
T2	3.38	2.95	2.66	0.83
T3	3.25	2.91	2.61	0.84
T4	3.42	3.09	2.70	0.86

Note: * See note beneath Table 1

3.6 Depth of water layer in the paddy field

Depth of water layer in the paddy field was correlated positively with CH_4 emission in T4 (R = 0.482), T3 (R = 0.387) and T1 (R = 0.133), and negatively with CH_4 emission in T2 (R = -0.310, n = 15). The results support the viewpoints of Cai and other workers (Yagi, 1996; Cai, 2003b; Charoensilp, 2000). In sequencing the relevancy degree of the 7 influencing factors investigated in this study, depth of water layer in the paddy field took the 4th place in all the treatments. Water layer in paddy fields serves as a seal and helps to create an anaerobic condition. Therefore, its state greatly influences CH_4 production, oxidation and emission (Setyanto, 2000). CH_4 emission was reported to increase with water layer depth in paddy fields up to 10 cm and decline with further increase in water layer depth (Christian, 2003). In the land use patterns of T4 and T3, the field was drained for upland crop (wheat) growing after rice harvest and re-flooded for cultivating the rice crop. In this way, more stubbles of the plants were left in the soil, as a result, the anaerobic condition created by flooding during the rice growing season contributed more to CH_4 production than in T1 and T2. The difference in correlation coefficient of water layer depth with CH_4 emission between T3 and T4 was due to the fact that the conditions in T3 were more favorable to the gas exchange between the soil and the adjacent environment, and the ridges in T3 were exposed to the air during the rice-growing season and therefore the overall environments were not so favorable for CH_4 production as compared with T4. A comparison of T2 and T1 showed that the rice plants were more densely grown on the ridges, the illumination was lower on the soil surface in T2 than on the water surface in T1, water layer depth in the ridge-ditches in T2 was greater than water layer depth in T1, and less solar radiation reached the soil in T2. Therefore, the conditions in T2 were less favorable for CH_4 production.

3.7 CH_4 concentration in the crop canopy

CH_4 concentration in the crop canopy is formed during the process of CH_4 emission by rice plants. CH_4 concentration is generally in a positive correlation with CH_4 emission flux (Jia, 2003). It can be seen from the correlation matrix in gray relevancy analysis that CH_4 concentration in the crop canopy was correlated with CH_4 emission flux positively in T4, T2 and T1 (R being 0.492, 0.449 and 0.271, respectively, n = 15) and negatively in T3 (R = −0.083, n = 15). In sequencing the relevancy degree of the 7 influencing factors investigated in this study, CH_4 concentration in the crop canopy took the 5th to the 7th place in the 4 treatments. In T4, the soil was more abundant in organic matter during the rice-growing season and the environment was more anaerobic, thus benefiting CH_4 production. When CH_4 was emitted into the atmosphere through the rice plants, a relatively higher concentration of CH_4 was formed in the crop canopy. With other factors being similar, T2 changed soil micro-environment and benefited the formation of a micro-CH_4 layer in the crop canopy. However, a negatively correlation was observed in T3 between CH_4 concentration in the crop canopy and CH_4 emission flux in the fields in this study, indicating that considerable uncertainty may exist in the relationship of CH_4 concentration in the crop canopy with CH_4 emission from rice fields.

4 Conclusions

With the development of the discussion about global change and the "missing carbon sink", the influences of the changes in land use patterns on carbon storage of the terrestrial ecosystem have attracted more and more attention throughout the world. Soil carbon cycle in paddy fields is a slow process and is closely related to the history of disturbance experienced by the soil and disturbance intensity. Estimation of the influence of land use change on the microcosmic cultivation scale on CH_4 emission from paddy fields showed that fluxes of CH_4 emission and the annual fluxes of CH_4 emission from paddy fields were considerably different under conventional plain culture of paddy rice (T1), no-tillage and ridge culture of rice (T2), rice-wheat rotation with no-tillage and ridge culture (T3) and traditional pattern of rice-wheat rotation (T4) in both the rice growing and non-rice growing seasons. The underlying causes for such differences may have resulted from the changes in the microenvironment of soil-plant-atmosphere continuum induced by land management practices. CH_4 emission from paddy fields is the result of the integrated actions of the generation, oxidation and transmission of paddy field CH_4. Therefore, any factor influencing any of the above 3 links will affect CH_4 emission from paddy fields, and, relative to the same pattern, the influencing factors are not dependent of one another but closely coupled. The responses of all the influencing factors for CH_4 emission from paddy fields to land management practices were significant, with the exception of air temperature. The results of multivariate statistical analysis and gray relevancy analysis of these factors showed that the degree of their influences were different under different land management practices. Generally speaking, chlorophyll content in rice leaves, air temperature and temperature at the 5 cm soil layer play a more important role in CH_4 emission from paddy fields than illumination in paddy fields, relative humidity in paddy fields, depth of water layer in the paddy field, and CH_4 concentration of the crop canopy. It is reasonable to conclude that protective land use patterns like T3 and T4 in this study are favorable for mitigating CH_4 emission from paddy fields. Previous studies demonstrated that crop yield and quality were markedly improved under no-tillage and ridge culture(rice and wheat) and rotation of rice with upland crops (Xie, 1993; 2002; Xiao, 2002). In conclusion, the studies for many years have proved that land management practices at the microcosmic cultivation scale have significant ecological and productive effects and, therefore, should be taken as the starting point in researches of the problem of global (climate) changes and as effective measures for its solution.

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