Estimation of methane and nitrous oxide emissions from paddy fields in Taiwan

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ARTICLE INFO

Article history:

Available online 20 January 2009

Keywords:

Methane

Nitrous oxide

Paddy field

Intermittent irrigation

IPCC

ABSTRACT

To investigate the greenhouse gases emissions from paddy fields, methane and nitrous oxide emissions were estimated with the local measurement and the IPCC method during 1990–2006 in Taiwan. Annual methane emission ranged from 9001 to 14,980 ton in the first crop season for 135,314–242,298 ha of paddy fields, and it was between 16,412 and 35,208 ton for 101,710–211,968 ha in the second crop season with the local measurement for intermittent irrigation. The value ranged from 31,122 to 55,729 ton of methane emission in the first crop season, and it was between 29,493 and 61,471 ton in the second crop season with the IPCC guideline for continuous flooding. Annual nitrous oxide emission from paddy fields was between 371 and 728 ton in the first crop season, and the value ranged from 163 to 365 ton in the second crop season with the local measurement. Methane emission from paddy fields in Taiwan for intermittent irrigation was only 26.72–28.92%, 55.65–57.32% and 41.19–43.10% with the IPCC guidelines for continuous flooding and mean temperature of transplanting stage in the first crop, the second crop and total paddy fields, respectively. The values were 53.44–57.84%, 111.29–114.55% and 82.38–86.20% with the IPCC guidelines for single aeration and mean temperature of transplanting stage, respectively; and the values were 133.60–144.61%, 282.56–286.62% and 205.96–215.49% with the IPCC guidelines for multiple aeration and mean temperature of transplanting stage, respectively. Intermittent irrigation in paddy fields reduces methane emission significantly; appropriate application of nitrogen fertilizer and irrigation in paddy fields also decreases nitrous oxide emission.

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1. Introduction

Global warming induced by increasing greenhouse gases concentrations in the atmosphere is a matter of great environmental concern. Methane, carbon dioxide, nitrous oxide and chlorofluorocarbons (CFCs) are the greenhouse gases, which have strong infrared absorption bands and trap part of the thermal radiation from the earth's surface. Concentrations of carbon dioxide, methane, nitrous oxide and CFCs increased from 337 to 360, 1.50 to 1.72, 0.302 to 0.320, and 4.68×10^{-4} to $7.69 \times 10^{-4} \text{ g m}^{-3}$, respectively, during last decade in the atmosphere [1].

About 80% of methane is produced biologically and the major source sites are rice paddy, wetland, sediment, enteric fermentation, animal wastes treatment, agricultural waste burning, savannah burning, landfill and sewage treatment under low redox

potential conditions by obligate anaerobes [2–12]. The release of nitrous oxide was increasing in recent years due to more intensive agricultural practices. Denitrification of heterotrophic microbes in oxygen deficient environments, nitrification of autotrophic and heterotrophic nitrifying microbes and dissimilate nitrate to ammonium of heterotrophic microbes in aerobic conditions produced nitrous oxide [13]. The contribution of agriculture to the global annual nitrous oxide emission was estimated at approximately 35% [14].

In Taiwan, there were 263,188 ha of paddy fields and more than 4 million tons of crop residues in 2006. Rice was cultivated with intermittent irrigation in Taiwan, while continuous flooding was used in other countries. There are two crop seasons in Taiwan, the first crop season is cultivated in February and harvested in July, and the second crop season is cultivated in August and harvested in December. Estimation of methane and nitrous oxide emissions from paddy fields during 1990–2006 with the country-specific emission factors were used, whereas the local data were unavailable and the emission factors recommended by the IPCC guideline [15,16] were used.

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2. Materials and methods

2.1. Cultivation area

Cultivation areas of paddies in Taiwan from 1990 to 2006 are adapted from the Taiwan Agriculture Yearbook from 1991 to 2007 [17,18].

2.2. Measurement of methane and nitrous oxide emissions

Methane and nitrous oxide emissions were measured by home-made acrylic chamber (length 40 cm, width 40 cm and height 65 cm, about 96 l) [19]. Methane and nitrous oxide were analyzed by gas chromatograph using FID and ECD, respectively [20].

2.3. Methane and nitrous oxide emission factors of paddy fields

Methane and nitrous oxide emission factors from paddy fields of Taiwan were measured by the local measurement and listed in

Table 1. Other emission factors were recommended by the IPCC guidelines [15]. Most of the paddies were applied chemical fertilizers; only the organic paddies production used organic fertilizers.

2.4. Estimation of methane and nitrous oxide emissions

Methane and nitrous oxide emissions from paddy fields were calculated from the experimental data and estimated by the following equation at each growth stage [7,32].

$$F = (V/A)(\Delta C/\Delta t)$$

Where F is the methane or nitrous oxide emission rate ($\text{mg m}^{-2} \text{h}^{-1}$), V is the volume of chamber above the soil (m^3), A is the cross-section of chamber (m^2), ΔC is the concentration difference between zero time and time t (mg m^{-3}), and Δt is the time duration between two sampling period (h). The total methane or nitrous oxide emission from paddy fields was the summation of methane and nitrous oxide emissions in all growth stages of crops.

Table 1
Greenhouse gas emission from paddy fields.

Location	Treatment	Methane emission		Nitrous oxide emission		
		1st crop	2nd crop	1st crop	2nd crop	Full year
		g m^{-2}				
NTU Exper. Station	Inter. irrigation	2.55–11.70 ^k	13.73 ^k	0.30–0.39 ^g	0.07–0.75 ^g	–
	Cont. flooding	–	28.85 ^k	–	–	–
Taoyuan Dist. AIS	Inter. irrigation	1.73–5.23 ^k	10.54–10.56 ^k	0.44–0.54 ^g	0.06–0.40 ^g	–
	W/green manure	5.55 ^k	14.43–30.12 ^k	–	1.22 ^g	–
Miaoli farm	Inter. irrigation	9.82 ^k	39.50 ^k	–	–	–
NCHU Exper. Station	Inter. irrigation	8.18 ^j	1.18 ^j	–0.11–0.60 ^a	–0.11–0.50 ^a	0.22–1.25 ^a
						0.61 ^b
Huatan-CH farm	Inter. irrigation	9.00–19.80 ^{c,l}	12.03–33.11 ^{c,l}	0.32 ^h	0.48–0.52 ^{h,l}	–
	Inter. irrigation	–	4.76 ^l	–	0.27 ^l	–
Chihu-CH farm	Inter. irrigation	0.15 ^j	10.45 ^j	–	–	–0.05–1.11 ^a
Chihu-CH farm	Inter. Irrigation	23.06 ^c	–	–	–	–
Tachen-CH farm	Inter. Irrigation	0.94 ^g	–	–	–	–
Tienwei-CH farm	Inter. Irrigation	–	–	–	–	0.59 ^b
Chiayi farm	Inter. irrigation	3.48 ^j	10.17 ^j	–	–	0.24–0.99 ^a
Lutsao-Chiayi	Inter. Irrigation	4.78 ^d	35.27 ^d	–	–	0.44 ^b
	Inter. Irrigation	9.20 ^e	49.00 ^e	–	–	–
	W/burned rice straw	4.10 ^d	41.79 ^d	–	–	–
	W/rice straw	5.72 ^d	80.62 ^d	–	–	–
	W/chicken manure	–	66.90 ^e	–	–	–
	W/soybean cake	–	46.65 ^e	–	–	–
	W/rice bran	14.89 ^e	–	–	–	–
	Cont. flooding	55.80 ^e	84.50 ^e	–	–	–
Kaohsiung Dist. AIS	Inter. irrigation	2.36 ^j	8.47 ^j	–	–	0.05–1.14 ^a
	Inter. Irrigation	–	–	–	–	0.49 ^e
Hwalien-Lotung AIS	Inter. irrigation	2.92 ^k	24.64 ^k	0.35–0.78 ^g	0.0–0.06 ^g	–
Hwalien-Chian AIS	Inter. irrigation	1.42–2.42 ⁱ	0.26–2.33 ⁱ	–	–	–
	W/rice straw	2.77–2.85 ⁱ	3.13–7.60 ⁱ	–	–	–
Hwalien-Fuli AIS	Inter. irrigation	7.40–13.10 ⁱ	12.50–24.30 ⁱ	–	–	–
	W/high N fertile.	11.60–19.73 ⁱ	21.14–48.37 ⁱ	–	–	–
IPCC	Cont. flooding	23 ^f	29 ^f	–	–	–
	Single drain	11.50 ^f	14.50 ^f	–	–	–
	Multiple drains	4.6 ^f	5.8 ^f	–	–	–

^a Chao [21].

^b Chao [22].

^c Chen et al. [23].

^d Huang et al. [24].

^e Huang et al. [25].

^f IPCC [15].

^g Lai [26].

^h Lai et al. [27].

ⁱ Huang et al. [28].

^j Wang and Shieh [29].

^k Yang and Chang [6,30].

^l Yang and Lai [31].

Table 2

Methane emission from paddy fields in Taiwan with local measurement from 1990 to 2006 (ton).

Year	Taipei, Keelung	I-lan	Taoyuan, Hsinchu	Miaoli	Taichung, Changhua, Nantou	Yuanlin, Chiayi, Tainan	Kaohsiung, Pingtung	Taitung, Hualien	Total
1990 1st crop	265.9	319.2	989.4	1,327.8	6,161.8	4,510.8	496.0	908.6	14,979.5
2nd crop	240.4	1,371.9	3,823.0	5,372.3	6,058.6	15,009.1	1,702.5	1,631.1	35,208.4
Sub-total	506.3	1,691.0	4,812.4	6,700.1	12,220.3	19,519.9	2,198.5	2,539.7	50,187.9
1991 1st crop	206.1	286.0	934.1	1,219.0	5,800.0	4,357.4	435.7	862.9	14,101.2
2nd crop	198.8	1,272.1	3,778.9	4,828.2	5,950.1	14,104.4	1,502.4	1,526.7	33,161.6
Sub-total	404.9	1,558.1	4,712.9	6,047.1	11,750.1	18,461.8	1,938.1	2,389.7	47,262.8
1992 1st crop	167.1	288.5	909.9	1,136.3	5,648.2	3,641.9	390.9	851.5	13,034.3
2nd crop	131.1	819.7	3,587.5	4,711.2	5,675.3	13,303.0	1,233.1	1,496.0	30,956.9
Sub-total	298.2	1,108.3	4,497.3	5,847.5	11,323.5	16,944.9	1,623.9	2,347.6	43,991.2
1993 1st crop	142.1	276.7	862.7	1,079.7	5,337.4	4,272.2	357.4	798.8	13,127.0
2nd crop	96.9	754.9	3,468.9	4,388.4	5,448.4	12,952.9	1,053.0	1,451.5	29,614.9
Sub-total	239.0	1,031.5	4,331.6	5,468.1	10,785.8	17,225.1	1,410.4	2,250.3	42,741.9
1994 1st crop	99.6	278.3	723.2	1,055.4	5,077.6	3,808.2	375.3	816.4	12,234.0
2nd crop	84.4	480.4	3,185.6	4,270.2	5,187.7	12,377.6	988.7	1,457.0	28,031.6
Sub-total	184.0	758.7	3,908.8	5,325.6	10,265.3	16,185.8	1,364.0	2,273.4	40,265.6
1995 1st crop	106.2	270.2	782.5	982.6	4,923.9	4,033.6	329.4	799.0	12,227.4
2nd crop	76.8	301.5	3,239.9	4,264.1	4,985.1	12,182.0	895.9	1,543.7	27,489.0
Sub-total	182.9	571.7	4,022.3	5,246.8	9,909.0	16,215.6	1,225.3	2,342.7	39,716.4
1996 1st crop	76.0	267.5	655.9	951.3	4,777.2	3,540.9	316.5	870.2	11,455.5
2nd crop	71.9	264.7	3,115.5	3,994.9	4,875.2	12,400.8	925.8	1,632.9	27,281.7
Sub-total	147.9	532.2	3,771.4	4,946.2	9,652.4	15,941.7	1,242.3	2,503.1	38,737.2
1997 1st crop	86.5	282.6	783.1	960.1	4,923.3	4,205.9	303.7	963.9	12,509.1
2nd crop	64.4	207.3	3,231.5	4,102.1	4,787.6	11,886.0	813.4	1,728.0	26,820.3
Sub-total	150.9	489.8	4,014.5	5,062.2	9,710.9	16,091.9	1,117.1	2,691.9	39,329.4
1998 1st crop	72.0	275.2	792.5	956.0	4,782.2	4,260.3	305.5	977.0	12,420.7
2nd crop	60.7	29.1	3,108.1	3,886.5	4,624.2	11,759.0	720.2	1,677.9	25,865.7
Sub-total	132.7	304.3	3,900.7	4,842.4	9,406.4	16,019.3	1,025.8	2,654.9	38,286.4
1999 1st crop	67.1	272.7	747.1	897.7	4,680.9	4,174.5	303.5	970.9	12,114.4
2nd crop	53.2	76.5	2,821.6	3,776.8	4,639.2	11,910.1	789.2	1,745.6	25,812.2
Sub-total	120.3	349.2	3,568.7	4,674.6	9,320.1	16,084.6	1,092.7	2,716.5	37,926.6
2000 1st crop	62.7	268.0	710.4	904.0	4,518.1	4,252.0	317.7	978.6	12,011.5
2nd crop	50.0	42.6	2,461.2	3,245.3	4,449.9	11,095.6	695.9	1,693.3	23,734.7
Sub-total	112.7	310.6	3,171.6	4,149.3	8,968.0	15,347.6	1,013.6	2,671.9	35,745.3
2001 1st crop	56.8	258.9	667.6	853.1	4,499.4	4,078.3	307.3	917.8	11,639.2
2nd crop	49.7	8.5	2,325.6	2,889.6	4,485.3	11,304.4	656.4	1,726.6	23,446.1
Sub-total	106.6	267.4	2,993.2	3,742.7	8,984.8	15,382.7	963.8	2,644.5	35,085.3
2002 1st crop	50.9	236.3	538.6	723.1	4,430.7	3,939.3	289.8	946.0	11,154.7
2nd crop	43.8	7.2	1,714.6	2,790.9	4,257.3	10,354.1	518.1	1,587.6	21,273.6
Sub-total	94.7	243.5	2,253.2	3,514.0	8,688.1	14,293.4	807.9	2,533.6	32,428.3
2003 1st crop	42.0	234.0	269.5	743.7	4,309.1	3,637.1	286.5	900.3	10,422.2
2nd crop	40.1	0.3	1,136.9	2,305.3	3,843.3	9,000.5	425.5	1,476.0	18,227.9
Sub-total	82.1	234.3	1,406.4	3,049.0	8,152.4	12,637.6	712.0	2,376.3	28,650.1
2004 1st crop	39.6	215.9	133.9	546.4	4,181.3	2,733.4	270.9	879.8	9,001.1
2nd crop	43.4	0.8	944.0	2,039.3	3,760.0	7,786.7	323.6	1,514.0	16,411.7
Sub-total	83.0	216.7	1,077.8	2,585.7	7,941.3	10,520.1	594.4	2,393.8	25,412.8
2005 1st crop	38.2	215.2	342.9	654.6	4,247.0	3,560.0	268.9	879.7	10,206.5
2nd crop	39.1	0.3	1,103.2	2,305.7	3,866.4	9,133.9	295.9	1,544.3	18,288.8
Sub-total	77.3	215.5	1,446.1	2,960.3	8,113.4	12,693.9	564.7	2,424.0	28,495.3
2006 1st crop	33.0	215.1	287.8	620.7	4,188.9	3,591.1	243.5	906.4	10,086.5
2nd crop	33.6	0.5	886.5	2,135.1	3,730.0	9,357.3	219.0	1,580.0	17,942.0
Sub-total	66.6	215.6	1,174.3	2,755.8	7,918.9	12,948.4	462.5	2,486.4	28,028.5
Average 1st crop	94.8	262.4	654.8	918.3	4,852.2	3,917.5	329.3	895.8	11,924.6
2nd crop	81.1	331.7	2,584.3	3,606.2	4,742.6	11,524.6	809.3	1,589.0	25,268.8
Sub-total	175.9	594.1	3,239.1	4,524.5	9,594.8	15,442.1	1,138.6	2,484.8	37,193.4

3. Results and discussion

3.1. Methane emission from paddy fields

There are two crop seasons for paddy rice in Taiwan. Total growth period of paddy rice in the first crop season (February to July) was between 122 and 149 days, and it ranged from 112 to 135 days in the second crop season (August to December). The daily temperature increased gradually during rice cultivation in the first crop season, and it was reversed in the second crop season. The mean temperature in the first crop season (February to July) was 19.17–26.25 °C, and the value was 19.54–26.56 °C in the second

crop season (August to December). While the mean temperature during the transplanting stages of rice cultivation was 16.27–24.10 °C in the first crop season (February to April), and the value was 21.20–28.37 °C in the second crop season (August to October). Most of mean temperatures in the second crop were higher than those in the first crop except in 1991 and some areas in 1994, 1999, 2001, 2002, 2003 and 2004. This is different from the single crop season countries such as Japan, Korea, USA and Italy [33–36]. Therefore, the methane emission patterns of the two crop seasons in Taiwan were also different from other locations with single crop season. Methane emission was high at the active tillering, booting, flowering and ripening stages for the active degradation of organic

matter and high concentration of root secreted [6,7]. However, drainage was practiced at the flowering and ripening stages in the intermittent irrigation system, and the methane emission rate decreased at these stages. Methane emission was high at the flooding and the transplanting stages in the second crop season for organic matter degradation with high temperature. While methane emission was low at the flooding and the transplanting stages in the first crop season for low temperature, and it was also low at the flowering and the ripening stages for the intermittent irrigation and high redox potential repressed methane emission. Therefore, methane emission from paddy field in the second crop season was higher than those in the first crop season.

Methane emission was between 0.15 and 19.80 g m⁻² with intermittent irrigation in the first crop season, and it ranged from 1.18 to 49.00 g m⁻² in the second crop season. Methane emission increased with green manure, burn rice straw, rice straw, rice bran, soybean cake and chicken manure amendment. It was 1.06–3.20, 0.86, 1.18–1.95, and 1.62 times higher than those with intermittent irrigation and convention chemical fertilizer application for green manure, burn rice straw, rice straw and rice bran amendment in the first crop season, respectively; and the value was 1.36–2.85, 1.18, 1.34–3.26, 1.37, and 0.95 times higher than those with intermittent irrigation for green manure, burn rice straw, rice straw, chicken manure and soybean cake amendment in the second crop season, respectively [6,24,25,28,30]. High nitrogen fertilizer application also enhanced 1.51–1.57 and 1.69–1.99 times of methane emission higher than those with convention nitrogen chemical fertilizer application in the first and second crop seasons, respectively [28]. Green manure amendment stimulated methane emission rate and it also increased the soil organic matter content [6,30]. Similar results were also found in rice cultivated during dry and wet crop seasons in the Philippines paddy fields [37].

Methane emission factors of paddy fields at different locations in Taiwan with the local measurement were the average of the local measurement at different years and different paddy fields in each location. Methane emission in the second crop season was 1.15–12.94 times higher than those in the first crop season with intermittent irrigation; the reverse was true in the pot cultivation with continued flooding [6,38]. There was a 10–15 cm depth of flooding in the soil surface during the rice cultivation in Italian, Louisiana and California paddy fields [4,37]. However, the intermittent irrigation system was very popular in the late stage of paddy rice cultivation in Taiwan to reduce the water resource for rice growth, to increase the rice yield and to eliminate toxic substances in the rice root. The accumulative methane emission was around 47–58% lower with intermittent irrigation than with continuous flooding treatment. Miaoli area had high methane emission due to the high soil organic matter content [7].

Cultivation area of paddy fields in the first crop was 1.14 times higher than that of the second crop in 1990, the value increased gradually to 1.45 times in 2003, and then the value slightly decreased to 1.44 in 2006. Cultivation area of paddy fields in the first crop was higher than the second crop due to the cultivation of vegetable and upland crop, and the low rice productivity (71–91% of the first crop) in the second crop season. Cultivation area of paddy fields was also decreased because of the change of culture system and agriculture policy in Taiwan. The first crop, second crop and total cultivation area were 242,298, 211,968 and 454,266 ha in 1990, respectively and the cultivation areas decreased to 155,248, 107,940 and 263,188 ha in 2006. Taichung, Changhua, Nantou, Yuanlin, Chiayi, and Tainan in the central Taiwan are the major cultivation area. It had 59.06–67.71%, and 60.48–71.49% of total paddy cultivation area in the first and the second crop, respectively, and the ratio increased gradually due to the change of land use and culture system in the northern and southern Taiwan.

Annual methane emission from paddy fields was calculated with the emission factors and cultivation area at each location and the results are illustrated in Table 2. Annual methane emission decreased with the decreasing of cultivation area of rice. Total methane emissions were 14,980 and 35,208 ton at the first and the second crop seasons in 1990, respectively, and it decreased to 10,087 and 17,942 ton in 2006. Although the cultivation area of the first crop was higher than that of the second crop, however, methane emission of the second crop season was higher than that of the first crop season. Methane emission of the second crop season was 2.35 times higher than that of the first crop season in 1990, and the value decreased to 1.78 times in 2006 due to the cultivation of vegetable and upland crop and the decreasing of cultivation area of rice paddy in the second crop.

Table 3

Methane emission from paddy fields in Taiwan calculated with local measurement and IPCC guidelines from 1990 to 2006(ton).

Year	Local measurement	IPCC continuous	IPCC single aeration	IPCC multiple aeration
1990 1st crop	14,979.5	55,728.9	27,864.3	11,145.7
2nd crop	35,208.4	61,470.7	30,735.4	12,294.1
Sub-total	50,187.9	117,199.6	58,599.7	23,439.8
1991 1st crop	14,101.2	52,305.2	26,152.6	10,461.0
2nd crop	33,161.6	58,399.3	29,199.7	11,679.9
Sub-total	47,262.8	110,704.5	55,352.3	22,140.9
1992 1st crop	13,034.3	48,178.1	24,089.1	9,635.6
2nd crop	30,956.9	54,424.3	27,212.2	10,884.9
Sub-total	43,991.2	102,602.4	51,301.2	20,520.5
1993 1st crop	13,127.0	48,711.7	24,355.9	9,742.3
2nd crop	29,614.9	51,949.7	25,974.9	10,389.9
Sub-total	42,741.9	100,661.4	50,330.7	20,132.3
1994 1st crop	12,234.0	45,152.9	22,576.5	9,030.6
2nd crop	28,031.6	49,160.8	24,580.4	9,832.2
Sub-total	40,265.6	94,313.7	47,156.9	18,862.7
1995 1st crop	12,227.4	45,441.3	22,720.7	9,088.3
2nd crop	27,489.0	48,113.3	24,056.7	9,622.7
Sub-total	39,716.4	93,554.6	46,777.3	18,711.0
1996 1st crop	11,455.5	42,045.6	21,022.8	8,409.1
2nd crop	27,281.7	47,837.0	23,918.5	9,567.4
Sub-total	38,737.2	89,882.6	44,941.3	17,976.5
1997 1st crop	12,509.1	46,462.3	23,231.2	9,292.5
2nd crop	26,820.3	47,038.3	23,519.1	9,407.7
Sub-total	39,329.4	93,500.6	46,750.3	18,700.2
1998 1st crop	12,420.7	46,327.5	23,163.8	9,265.5
2nd crop	25,865.7	45,316.3	22,658.1	9,063.3
Sub-total	38,286.4	91,643.8	45,821.9	18,328.8
1999 1st crop	12,114.4	45,338.3	22,669.1	9,067.7
2nd crop	25,812.2	45,223.2	22,611.6	9,044.6
Sub-total	37,926.6	90,561.5	45,280.8	18,112.3
2000 1st crop	12,011.5	44,862.7	22,431.3	8,972.5
2nd crop	23,734.7	41,918.3	20,959.2	8,383.7
Sub-total	35,746.2	86,781.0	43,390.5	17,356.2
2001 1st crop	11,639.2	43,367.2	21,683.6	8,673.4
2nd crop	23,446.1	41,489.1	20,744.6	8,297.8
Sub-total	35,085.3	84,856.3	42,428.2	16,971.3
2002 1st crop	11,154.7	40,913.3	20,456.7	8,182.7
2nd crop	21,273.6	37,397.2	18,698.6	7,479.4
Sub-total	32,428.3	78,310.5	39,155.3	15,662.1
2003 1st crop	10,422.2	37,072.3	18,536.2	7,414.5
2nd crop	18,227.9	32,172.6	16,086.3	6,434.5
Sub-total	28,650.1	69,244.9	34,622.5	13,849.0
2004 1st crop	9,001.1	31,122.2	15,561.1	6,224.4
2nd crop	16,411.7	29,493.3	14,746.6	5,898.7
Sub-total	25,412.8	60,615.5	30,307.7	12,123.1
2005 1st crop	10,206.5	36,444.0	18,222.0	7,288.8
2nd crop	18,288.8	32,065.6	16,032.8	6,413.1
Sub-total	28,495.3	68,509.6	34,254.8	13,701.9
2006 1st crop	10,080.5	35,707.0	17,853.5	7,141.4
2nd crop	17,944.1	31,302.9	15,651.4	6,260.6
Sub-total	28,024.6	67,009.9	33,504.9	13,402.0
Average 1st crop	11,924.6	43,834.1	21,917.1	8,766.8
2nd crop	25,268.8	44,398.3	22,199.2	8,879.7
Sub-total	37,193.4	88,232.4	44,116.3	17,646.5

Average methane emission factors from paddy fields with 52 samples in 11 locations of the world except Taiwan were 26.00 g m^{-2} . Hour et al. [39] reported the average methane emission factors from the Japan, Korea, Philippines, Thailand and Texas were 20 g m^{-2} . The methane emission factors were 20 and 26 g m^{-2} in northern and southern Taiwan at the first crop season, respectively; while the values were 25 and 30 g m^{-2} at the second crop season, respectively. From the mean temperature of the first and the second crop growth season, it showed that the average temperatures of 7 locations from 1990 to 2006 were 23.93 and 24.43 °C during the growth period at the first crop (February to July) and the second crop (August to December) season, respectively. While the mean temperatures during the flooding and the

transplanting stage at the first crop (February to April) and the second crop (August to October) were 20.41 and 26.53 °C, respectively. Methane emission from paddy fields is high at the flooding and the transplanting stages for the organic matter degradation and the submerged state [30,38]. A positive linear correlation between methane production (Y) and temperature (X) ($Y = 0.22X - 3.94$) ($r^2 = 0.93$) between 15 and 37 °C was described in previous paper [30]. Therefore, the methane emission factors calculated with the IPCC guideline and mean temperature of the flooding and the transplanting stages are estimated as 23 and 29 g m^{-2} .

Annual methane emissions from the paddy fields in Taiwan with the IPCC guideline from 1990 to 2006 are calculated in Table 3.

Table 4

Nitrous oxide emission from paddy fields in Taiwan with local measurement from 1990 to 2006 (ton).

Year	Taipei, Keelung	I-lan	Taoyuan, Hsinchu	Miaoli	Taichung, Changhua, Nantou	Yuanlin, Chiayi, Tainan	Kaohsiung, Pingtung	Taitung, Hualien	Total
1990 1st crop	16.05	80.49	187.87	76.85	147.54	120.96	22.99	74.93	727.68
2nd crop	1.54	1.54	57.12	24.31	116.01	99.87	60.80	3.87	365.06
Sub-total	17.59	82.03	244.99	101.16	263.55	220.83	83.79	78.80	1,092.72
1991 1st crop	12.44	72.12	177.37	70.55	138.87	116.85	20.19	71.16	679.55
2nd crop	1.27	1.42	56.46	21.85	113.94	93.85	53.66	3.63	346.08
Sub-total	13.71	73.54	233.83	92.40	252.81	210.70	18.11	74.79	1,025.63
1992 1st crop	10.09	72.76	172.77	65.76	135.24	97.66	44.04	70.22	668.54
2nd crop	0.84	0.92	53.60	21.32	108.68	88.52	62.15	3.55	339.58
Sub-total	10.93	73.68	226.37	87.08	243.92	186.18	106.19	73.77	1,008.12
1993 1st crop	8.58	69.76	163.81	62.49	127.80	114.56	16.56	65.87	629.43
2nd crop	0.62	0.85	51.82	19.86	104.33	86.19	37.61	3.45	304.73
Sub-total	9.20	70.61	215.63	82.35	232.13	200.75	54.17	69.32	934.16
1994 1st crop	6.01	70.18	137.32	61.08	121.58	102.12	17.39	67.32	583.00
2nd crop	0.54	0.54	47.59	19.33	99.34	82.36	35.31	3.46	288.47
Sub-total	6.55	70.72	184.91	80.41	220.92	184.48	52.70	70.78	871.47
1995 1st crop	6.41	68.15	148.58	56.87	117.90	108.16	15.27	65.89	587.23
2nd crop	0.49	0.34	48.40	19.30	95.46	81.06	32.00	3.67	280.72
Sub-total	6.90	68.49	196.98	76.17	213.36	189.22	47.27	69.56	867.95
1996 1st crop	4.59	67.45	124.55	55.06	114.38	94.95	14.67	71.76	547.41
2nd crop	0.46	0.30	46.54	18.08	93.35	82.51	33.06	3.88	278.18
Sub-total	5.05	67.75	171.09	73.14	207.73	177.46	47.73	75.64	825.59
1997 1st crop	5.22	71.26	148.69	55.57	117.88	112.78	14.07	79.49	604.96
2nd crop	0.41	0.23	48.28	18.56	91.68	79.09	29.05	4.10	271.40
Sub-total	5.63	71.49	196.97	74.13	209.56	191.87	43.12	83.59	876.36
1998 1st crop	4.35	69.40	150.49	55.33	114.50	114.24	14.16	80.57	603.04
2nd crop	0.39	0.03	46.43	17.59	88.55	78.24	25.72	3.99	260.94
Sub-total	4.74	69.43	196.92	72.92	203.05	192.48	39.88	84.56	863.98
1999 1st crop	4.05	68.77	141.87	51.96	112.08	111.94	14.06	80.06	584.79
2nd crop	0.34	0.09	42.15	17.09	88.84	79.25	28.19	4.15	260.10
Sub-total	4.39	68.86	184.02	69.05	200.92	191.19	42.25	84.21	844.89
2000 1st crop	3.79	67.57	134.89	52.32	108.18	114.02	14.72	80.70	576.19
2nd crop	0.33	0.05	36.77	14.69	85.21	73.83	24.85	4.02	239.75
Sub-total	4.12	67.62	171.66	67.01	193.39	187.85	39.57	84.72	815.94
2001 1st crop	3.43	65.29	126.77	49.37	107.73	109.36	14.24	75.69	551.88
2nd crop	0.32	0.01	34.74	13.08	85.89	75.22	23.44	4.10	236.80
Sub-total	3.75	65.30	161.51	62.45	193.62	184.58	37.68	79.79	788.68
2002 1st crop	3.07	59.59	102.27	41.85	106.09	105.63	13.43	78.01	509.94
2nd crop	0.28	0.01	25.62	12.63	81.52	68.89	18.51	3.77	211.23
Sub-total	3.35	59.60	127.89	54.48	187.61	174.52	31.94	81.78	721.17
2003 1st crop	2.53	59.02	51.17	43.04	103.18	97.53	13.28	74.24	443.99
2nd crop	0.26	0.00	16.99	10.43	73.59	59.89	15.20	3.51	179.87
Sub-total	2.79	59.02	68.16	53.47	176.77	157.42	28.48	77.75	623.86
2004 1st crop	2.39	54.45	25.42	31.62	99.07	73.30	12.55	72.55	371.36
2nd crop	0.28	0.01	14.10	9.23	72.00	51.84	11.56	3.60	162.60
Sub-total	2.67	54.46	39.52	40.85	171.07	125.14	24.11	76.15	533.96
2005 1st crop	2.31	54.28	65.10	37.89	100.63	95.46	12.46	72.55	440.67
2nd crop	0.25	0.01	16.48	10.43	74.04	60.81	10.57	3.67	176.25
Sub-total	2.56	54.29	81.59	48.32	174.66	156.28	23.03	76.22	616.92
2006 1st crop	1.99	54.25	53.50	35.93	99.25	96.30	11.28	74.74	427.24
2nd crop	0.22	0.01	13.24	9.66	71.43	62.30	7.82	3.76	168.43
Sub-total	2.21	54.26	66.74	45.59	170.68	158.60	19.10	78.50	595.67
Average 1st crop	5.72	66.16	124.26	53.15	115.99	105.05	16.79	73.87	560.99
2nd crop	0.52	0.37	38.61	16.32	90.82	76.69	29.97	3.78	257.07
Sub-total	6.14	66.53	162.87	69.47	206.81	181.74	46.76	77.65	818.06

Methane emission from the paddy fields in Taiwan that were proposed by the IPCC guidelines ranged from 31,122.2 to 55,728.9, 29,493.3 to 60,615.5 and 69,244.9 to 117,119.6 ton with continuous flooding at the first crop, the second crop and the total paddy field during 1990 to 2006, respectively. Methane emission from the paddy fields with the local measurement were 26.72–28.11%, 55.65–57.32% and 41.19–43.10% of those calculated with the IPCC guideline for continuous flooding method at the first crop, the second crop and total paddy field, respectively. However, the intermittent irrigation management at the latter stage of rice growth was used in Taiwan to decrease the toxic substances accumulation in the flooding soil and the water requirement for rice growth. Methane emissions from the paddy fields with continuous flooding for single aeration and continuous flooding for multiple aerations were 50% and 20% of that with continuous flooding [15]. Sass et al. [40] also reported that the paddy fields of Houston with midseason drain and three aerations were 52.46% and 12.4% of that continuous flooding, respectively. Methane emissions from the paddy fields with the local measurement were 53.44–57.84%, 111.29–114.07% and 82.38–86.20% of those calculated with the IPCC guidelines for continuous flooding and single aeration at the first crop, the second crop and total paddy fields, respectively. However, the values were 133.60–144.61%, 278.32–286.62% and 205.96–215.49% of those calculated with the IPCC guidelines for continuous flooding and multiple aerations at the first crop, the second crop and total paddy fields, respectively. The differences among these paddy fields might be due to the different irrigation managements. Paddy fields in Taiwan had multiple aerations (more than three aerations) during the flowering and ripening stages. However, the temperature was low in the flooding and transplanting stages at the first crop season with continuous flooding and temperature was high in the flowering and ripening stages with drain; while the temperature was high in the flooding and transplanting stages at the second crop season and the temperature was low in the flowering and ripening stages. Therefore, methane emission from the paddy fields in Taiwan was lower than that with continuous flooding and single aeration treatments in the first crop season, while the value was reversed in the second crop season. Methane emission from the paddy fields in Taiwan was lower than those with continuous flooding or continuous flooding with single aeration, but the value was higher than those with continuous flooding and multiple aerations by the IPCC guideline in both crop seasons.

3.2. Nitrous oxide emission from paddy fields

Agriculture is the main source of most nitrous oxide emissions. Nitrous oxide was produced from soil processes as an intermediate product of microbial nitrification and denitrification. Nitrous oxide emission was between -0.11 and 0.78 g m^{-2} with intermittent irrigation in the first crop season, and it ranged from -0.11 to 0.75 g m^{-2} in the second crop season (Table 1) [21,26,31]. Nitrous oxide emission also increased with green manure amendment [26]. It was 3 to 20 times higher than those with convention chemical fertilizer. Green manure amendment stimulated nitrous oxide emission rate due to the increase of soil organic matter and nitrogen content. Nitrous oxide emission increased with the increasing of nitrogen fertilizer application and decreased with the nitrification inhibitor added [41].

Nitrous oxide emission coefficient of paddy field at different locations in Taiwan was between 0.038 and $0.174 \text{ mg m}^{-2} \text{ h}^{-1}$ in the first crop season, and the value ranged from 0.010 to $0.105 \text{ mg m}^{-2} \text{ h}^{-1}$ in the second crop season. Nitrous oxide emission coefficient in the first crop season was higher than those in the second crop season because of the intermittent irrigation and high

temperature at the later growth stage. Slow-release N fertilizer application reduced nitrous oxide emission [40]. Annual nitrous oxide emission from paddy fields was calculated with the local emission factors at each location and cultivation area, and the results are also presented in Table 4. Annual nitrous oxide emission decreased with the decreasing of cultivation area of paddy. Total nitrous oxide emission was 1092 ton in 1990 and the value decreased to 596 ton in 2006. Nitrous oxide derived from N fertilizer in paddy field was between 0.05 and 0.28% in the central and southern Taiwan [41]. Appropriate fertilization could reduce the nitrous oxide emission from the paddy fields.

Acknowledgements

The author thanks Professors H. P. Wu, C. C. Chao, S. N. Huang, R. M. Liou, J. J. Horng, U. Hegde, and I. C. Lin for their helpful assistances and comments, National Science Council and Environmental Protection Administration of Taiwan for financial supports.

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