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Methane emission from wetlands in Taiwan

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Abstract

To investigate methane emission from wetlands in Taiwan, soil properties, environmental conditions and methane emission were determined at three wetlands in northern Taiwan from September 1995 to April 1999. Soil pH values ranged from 6.15 to 7.80. Total organic carbon and total nitrogen contents were high in Kuan-du wetland and Kang-nan lake area, where the soils were sandy loam. In Kang-nan wetland, total organic carbon and total nitrogen contents were low and the soil was clay loam. Soil redox potential of Kuan-du wetland and Kang-nan lake area was lower than that of Kang-nan wetland. Atmospheric methane concentration was 0.8–2.7, 0.7–1.6 and 0.8–1.7 ppm ($mg\,kg^{-1}$) in Kang-du wetland, Kang-nan wetland and Kang-nan lake area, respectively. Average methane emission rate was 1.82, 0.14 and 0.23 $mg\,m^{-2}\,h^{-1}$ and annual methane emission was about 1.59×10^{-1}, 1.23×10^{-2} and 2.02×10^{-2} $ton\,ha^{-1}$, respectively. Annual methane emission from 11,896 ha of nine wetlands is estimated around 340 ton in Taiwan.

Keywords: Methane flux; Wetland; Soil properties; Environmental conditions

1. Introduction

Methane is considered as one of the most important greenhouse gases because of its high potential for thermal absorption (Segers, 1998). The increase in atmospheric methane from 0.72 to 1.78 ppmv is estimated to be responsible for about 15% enhancement in the greenhouse effect (Wang et al., 1996). The major sources are rice paddies, wetlands, sediments, enteric fermentation, animal wastes treatment and landfills under low redox potential conditions and the producers are obligate anaerobes (Yang, 1998; Clair et al., 2002; Hegde et al., 2003; Yang et al., 2003a, b). Methane emission from wetlands is estimated to 110 $Tg\,yr^{-1}$, and it is one of the largest natural sources of atmospheric methane, accounting for about 21% of the current global annual methane budget (Watson et al., 1992). Methane production and emission from wetland involved complex physiological processes of plants and microorganisms which were regulated by climatic and environmental factors (Cao et al., 1998).

Recently, it has increased interest in the contribution of wetlands to global methane budget (Nakano et al., 2000; Takeuchi et al., 2003). Natural wetlands were permanently or temporarily waterlogged, so that anaerobic conditions consequently developed for methanogenesis to occur. In order to understand the observed trends and predict the future atmospheric methane concentration, an accurate budget of the sources and sinks of atmospheric methane is required. In this paper, we focus on the seasonal variations of methane emissions from three different wetlands located in

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northern Taiwan and role of environmental factors in regulation of methane emission from these wetlands.

2. Materials and methods

2.1. Sampling location

Kuan-du wetland (25°07′N, 120°27′E, about 170 ha), Kang-nan wetland (24°45′N, 120°53′E, about 3000 ha) and Kang-nan lake area (24°45′N, 120°53′E, about 0.2 ha) in the northern Taiwan were selected for investigation. The Kuan-du musk was collected from the crossing place of the Tanswei and Keelung Rivers. The Kang-nan musk was collected from the riverside of Kehya Brook. The sedges that grow in Kuan-du wetland are tufted *Phragmites communis* and tufted *Cyperus malaccensis*. The plants that grow in Kang-nan wetland are *Kandelia candel*. There is a diurnal variation of flood tide and ebb tide twice a day in these wetlands and it takes 12 h 24 min for each tide cycle.

2.2. Environmental conditions

Air temperature was higher than soil temperature in summer and it was reverse in winter. The highest light intensity of Kuan-du wetland appeared in August 1996 and ranged from 5894 to 9332 $\mu mol\,m^{-2}\,s^{-1}$, while Kang-nan wetland had the highest light intensity in May 1998 and was between 10805 and 14734 $\mu mol\,m^{-2}\,s^{-1}$. The lowest value was in January 1998 and was between 785 and 982 $\mu mol\,m^{-2}\,s^{-1}$ and between 687 and 2456 $\mu mol\,m^{-2}\,s^{-1}$, respectively. The highest air temperature was 38°C and 39°C in August 1996 and the lowest one was 13°C and 14°C in January 1998 in Kuan-du wetland and Kang-nan wetland, respectively. The highest soil temperature was 34°C and 33°C in August 1996 and the lowest one was 15°C and 10°C in January 1998, respectively.

2.3. Soils

The properties of Kuan-du wetland soil were sandy loam, pH 6.7±0.5, total organic carbon 2.07±0.04% (dry weight), total nitrogen 0.18±0.02%, NH_4^+—N 13.0±0.1 $mg\,kg^{-1}$, NO_3^-—N 4.8±0.3 $mg\,kg^{-1}$, CEC 7.12±0.92 $ms\,cm^{-1}$ and redox potential (Eh) −425 to −300 mV, while those of Kang-nan wetland soil were clay loam, pH 7.2±0.2, total organic carbon 1.53±0.19% (dry weight), total nitrogen 0.15±0.02%, NH_4^+—N 20.0±0.10 $mg\,kg^{-1}$, NO_3^-—N 3.0±0.0 $mg\,kg^{-1}$, CEC 12.77±1.98 $ms\,cm^{-1}$ and Eh −180–200 mV. Kang-nan lake area soil was sandy loam, pH 7.2±0.5, total organic carbon 2.05±0.27% (dry weight), total nitrogen 0.21±0.05%, NH_4^+—N 34.0±0.1 $mg\,kg^{-1}$, NO_3^-—N 3.0±0.1 $mg\,kg^{-1}$, CEC 7.26±1.11 $ms\,cm^{-1}$ and Eh −400 to −180 mV. Most of soil Eh after ebb was lower than that before flooding.

2.4. Gas sampling method

Gas samples were collected using a home-made acrylic chamber (length 40 cm, width 40 cm and height 65 cm, about 96 l) that was equipped with an electronic fan, a thermometer and a sampling hole. For methane emission measurement, the acrylic chamber was installed on the surface of wetland soils and four chambers were used in each measurement. Methane emission rate was measured at 0.5 h intervals for 1.0 h by examine the changes of methane concentration in the acrylic chamber. Five ml of the gas sample was injected into a serum bottle that had been flushed with oxygen-free nitrogen gas. The gas sample in the headspace was injected on a Shimadzu 14A gas chromatograph (Shimadzu Co., Japan) with a Porapak Q glass column (0.26 mm × 2 m) and an FID detector. The column temperature was set at 100°C, and the injection and detector temperatures were set at 130°C. Methane concentration was calculated with a standard curve from 0.1 to 1000 $mg\,kg^{-1}$ (vol) (Chang and Yang, 1997).

2.5. Estimation of methane emission

Methane emission from wetlands was calculated by the experimental data and estimated by the following equation (Rolston, 1986): $F = (V/A)(\Delta C/\Delta t)$, where F is the methane emission rate ($mg\,m^{-2}\,h^{-1}$), V is the volume of chamber above soil (m^3), A is the cross-section of chamber (m^2), ΔC is the concentration difference between zero and t times ($mg\,cm^{-3}$), and Δt is the time duration between two sampling periods (h). Methane emission from wetland soil was calculated from the summation of methane emission in each year for 4-year measurement.

2.6. Analytical methods

Total organic carbon was analyzed by the wet oxidation Walkley–Black method, and organic matter content was calculated as C × 1.724 (Nelson and Sommers, 1982). Total nitrogen was measured by the modified Kjeldahl method (Yang et al., 1991). Light intensity was measured with a Toshiba SPI-5 photometer. Soil pH (10 cm depth) or water pH was directly determined in the wetland or on 1:1 (w/w) soil to water suspension with a pH meter. Redox potential was measured with a Hanna No. 081–854 potential meter under 5–20 cm depth of topsoil using the Pt electrode for 20–25 min equilibrium with the soil (Yang and Chang, 1997). A thermometer-determined air, water and soil temperatures. Experiments were carried out to obtain four measurements, and flux data subjected to analysis of variance and Duncan's multiple range tests ($p = 0.05$) using the Statistical Analysis System (SAS Institute, 2002).

3. Results

3.1. Methane emission in Kuan-du wetland

Methane emission is the net result of methane production and methane oxidation. Atmospheric methane concentrations, methane emission rates, total organic carbon, total nitrogen and soil Eh of Kuan-du wetland are given in Fig. 1. Average atmospheric methane concentration was 1.57 ± 0.13 ppmv with the maximum value 2.62 ppmv before flooding tide in January 1996 and the minimum one 0.82 ppmv before flooding tide in January 1998. Average methane emission rate was 1.82 mg $m^{-2}h^{-1}$, where the maximum value was 5.67 mg $m^{-2}h^{-1}$ after ebb tide in October 1996 with high total organic carbon (2.89%), total nitrogen (0.22%) and soil temperature (28°C), and low Eh (−376 mV) and pressure (1012.1 hPa), while the minimum one was 0.01 mg $m^{-2}h^{-1}$ before flooding tide in March 1996 with low total nitrogen (0.12%) and soil temperature (12°C), and mediate soil Eh (−315 mV) and pressure (1018.0 hPa).

3.2. Methane emission in Kang-nan wetland

Atmospheric methane concentrations, methane emission rates, total organic carbon, total nitrogen and soil Eh of Kang-nan wetland are presented in Fig. 2. Average atmospheric methane concentration was 1.04 ± 0.19 ppmv with the highest value 1.51 ppmv before flooding tide in October 1995 and the lowest one 0.78 ppmv before flooding tide in January 1996. Average methane emission rate was 0.14 mg $m^{-2}h^{-1}$ and the highest value was 0.17 mg $m^{-2}h^{-1}$ after ebb tide in August 1996 with high total organic carbon (1.67%), total nitrogen (0.15%) and soil temperature (33.5°C), and low Eh (−180 mV) and pressure (1000.3 hPa), while the lowest one was 0.01 mg $m^{-2}h^{-1}$ before flooding tide in November 1995 with low total organic carbon (1.45%), total nitrogen (0.12%) and soil temperature (28.5°C), and high Eh (190 mV) and pressure (1013.5 hPa).

3.3. Methane emission in Kang-nan lake area

For the investigation of anthropogenic contaminations on methane emission rate, Kang-nan lake area with high total organic carbon and near Kang-nan

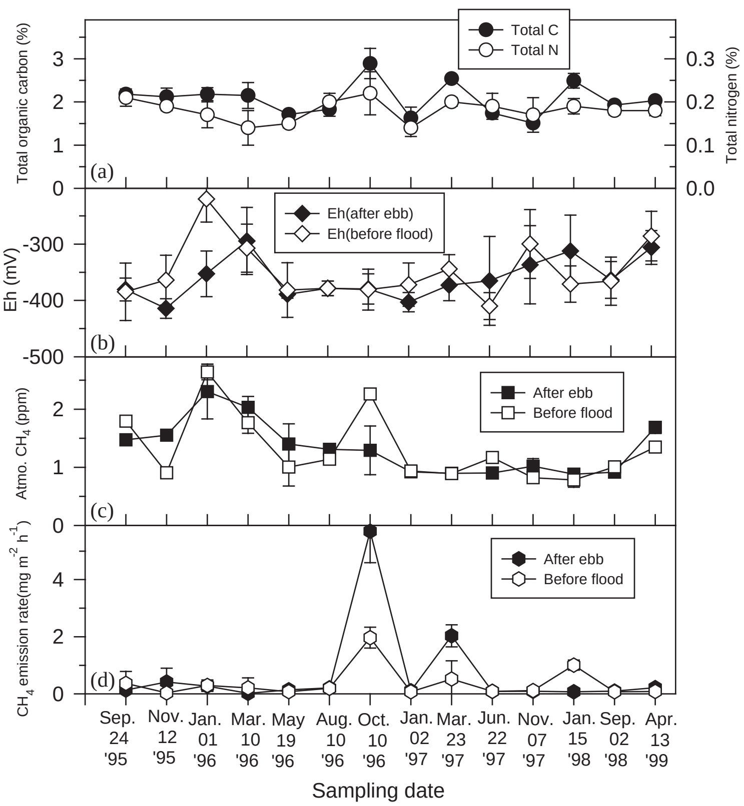

Fig. 1. Soil properties, atmospheric methane and methane emission rate of Kuan-du wetland: (a) total organic carbon and total nitrogen, (b) soil redox potential, (c) atmospheric methane, (d) methane emission rate.

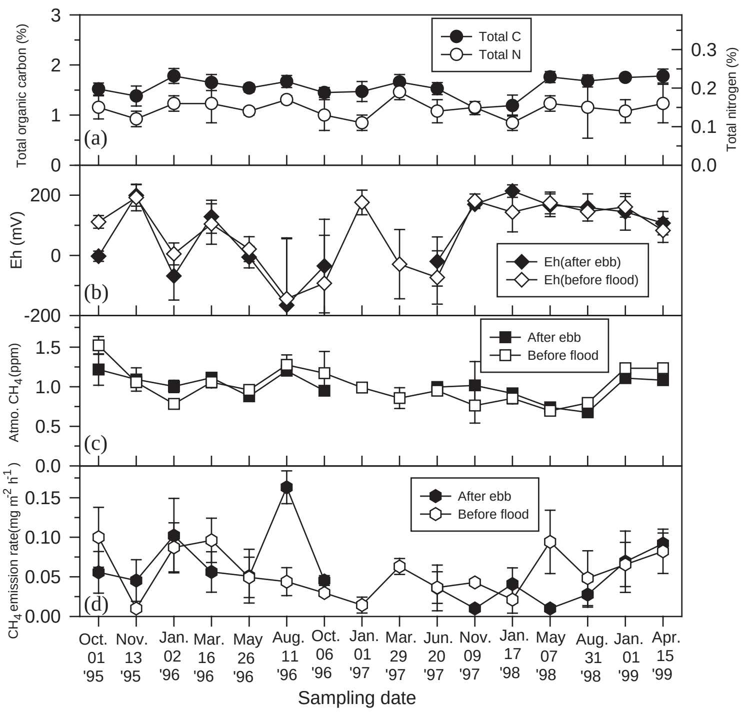

Fig. 2. Soil properties, atmospheric methane and methane emission rate of Kang-nan wetland: (a) total organic carbon and total nitrogen, (b) soil redox potential, (c) atmospheric methane, (d) methane emission rate.

wetland was chosen. The effluents from fish farm are discharged in this area. Average atmospheric methane concentration was 1.05 ± 0.21 ppmv and the value was very similar with that measured in Kang-nan wetland (Figs. 2 and 3). The average methane emission rate was found to be $0.23\,mg\,m^{-2}\,h^{-1}$ and the maximum rate $5.42\,mg\,m^{-2}\,h^{-1}$ in January 1998 with high total organic carbon (2.80%) and total nitrogen (0.37%) and low soil Eh (-350 mV) and pressure (1008.4 hPa), while the minimum rate $0.01\,mg\,m^{-2}\,h^{-1}$ in November 1997 with low total organic carbon (1.66%) and total nitrogen (0.17%) and high soil Eh (-230 mV) and pressure (1017.2 hPa).

3.4. Seasonal variation of methane emission from wetlands

Seasonal variations of atmospheric methane concentrations and methane emission rates are demonstrated in Table 1. Atmospheric methane concentrations showed no significant differences among the seasons at three tested wetlands. However, methane emission rates had significant differences. Spring and autumn had high methane emission rates, and summer and winter had low values in Kuan-du wetland and Kang-nan lake area, while methane emission rates had high values in summer and autumn and they had low rates in spring and winter in Kang-nan wetland.

3.5. Effect of soil properties and environmental conditions on methane emission

Methane emissions from Kuan-du wetland were higher than those from Kang-nan wetland due to the high total organic carbon and total nitrogen and low soil Eh. Therefore, the correlations between methane emission rates and soil properties or environmental conditions were studied and the results are shown in Table 2. It was found that methane emission rates had high correlation coefficient with total organic carbon ($r^2 = 0.38-0.67$) and total nitrogen ($r^2 = 0.29-0.61$), while the values were low in soil Eh ($r^2 = 0.01-0.45$), light intensity ($r^2 = 0.09-0.43$), soil temperature ($r^2 = 0.01-0.23$), air temperature ($r^2 = 0.01-0.18$), chamber temperature ($r^2 = 0.01-0.10$) and soil pH ($r^2 = 0.01-0.11$).

4. Discussion

Soil properties are the major factors influencing methane emission in all tested wetlands. Methanogenic bacteria are pH sensitive and most of them grow over a relatively narrow pH range of about 6–8. Crozier et al. (1995) reported an optimum pH of 7.7 for methane emission in coastal wetlands. The tested wetlands had pH values between 6.15 and 7.80 which are within the

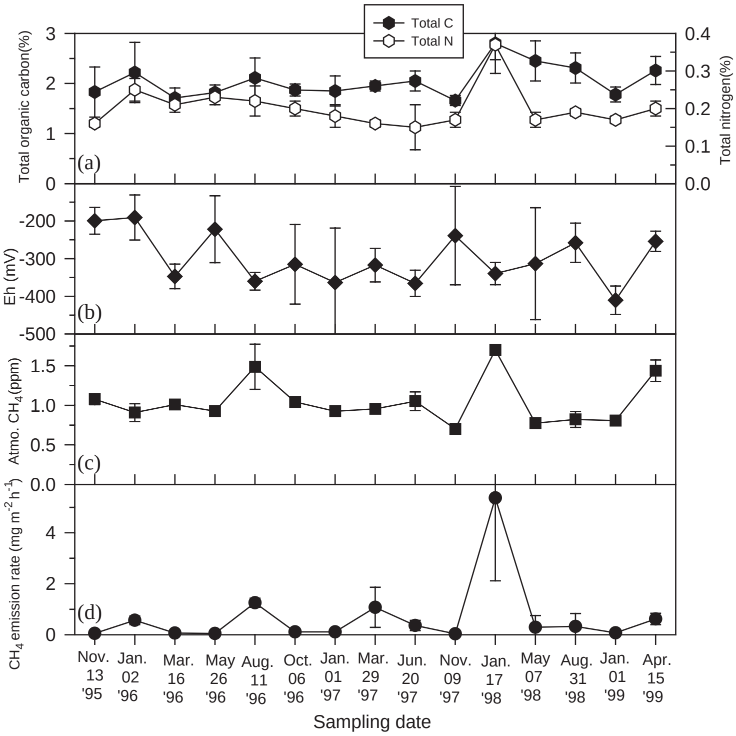

Fig. 3. Soil properties, atmospheric methane and methane emission rate of lake area of Kang-nan wetland: (a) total organic carbon and total nitrogen, (b) soil redox potential, (c) atmospheric methane, (d) methane emission rate.

Table 1
Seasonal variation of atmospheric methane concentration and methane emission rate of wetlands

Season	Kuan-du wetland	Kang-nan wetland	Kang-nan lake area
(a) *Atmospheric methane concentration* (ppm)			
Spring	1.44 ± 0.25^a	0.98 ± 0.07^a	1.05 ± 0.27^a
Summer	1.22 ± 0.05^a	1.09 ± 0.03^a	1.01 ± 0.05^a
Autumn	1.40 ± 0.24^a	0.96 ± 0.22^a	1.04 ± 0.06^a
Winter	1.20 ± 0.21^a	1.02 ± 0.12^a	1.02 ± 0.05^a
(b) *Methane emission rate* ($mg\,m^{-2}\,h^{-1}$)			
Spring	0.51 ± 0.21^a	0.06 ± 0.03^b	0.51 ± 0.09^a
Summer	0.18 ± 0.04^c	0.09 ± 0.01^a	0.21 ± 0.11^b
Autumn	0.59 ± 0.14^a	0.09 ± 0.03^a	0.44 ± 0.23^a
Winter	0.25 ± 0.11^b	0.04 ± 0.01^c	0.06 ± 0.05^c

Mean $\pm$ S.D. ($n = 14$). Means in the same row that did not share the same alphabetic superscript were significantly different at 5% level according to Duncan's multiple range tests.

pH range for optimum growth of methanogens. Therefore, the effect of soil pH on methane emission in tested wetlands was low ($r^2 = 0.01-0.11$). About 80% of methane is produced biologically under low Eh conditions by obligate anaerobes. Kuan-du wetland and Kang-nan lake area soils were sandy loam with low Eh (below -250 mV) and hence favored methane production. In contrast, Kang-nan wetland was clay loam with high Eh (between -180 and 200 mV) and so was unfavorable methane production. Soil Eh below -150 mV was considered to be critical for the initiation of methane production (Wang et al., 1996; Yang and Chang, 1998). Soil Eh ranged from -180 to 200 mV in Kang-nan wetland, and the effect of Eh on methane emission was high after ebb ($r^2 = 0.45$); while Eh was between -425 and -300 mV in Kuan-du wetland and between -400 and -180 mV in Kang-nan lake area, and the effect of Eh on methane emission was low in both tested areas ($r^2 = 0.01-0.04$).

Kuan-du wetland is located at the crossing place of the Tanswei and Keelung Rivers and has heavy pollution in the downstream area with high methane emission; while Kang-nan wetland is located in the Kehya Brook and has light pollution in the downstream area with low methane emission. Yagi and Minami (1990) reported that methane production increased with the amount of soil organic matter content. Total organic carbon had the highest correlation coefficient with methane emission ($r^2 = 0.38-0.67$), followed by total nitrogen ($r^2 = 0.32-0.61$) and C/N ratio ($r^2 = 0.11-0.35$). Rask et al. (2002) indicated that methane fluxes were high in the string and deep bay and had

Table 2
Correlations between methane emission rate (Y) and soil properties or environmental conditions

Wetland	Properties or conditions (X)	Equation	r^2
Kuan-du wetland	Total organic carbon	$Y = 2.86X - 5.22$ (after ebb)	0.52
		$Y = 1.13X - 1.97$ (before flood)	0.67
Kang-nan wetland		$Y = 0.13X - 0.13$ (after ebb)	0.38
		$Y = 0.10X - 0.09$ (before flood)	0.42
Kang-nan lake area		$Y = 3.13X - 5.72$ (after ebb)	0.54
Kuan-du wetland	Total nitrogen	$Y = 34.79X - 5.57$ (after ebb)	0.32
		$Y = 12.25X - 1.83$ (before flood)	0.34
Kang-nan wetland		$Y = 1.18X - 0.11$ (after ebb)	0.29
		$Y = 0.93X - 0.08$ (before flood)	0.45
Kang-nan lake area		$Y = 20.28X - 3.57$ (after ebb)	0.61
Kuan-du wetland	C/N ratio	$Y = 0.23X - 5.00$ (after ebb)	0.23
		$Y = 0.22X - 2.07$ (before flood)	0.35
Kang-nan wetland		$Y = 0.01X - 0.06$ (after ebb)	0.20
		$Y = 0.01X - 0.05$ (before flood)	0.19
Kang-nan lake area		$Y = 0.22X + 2.98$ (after ebb)	0.11
Kuan-du wetland	Soil redox potential	$Y = -0.01X - 2.48$ (after ebb)	0.04
		$Y = -0.002X - 0.269$ (before flood)	0.03
Kang-nan wetland		$Y = -0.0002X - 0.0736$ (after ebb)	0.45
		$Y = 0.01X - 0.05$ (before flood)	0.01
Kang-nan lake area		$Y = -0.004X - 0.441$ (after ebb)	0.04
Kuan-du wetland	Soil pH	$Y = 0.40X - 2.12$ (after ebb)	0.01
		$Y = -0.18X + 1.66$ (before flood)	0.02
Kang-nan wetland		$Y = 0.01X + 0.04$ (after ebb)	0.01
		$Y = 0.04X - 0.26$ (before flood)	0.11
Kang-nan lake area		$Y = 0.70X - 4.29$ (after ebb)	0.03
Kuan-du wetland	Air temperature	$Y = 0.02X + 0.22$ (after ebb)	0.01
		$Y = -0.02X + 0.81$ (before flood)	0.06
Kang-nan wetland		$Y = 0.01X + 0.04$ (after ebb)	0.02
		$Y = 0.01X + 0.05$ (before flood)	0.05
Kang-nan lake area		$Y = 0.03X - 0.44$ (after ebb)	0.18
Kuan-du wetland	Chamber temperature	$Y = -2.43X + 0.74$ (after ebb)	0.01
		$Y = -0.02X + 0.81$ (before flood)	0.06
Kang-nan wetland		$Y = 0.0014X + 0.0121$ (after ebb)	0.06
		$Y = 0.0006X + 0.00359$ (before flood)	0.02
Kang-nan lake area		$Y = 0.02X - 0.22$ (after ebb)	0.10
Kuan-du wetland	Soil temperature	$Y = 0.08X - 0.99$ (after ebb)	0.06
		$Y = 3.10X + 0.29$ (before flood)	0.01
Kang-nan wetland		$Y = 0.0013X + 0.0232$ (after ebb)	0.04
		$Y = 0.00205X + 0.00208$ (before flood)	0.15
Kang-nan lake area		$Y = 0.03X - 4.29$ (after ebb)	0.23
Kuan-du wetland	Light intensity	$Y = -5.66 \times 10^{-6}X + 0.49$ (after ebb)	0.09
		$Y = 5.74 \times 10^{-6}X + 0.20$ (before flood)	0.12
Kang-nan wetland		$Y = 3.5 \times 10^{-3}X + 3.47$ (after ebb)	0.09
		$Y = 5.8 \times 10^{-3}X - 2.24 \times 10^{-2}$ (before flood)	0.43

positive correlations with C/N ratio, but there was no relationship between methane flux and C/N ratio in the shallow bay. Nitrogen mineralization was not likely directly related to methane production.

Methane emission was high in summer and low in winter. Methane production is enhanced with increasing temperature in wetlands (Freeman et al., 2002). Methane emission had a linear correlation with soil temperature between 15°C and 30°C and the emission was undetectable when the soil temperature was below 10°C (Rask et al., 2002). The soil temperature effect on methane emission was high, and then followed by chamber and air temperatures. Light might affect the oxygen distribution and penetration in the water–air interface, and enhance methane oxidation (Khalil, 1995). King (1990) indicated that illumination could possibly induce the growth and photosynthesis of algae and the oxidation of methane, but reduces the emission of methane. In contrast, the correlation between methane emission and light intensity was low after ebb

($r^2 = 0.09$), and the value was mediate before flooding ($r^2 = 0.12-0.43$). The difference might be due to the high temperature and low moisture content of tested wetlands before flooding.

Atmospheric methane concentrations at the period after ebb were higher than those at the period before flooding due to the low Eh at submerged anaerobic conditions for methanogen growth and methane production (Sass et al., 1994; Singh et al., 2000). Methane emission rate of Kuan-du wetland ($1.82\,mg\,m^{-2}\,h^{-1}$) was the highest among the tested areas, while Kang-nan wetland was the lowest ($0.14\,mg\,m^{-2}\,h^{-1}$). These values were higher than that was measured by Wang et al. (1997) in the shallow seashore areas of southern Taiwan ($0.02\,mg\,m^{-2}\,h^{-1}$), Wang and Shieh (1997) in Tadu wetland in central Taiwan ($0.051\,mg\,m^{-2}\,h^{-1}$) and Tzuwen wetland in southern Taiwan ($0.005\,mg\,m^{-2}\,h^{-1}$), and Velichko et al. (1998) in tundra, forest-tundra, and bogs within the boreal zone in northern Eurasia ($0.46–0.63\,mg\,m^{-2}\,h^{-1}$). It was same level as that was determined by Aselmann and Crutzen (1989) in the assessment methane emission from global wetlands ($1.66\,mg\,m^{-2}\,h^{-1}$), Cao et al. (1998) in the northern natural wetlands ($1.67\,mg\,m^{-2}\,h^{-1}$), and Nakano et al. (2000) in the waterlogged site at Tiksi (Arctic Siberia) near the mouth of Lena River ($1.93\,mg\,m^{-2}\,h^{-1}$). However, methane emission from Kuan-du wetland was less than that was proposed by Shurpali et al. (1993) in Minnesota peatland ($1.25–6.67\,mg\,m^{-2}\,h^{-1}$), Boeckx and van Cleemput (1997) in global wetlands ($2.08–4.15\,mg\,m^{-2}\,h^{-1}$), Cao et al. (1998) in the temperate and tropical natural wetlands ($6.26–8.13\,mg\,m^{-2}\,h^{-1}$), Nakano et al. (2000) in the waterlogged site at Chersky on the lower Kolyma River ($11.71\,mg\,m^{-2}\,h^{-1}$), Singh et al. (2000) in the vegetated surface of five natural wetlands in north India ($7.30–67.72\,mg\,m^{-2}\,h^{-1}$), and Takeuchi et al. (2003) in the open bog of west Siberian wetland ($9.71 \pm 13.59\,mg\,m^{-2}\,h^{-1}$). Shurpali et al. (1993) showed that episodic methane emission had 2–3 times larger than gradual (nonepisodic) pattern. Episodic emissions are associated with significant drops in atmospheric pressure and decline in water table. The effect of atmospheric pressure on methane emission from wetland was less significant in Taiwan. Therefore, these differences of methane emission from wetland might be due to the locations, soil properties and environmental conditions.

Seasonal variation of methane emission rate was significantly different among the tested wetlands in Taiwan. Spring and autumn had high values in Kuan-du wetland and Kang-nan lake area, while there was a high rate in summer and autumn in Kang-nan wetland. Harriss et al. (1985) indicated that methane emission rate was between 8.33 and $25.0\,mg\,m^{-2}\,h^{-1}$ in summer and autumn of the wetland near Minnesota, and Roulet et al. (1992) reported that methane emission rate was only $0.13–0.54\,mg\,m^{-2}\,h^{-1}$ in winter season, and Singh et al. (2000) showed that methane emission rate from the vegetated surface of Gomti River was maximum in summer season ($67.72\,mg\,m^{-2}\,h^{-1}$), followed by rainy season ($28.83\,mg\,m^{-2}\,h^{-1}$), and had the least in winter season ($14.92\,mg\,m^{-2}\,h^{-1}$).

In this study, annual methane emission from Kuan-du wetland, Kang-nan wetland and Kang-nan lake area with 4-year data was 1.59×10^{-1}, 1.23×10^{-2} and $2.02 \times 10^{-2}\,ton\,ha^{-1}$, respectively. Average methane emission was $6.38 \times 10^{-2}\,ton\,ha^{-1}$. Annual methane emission from 11,896 ha of nine wetlands in Taiwan is estimated at around 340 ton.

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