Estimation of methane and nitrous oxide emission from paddy fields and uplands during 1990–2000 in Taiwan

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Received 25 July 2002; received in revised form 10 December 2002; accepted 20 December 2002

Abstract

To investigate the greenhouse gases emissions from paddy fields and uplands, methane and nitrous oxide emissions were estimated from local measurement and the IPCC guidelines during 1990–2000 in Taiwan. Annual methane emission from 182 807 to 242 298 ha of paddy field in the first crop season ranged from 8062 to 12 066 ton, and it was between 16 261 and 25 007 ton for 144 178–211 968 ha in the second crop season with local measurement. The value ranged from 12 132 to 17 465 ton, and from 16 046 to 24 762 ton of methane in the first and second crop season with the IPCC guidelines for multiple aeration treatments, respectively. Annual nitrous oxide emission was between 472 and 670 ton and between 236 and 359 ton in the first and second crop season, respectively. Methane and nitrous oxide emissions from uplands depend on crop, growth season, fertilizer application and environmental conditions. Annual methane emission from upland crops, vegetable, fruit, ornamental plants, forage crops and green manure crops was 138–252, 412–460, 97–100, 3–5, 4–5 and 3–51 ton, respectively. Annual nitrous oxide emission was 1080–1976, 1784–1994, 2540–2622, 31–54, 43–53 and 38–582 ton, respectively. Annual nitrous oxide emission ranged from 91 to 132 ton for 77 593–112 095 ton of nitrogen-fixing crops, from 991 to 1859 ton for 3 259 731–6 183 441 ton of non-nitrogen-fixing crops, and from 1.77 to 2.22 Gg for 921 169–1 172 594 ton of chemical fertilizer application. In addition, rice hull burning emitted 19.3–24.2 ton of methane and 17.2–21.5 ton of nitrous oxide, and corn stalk burning emitted 2.1–4.2 ton of methane and 1.9–3.8 ton of nitrous oxide. Methane emission from the agriculture sector was 26 421–37 914 ton, and nitrous oxide emission was 9810–11 649 ton during 1990–2000 in Taiwan. Intermittent irrigation in paddy fields reduces significantly methane emission; appropriate application of nitrogen fertilization and irrigation in uplands and paddy fields also decreases nitrous oxide emission.

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Keywords: Methane; Nitrous oxide; Paddy field; Upland; Intermittent irrigation

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 are the greenhouse gases, which have strong infrared absorption bands and trap part of the thermal radiation from the earth's surface. Atmospheric concentrations of carbon dioxide, methane and nitrous oxide increased from 337 to 360, 1.50 to 1.72 and 0.302 to 0.320 ppmv, respectively, during last decade (Rasmussen and Khalil, 1986; Battle et al., 1996).

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About 80% of methane is produced biologically and the major source sites are rice paddies, wetlands, sediments, enteric fermentation, animal wastes treatment and landfills under low redox potential conditions by obligate anaerobes (Watson et al., 1992; Liu et al., 1996; Yang, 1998; Yang and Chang, 1999; Yang et al., 2001). The release of nitrous oxide has been increasing in recent years due to intensive agricultural practices. Denitrification by heterotrophic microbes in oxygen deficient environments, nitrification by autotrophic and heterotrophic nitrifying microbes and dissimilation of nitrate to ammonium by heterotrophic microbes in aerobic conditions all produce nitrous oxide (Davidson et al., 1986; Yu et al., 2001). The contribution of agriculture to the global annual nitrous oxide emission has been estimated at approximately 35% (Isermann, 1994).

In Taiwan, there were 339 235 ha of paddy fields, 692 697 ha of uplands and more than 4 million tons of crop residues in 2000. Rice is cultivated with intermittent irrigation in Taiwan, while continuous flooding, continuous flooding with single aeration or multiple aerations are used in other countries (Sass et al., 1992). 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. Estimating methane and nitrous oxide emissions from paddy fields and uplands during 1990–2000 with country-specific emission factors was applied, whereas the local data were unavailable, the emission factors recommended by the IPCC guidelines (IPCC, 1997a,b) were used.

2. Materials and methods

2.1. Cultivation area

Cultivation areas of paddies and uplands in Taiwan from 1990 to 2000 are adapted from the Taiwan Agriculture Yearbook from 1991 to 2001 (Department of Agriculture and Forest/Provincial Taiwan Government, 1991–2000; Council of Agriculture/ROC, 2001). Uplands include upland crops, vegetables, fruits, ornamental plants, forage crops and green manure crops.

2.2. Amount of crop residue production

The amount of crop residue production was calculated according to Yang et al. (1991) and recommended by the IPCC guidelines. The dry weight content of crop, N/C ratio, percent of burning and oxidation were adapted from the IPCC guidelines (IPCC, 1997a,b).

2.3. Methane and nitrous oxide emissions

Methane and nitrous oxide emissions from paddy fields and uplands were measured by homemade acrylic chamber (length 40 cm, width 40 cm and height 65 cm, about 96 l) (Chang and Yang, 1997). Methane and nitrous oxide emission rates were determined at a 0.5 h interval for 1.0 h by measuring the changes of methane and nitrous oxide concentrations (the net change between greenhouse gas emission and sink) in the acrylic chamber. Methane and nitrous oxide were analyzed by gas chromatograph using FID and ECD, respectively (Yang et al., 1994; Chao, 1997; Chang et al., 2000).

2.4. Methane and nitrous oxide emission factors

Methane and nitrous oxide emission factors of paddy fields and uplands are listed in Table 1. Most of paddies applied both chemical and organic fertilizers; while organic paddies production used only organic fertilizer. Methane emission factors of paddy fields and uplands were measured by Chung et al. (1997), Wang and Shieh (1997), Yang and Chang (1997, 1999, 2001a,b), Perng and Huang (1998) and Huang et al. (1999). Nitrous oxide emission factors were determined by Chao (1997) and Lai (1998, 2000). Other emission factors were recommended by the IPCC guidelines.

2.5. Estimation of methane and nitrous oxide emissions

Methane and nitrous oxide emissions from paddy fields and uplands were calculated from the experimental data and estimated by the following equation at each growth stage (Rolston, 1986):

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

where F is the methane or nitrous oxide emission rate ($\text{mg m}^{-2} \text{h}^{-1}$), V is the volume of chamber above soil (m^3), A is the cross-section of chamber (m^2), ΔC is the concentration difference between time zero 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 or uplands was the summation of methane and nitrous oxide emissions in all growth stages of crops (Chao, 1997; Yang and Chang, 1998).

2.6. Methane and nitrous oxide emissions from crop residue burning

Methane and nitrous oxide emissions from crop residue burning were calculated from annual crop production, crop residue ratio, dry matter content, burning and oxidation percent, carbon content, nitrogen content, N/C ratio, emission factor and conversion factor as

Table 1
Greenhouse gas emission from paddy fields

Location	Treatment	Methane emission (g m ⁻²)		Nitrous oxide emission (g m ⁻²)		
		First crop	Second crop	First crop	Second crop	Full year
NTU Exper. Station	Inter. irrigation	2.55–11.70 ^a	13.73 ^a	0.30–0.39 ^b	0.07–0.75 ^b	–
	Cont. flooding	–	28.85 ^a	–	–	–
Taoyuan Dist. AIS	Inter. irrigation	1.73–5.23 ^a	10.54–10.56 ^a	0.44–0.54 ^b	0.06–0.40 ^b	–
	W/green manure	5.55 ^a	14.43–30.12 ^a	–	1.22 ^b	–
Miaoli farm	Inter. irrigation	9.82 ^a	39.50 ^a	–	–	–
Hwalien-Lotung AIS	Inter. Irrigation	2.92 ^a	24.64 ^a	0.35–0.78 ^b	0.0–0.06 ^b	–
Huatan-CH farm	Inter. irrigation	–	5.58	–	0.48	–
	–	–	4.76	–	0.27	–
NCHU Exper. Station	Inter. irrigation	8.18 ^c	1.18 ^c	–0.11–0.60 ^d	–0.11–0.50 ^d	0.22–1.25 ^d
Chihu-CH farm	Inter. irrigation	0.15 ^c	10.45 ^c	–	–	–0.05–1.11 ^d
Chiayi farm	Inter. irrigation	3.48 ^c	10.17 ^c	–	–	0.24–0.99 ^d
Kaohsiung Dist. AIS	Inter. irrigation	2.36 ^c	8.47 ^c	–	–	0.05–1.14 ^d
Hwalien-Chian AIS	Inter. irrigation	1.42–2.42 ^c	0.26–2.33 ^c	–	–	–
	W/rice straw	2.77–2.85 ^c	3.13–7.60 ^c	–	–	–
Hwalien-Fuli AIS	Inter. irrigation	7.40–13.10 ^c	12.50–24.30 ^c	–	–	–
	W/high N fertile	11.60–19.73 ^c	21.14–48.37 ^c	–	–	–
IPCC	Cont. flooding	35.64 ^f	38.94 ^f	–	–	–
	Single drain	18.70 ^f	20.43 ^f	–	–	–
	Multiple drains	4.42 ^f	7.24 ^f	–	–	–

^a Yang and Chang (1998, 1999, 2001a).

^b Lai (1998, 2000).

^c Wang and Shieh (1997).

^d Chao (1997).

^e Perng and Huang (1998) and Huang et al. (1999).

^f IPCC (1997a,b).

stated by the IPCC guidelines (IPCC, 1997a,b). Nitrous oxide emission from crop residue was calculated as following:

$$\begin{aligned} \text{N}_2\text{O emission} = & 2 \times [\text{Crop}_\text{O} \times \text{Frac}_{\text{NCRO}} + \text{Crop}_{\text{BF}} \\ & \times \text{Frac}_{\text{NCRBF}}] \times (1 - \text{Frac}_\text{R}) \\ & \times (1 - \text{Frac}_{\text{BURN}}) \times \text{EF} \\ & \times \text{Conversion ratio} \end{aligned}$$

where Crop_O = production of non-nitrogen-fixing crops in country, $\text{Frac}_{\text{NCRBF}}$ = fraction of nitrogen in nitrogen-fixing crops, $\text{Frac}_{\text{NCRO}}$ = fraction of nitrogen in non-nitrogen-fixing crops, Frac_R = fraction of crop residue that is removed from the field as crop, $\text{Frac}_{\text{BURN}}$ = fraction of crop residue that is burned rather than left on field, Crop_{BF} = production of nitrogen-fixing crops, EF = emission coefficient, and Conversion ratio = 44/28.

2.7. Nitrous oxide emission from cultivated soils

Nitrous oxide emitted from the application of chemical and organic fertilizers, animal wastes, nitrogen-fixing and non-nitrogen-fixing crops. Nitrous oxide emission from cultivated soils was estimated from the amount of chemical and organic fertilizers application,

annual production of crops, nitrogen content, cultivation area, total nitrogen in the atmosphere, emission factor and conversion factor as described in the IPCC guidelines.

Nitrous oxide emission from nitrogen-fixing crops was estimated from the following equation that proposed by the IPCC guidelines (IPCC, 1997a,b):

$$\begin{aligned} \text{N}_2\text{O emission} = & 2 \times \text{Crop}_{\text{BF}} \times \text{Frac}_{\text{NCRBF}} \times \text{EF} \\ & \times \text{Conversion ratio} \end{aligned}$$

where Crop_{BF} = production of nitrogen-fixing crops, and $\text{Frac}_{\text{NCRBF}}$ = fraction of nitrogen in nitrogen-fixing crops.

Nitrous oxide emission from chemical fertilizer application was calculated from the following equation:

$$\begin{aligned} \text{N}_2\text{O emission} = & N_{\text{FERT}} \times (1 - \text{Frac}_{\text{GASF}}) \times \text{EF} \\ & \times \text{Conversion ratio} \end{aligned}$$

where N_{FERT} = total application of chemical fertilizer in country (kg N/yr), and $\text{Frac}_{\text{GASF}}$ = fraction of total chemical fertilizer nitrogen that is emitted as $\text{NO}_x + \text{NH}_3$ (kg N/kg N).

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–July) was between 122 and 149 days, and it ranged from 112 to 135 days in the second crop season (August–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 was 22.46–24.68 °C, and the value was 23.07–25.72 °C in the second crop season. This is different from the single crop season countries such as Japan, Korea, USA and Italy (Holzapfel-Pschorn and Seiler, 1986; Minami and Neue, 1994; Lindau et al., 1995; Shin et al., 1995). Therefore, the methane emission patterns of the two crop seasons in Taiwan were also different to 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 secretes. However, drainage was practiced at the flowering and ripening stages in the intermittent irrigation system, and methane emission rate decreased at these stages. Methane emission was high at the flooding and transplanting stages in the second crop season for organic matter degradation at high temperature. While methane emission was low at the flooding and transplanting stages in the first crop season for organic matter degradation at low temperature, and it was also low at the flowering and ripening stages for the intermittent irrigation and high redox potential repressed methane emission (Yang and Chang, 1999, 2001b). Therefore, methane emission in the second crop season was higher than that in the first crop season because of high organic matter degradation with high temperature at the flooding, transplanting and active tillering stages in the second crop season.

Methane emission was between 0.15 and 13.10 g m⁻² with intermittent irrigation in the first crop season, and it ranged from 1.18 to 39.50 g m⁻² in the second crop

season (Table 1) (Wang and Shieh, 1997; Perng and Huang, 1998; Yang and Chang, 1998, 1999; Huang et al., 1999). Methane emission with green manure amendment was 1.06–3.20 times higher than those with intermittent irrigation and convention chemical fertilizer application in the first crop season, and the value was between 1.37 and 2.85-fold in the second crop season (Yang et al., 1994; Yang and Chang, 2001a). Methane emission with rice straw application was 1.17–1.95 and 3.26–12.03 times higher than those with convention chemical fertilizer application in the first and second crop season, respectively (Perng and Huang, 1998). High nitrogen fertilizer application also enhanced 1.50–1.56 and 1.69–1.99 times of methane emission higher than those with convention nitrogen level of chemical fertilizer application in the first and second crop season, respectively (Huang et al., 1999). The scaling factor of methane emission for organic matter amendment in the most of Taiwan paddy fields was slightly lower than 2 to 5-fold that proposed by the IPCC guidelines. This phenomenon might be due to the differences among the environmental conditions, the amount of organic matter amendment and irrigation management of paddy fields. Green manure amendment stimulated methane emission rate and it also increased the soil organic matter content. Similar results were also found in rice cultivated with dry and wet crop seasons in the Philippines paddy fields (Denier van der Gon and Neue, 1995). Methane emission of paddy field at different locations in Taiwan is presented in Table 2. The values were the average of local measurement at different years and different paddy fields in each location. Methane emission in the second crop season was higher than those in the first crop season with intermittent irrigation; the reverse was true in the pot cultivation or in the paddy fields with continuous flooding (Yang et al., 1994; Yang and Chang, 1997, 1999). There was a 10–15 cm depth of flooding in the soil surface during the rice cultivation in Italian, Louisiana and California paddy fields (Cicerone et al., 1983; Schutz et al., 1989; Lindau et al., 1993). Methane emission with continuous flooding was 2.02 times higher than that with intermittent irrigation in the second crop

Table 2
Methane and nitrous oxide emission factors of paddy fields in Taiwan

Location	CH ₄ emission coefficient (mg m ⁻² h ⁻¹)		N ₂ O emission coefficient (mg m ⁻² h ⁻¹)	
	First crop	Second crop	First crop	Second crop
Taipei	2.12	4.85	0.128	0.031
I-lan	0.69	8.93	0.174	0.001
Taoyuan, Hsinchu	0.89	4.15	0.169	0.062
Miaoli	2.92	13.70	0.169	0.062
Taichung, Changhua, Nantou	2.84	2.54	0.088	0.068
Yuanlin, Chiayi, Tainan	1.21	3.53	0.045	0.051
Kaohsiung, Pingtung	0.82	2.94	0.020	0.105
Hwalien, Taitung	2.11	4.21	0.174	0.001

season (Yang et al., 1994; Yang and Chang, 2001a). The scaling factor of methane emission with continuous flooding in Taiwan fell within the range of 2 with continuous flooding for single aeration and 5 for multiple aerations that was proposed by the IPCC guidelines. 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 with intermittent irrigation was around 20–50% lower than with continuous flooding treatment. Miaoli area had high methane emission due to the high soil organic matter content (Yang and Chang, 2001b). Annual methane emission from paddy field is calculated with the emission factors in each location and cultivation area, and the results are illustrated in Table 3. Annual methane emission decreased with the decreasing of rice cultivation area. Total methane emission was 37 073 ton in 1990 and it decreased to 25 678 ton in 2000. Methane emission from paddy fields in Taiwan that was proposed by the IPCC guidelines ranged from 117 198 to 169 864, 72 727 to 105 568 and 29 091 to 42 227 ton with continuous flooding, continuous flooding for single aeration and continuous flooding for multiple aerations, respectively. Methane emission from paddy fields in Taiwan was only 20.45–21.90%, 33.93–37.74% and 84.83–87.79% of those calculated with the IPCC guidelines, respectively. Methane emission from paddy fields of Houston with midseason drain and three aerations was 52.46% and 12.40% of that with continuous flooding, respectively (Sass et al., 1992). 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. Therefore, methane emission from paddy fields in Taiwan was slightly lower than that with three aeration treatments, but the value fell within the ranges that was proposed by the IPCC guidelines with multiple aeration treatments.

3.2. Nitrous oxide emission from paddy fields

Agriculture is the main source of most nitrous oxide emissions. Nitrous oxide is 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). Nitrous oxide emission also increased 3–20 times with green manure amendment (Lai, 1998). 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

Table 3
Methane and nitrous oxide emissions from paddy fields in Taiwan

Year	First crop season					Second crop season					Total				
	Cultiv. area (ha)	CH ₄ emission (ton)			N ₂ O emission (ton)	Cultiv. area (ha)	CH ₄ emission (ton)			N ₂ O emission (ton)	Cultiv. area (ha)	CH ₄ emission (ton)			N ₂ O emission (ton)
		Local	IPCC cont.	IPCC single			Local	IPCC cont.	IPCC single			Local	IPCC cont.	IPCC single	
1990	242 298	12 066	87 323	43 662	17 465	670	25 007	82 541	61 906	24 762	359	37 073	169 864	105 568	42 227
1991	227 417	11 239	81 051	40 526	16 210	639	23 515	78 420	58 815	23 526	359	34 754	159 471	99 341	39 736
1992	209 474	10 498	74 656	37 328	14 931	591	21 852	73 080	54 810	21 924	317	32 350	147 736	92 138	36 855
1993	211 790	10 400	75 482	37 741	15 096	577	20 780	69 757	52 318	20 927	300	31 180	145 239	90 059	36 023
1994	196 317	9736	69 882	34 941	13 976	535	19 604	66 011	49 508	19 803	284	29 340	135 893	84 449	33 779
1995	197 571	8062	60 660	30 330	12 132	472	17 398	56 529	42 397	16 959	239	25 460	117 198	72 727	29 091
1996	182 807	9129	65 153	32 577	13 031	503	16 495	48 176	19 270	18 949	273	27 970	129 387	80 753	32 301
1997	202 010	9871	71 998	35 999	14 400	554	16 202	63 162	47 372	18 949	267	28 644	135 160	83 371	33 349
1998	201 424	9779	71 787	35 894	14 357	552	17 947	60 848	45 636	18 254	258	27 726	132 635	81 530	32 611
1999	197 123	9559	70 253	35 127	14 051	536	17 813	60 724	45 543	18 217	256	27 372	130 977	80 670	32 268
2000	195 057	9417	69 517	34 759	13 903	526	16 261	53 485	40 114	16 046	236	25 678	123 002	74 873	29 949

nitrogen fertilizer application and decreased with the nitrification inhibitor addition (Lai, 2000). Nitrous oxide emission from paddy field in different locations of Taiwan is also summarized in Table 2. It was between 0.02 and 0.17 $\text{mg m}^{-2} \text{h}^{-1}$ in the first crop season, and the value ranged from 0.00 to 0.11 $\text{mg m}^{-2} \text{h}^{-1}$ in the second crop season. Nitrous oxide emission in the first crop season was higher than those in the second crop season because of intermittent irrigation and high temperature at the later growth stage. Slow-release N fertilizer application reduced nitrous oxide emission (Abao et al., 2000). Annual nitrous oxide emission from paddy fields was calculated with the emission factor in each location and cultivation area, and the results are also presented in Table 3. Annual nitrous oxide emission decreased with the decreasing of cultivation area of paddy. Total nitrous oxide emission was 1029 ton in 1990 and the value decreased to 762 ton in 2000. Nitrous oxide derived from N fertilizer in paddy field was between 0.05% and 0.28% in central and southern Taiwan (Chao, 1997).

3.3. Methane emission from uplands

Methane emission from uplands depends on crop, variety, soil type, water management, fertilizer application and environmental conditions. Methane emission was -0.01 to 1.06 (average was 0.09 g m^{-2} for seven locations), -0.40 to 1.00 (average was 0.24 g m^{-2} for eight locations), -0.46 to 0.59 (average was 0.43 g m^{-2} for five locations), and -0.62 to 0.44 (average was -0.17 g m^{-2} for three locations) g m^{-2} in upland crops, vegetables, fruit, and ornamental plants, respectively (Chung et al., 1997; Wang and Shieh, 1997; Young, 1997). Total cultivation area of upland crops (included other cereals, pulses, root crops, and special crops), vegetables, fruits, ornamental plants, forage crops, and green manure crops was 153 697–281 309, 170 182–190 946, 222 812–229 972, 6206–10 973, 8646–10 641, and 7717–117 893 ha, respectively. Annual methane emission from upland crops, vegetables, fruit, ornamental plants, forage crops, and green manure crops was 138–252, 412–460, 97–100, 3–5, 4–5 and 3–51 ton, respectively (Table 4). Annual methane emission from uplands was between 721 and 816 ton in 687 629 to 726 731 ha of cultivation area. Methane emission from upland crops and forage crops decreased due to the decreasing of cultivation area, while the value from vegetables, fruit, ornamental plants and green manure crops increased gradually because of the transfer planning encouragement and the change of living custom.

In the case of slopeland and forest, methane emission was between -7.91 and 1.87 g m^{-2} in banana cultivation (average was -0.46 g m^{-2}) and between -1.80 and 3.80 g m^{-2} in mango cultivation (average was 0.22 g m^{-2}). Annual methane emission from slopeland and forest

increased from 445 to 734 ton for 203 377–335 296 ha of cultivation area (Wang and Shieh, 1997).

3.4. Nitrous oxide emission from uplands

Nitrous oxide emission from upland crops, vegetables, fruits, and ornamental plants was between 0.11 and 17.61 (average was 0.70 g m^{-2} for seven locations), 0.36 and 2.81 (average was 1.04 g m^{-2} for eight locations), 0.56 and 2.23 (average was 1.14 g m^{-2} for five locations), and 0.21 and 0.77 (average was 0.49 g m^{-2} for three locations) g m^{-2} , respectively (Chao, 1997; Lai, 1998). The nitrogen fertilizer application was high in vegetable and fruit cultivations; therefore, nitrous oxide emission was also higher than those of upland crops and ornamental plants. Annual nitrous oxide emission ranged from 1080 to 1976, 1784 to 1994, 2540 to 2622, 31 to 54, 43 to 53, and 38 to 582 ton from upland crops, vegetables, fruit, ornamental plants, forage crops and green manure crops, respectively. Annual nitrous oxide emission from uplands was between 6167 and 6653 ton (Table 4). Nitrous oxide emission from upland crops and forage crops decreased gradually due to the decreasing of cultivation area. While nitrous oxide emission from vegetables, fruit, ornamental plants and green manure crops increased for the changes of living style and the market demand. In the case of slopeland and forest, nitrous oxide emission was in the range from 0.16 to 0.96 g m^{-2} for banana cultivation and from 0.10 to 1.16 g m^{-2} for mango cultivation. Annual nitrous oxide emission from slopeland and forest increased gradually from 1110 to 1831 ton.

3.5. Nitrous oxide emission from chemical fertilizer application

Nitrous oxide emission was stimulated by nitrogen fertilizer application. Nitrous oxide emission from nitrogen fertilizer application in paddy field of Taiwan ranged from 0.05% to 0.28% (Chao, 1997). The chemical fertilizers include ammonium sulfate, urea, calcium ammonium nitrate, and combined fertilizer. Nitrous oxide emission from chemical fertilizer application is demonstrated in Table 5. Ammonium sulfate, urea and combined fertilizer are the major nitrogen fertilizer, while calcium ammonium nitrate is the minor. Nitrous oxide emission was high in 1996 (22 177 ton), and then decreased gradually for the decreasing of cultivation area (1768 ton in 2000).

3.6. Nitrous oxide emission from nitrogen-fixing and non-nitrogen-fixing crops

Nitrous oxide emission from nitrogen-fixing and non-nitrogen-fixing crops is presented in Table 5. Nitrogen-

Table 4
Methane and nitrous oxide emissions from uplands in Taiwan

Year	Upland crops			Vegetable			Fruit			Ornamental plants		
	Cultiv. area (ha)	CH ₄ emission (ton)	N ₂ O emission (ton)	Cultiv. area (ha)	CH ₄ emission (ton)	N ₂ O emission (ton)	Cultiv. area (ha)	CH ₄ emission (ton)	N ₂ O emission (ton)	Cultiv. area (ha)	CH ₄ emission (ton)	N ₂ O emission (ton)
1990	281 309	252.2	1976.4	188 249	453.7	1965.9	222 812	96.5	2540.1	6206	2.7	30.7
1991	274 126	245.8	1925.9	190 946	460.2	1994.1	226 143	98.0	2578.0	6670	2.9	33.0
1992	269 541	241.7	1893.7	188 736	454.9	1971.0	226 274	98.0	2579.5	7580	3.3	37.5
1993	264 296	237.0	1856.9	184 309	444.2	1924.7	228 281	98.9	2602.4	9089	3.9	44.9
1994	261 859	234.8	1839.7	170 812	411.7	1783.8	226 380	98.1	2580.7	9401	4.1	46.4
1995	254 487	228.2	1787.9	173 048	417.1	1807.1	228 719	99.1	2607.4	9661	4.2	47.7
1996	233 203	209.1	1638.4	176 774	426.0	1846.1	229 972	99.7	2621.7	9968	4.3	49.2
1997	213 094	191.1	1497.1	180 209	434.3	1881.9	226 519	98.2	2582.3	10 427	4.5	51.5
1998	182 748	163.9	1283.9	180 072	434.0	1880.5	227 144	98.4	2589.4	10 172	4.4	50.3
1999	159 992	143.5	1124.1	183 600	442.5	1917.3	224 806	97.4	2562.8	10 765	4.7	53.2
2000	153 697	137.8	1079.8	177 057	426.7	1849.0	224 431	97.2	2558.5	10 973	4.8	54.2
	Forage crops			Green manure crops			Total					
	Cultiv. area (ha)	CH ₄ emission (ton)	N ₂ O emission (ton)	Cultiv. area (ha)	CH ₄ emission (ton)	N ₂ O emission (ton)	Cultiv. area (ha)	CH ₄ emission (ton)	N ₂ O emission (ton)			
1990	10 297	4.5	50.9	7717	3.3	38.1	716 590	812.9	6602.1			
1991	10 066	4.4	49.7	11 642	5.0	57.5	719 593	816.3	6638.2			
1992	10 564	4.6	52.2	24 036	10.4	118.7	726 731	812.9	6652.6			
1993	10 048	4.4	49.6	27 778	12.0	137.2	723 801	800.4	6615.7			
1994	10 641	4.6	52.6	41 041	17.8	202.7	720 134	771.1	6505.9			
1995	10 121	4.4	50.0	39 859	17.3	196.9	715 895	770.3	6497.0			
1996	9666	4.2	47.8	45 225	19.6	223.4	704 808	762.9	6426.6			
1997	9337	4.1	46.1	54 491	23.6	269.2	694 077	755.8	6328.1			
1998	9054	3.9	44.7	78 439	34.0	387.5	687 629	738.6	6236.3			
1999	8856	3.8	43.7	104 338	45.2	515.4	692 357	737.1	6216.5			
2000	8646	3.8	42.7	117 893	51.1	582.4	692 697	721.4	6166.6			

Upland crops include corn, wheat, millet, sorghum, soybean, peanut, common bean, adzuki bean, mung bean, sweet potato, tea, tobacco, sugar cane, sesame, repeseed, perfume plants and others.

Vegetables include radish, carrot, other root vegetable, ginger, taro, scallion, scallion bulb, onion, garlic, garlic bulb, water chestnut, leek, bamboo shoot, asparagus, water bamboo, other stem vegetable, leaf mustard, water convolvulus, celery, cabbage, Chinese cabbage, Chinese mustard, other leaf vegetable, cauliflower, lily flower, oriental picking melon, cucumber, white gourd, bitter gourd, eggplant, tomato, pepper, kidney bean, pea, vegetable soybean, other fruit vegetable, watermelon, muskmelon, cantaloupe, seed watermelon, strawberry, and mushroom.

Fruits include banana, pineapple, citrus-ponkan, citrus-tankan, wentan pomelon, citrus-tou pomelon, pai pomelon, satsuma orange, citrus-valencias, liuchengs, lemon, grapefruit, other citrus, longans, mango, betel nut, guava, wax apple, grape, loquat, plum, peach, persimmon, Japanese apricot, lichee, olive, carambola, pear, apple, papaya, jujube, sugar apple, passion fruit, coconut and others.

Ornamental plants include cut flower, bulb, herbaceous flower seed, nurseries and potted flower.

Forage crops include oat, pangola grass, napier grass and others.

Green manure crops include raphanus sativus, sesbania sesbean, soybean, field pea, astragalus sinicus, velvet bean, crotalaria, rape, tephrosia, ber seem clover, other single sowing and other mixed sowing.

fixing crops include soybean, peanut, common bean, adzuki bean, and mung bean; while non-nitrogen-fixing crops include sweet potato, cassava, potato, tea, tobacco, sugar cane, sesame, repeseed, and perfume plants. Annual production of nitrogen-fixing crops was between 77 593 and 112 095 ton, and annual nitrous oxide emis-

sion ranged from 91 to 132 ton. The maximal value was in 1995 and the minimal was in 1999. In the case of non-nitrogen-fixing crops, annual production decreased from 6 153 079 ton in 1990 to 3 259 731 ton in 2000. Annual nitrous oxide emission from non-nitrogen-fixing crops also decreased from 1847 ton in 1990 to 991 ton in 2000.

Table 5

Nitrous oxide emission from chemical nitrogen fertilizers, nitrogen-fixing and non-nitrogen-fixing crops

Year	Chemical nitrogen fertilizer		Nitrogen-fixing crops		Non-nitrogen-fixing crops	
	Application (ton)	N ₂ O emission (ton)	Yield (ton)	N ₂ O emission (ton)	Yield (ton)	N ₂ O emission (ton)
1990	1 060 917	2039.5	89 840	105.9	6 153 079	1847.4
1991	1 135 096	2160.8	104 592	123.3	5 134 846	1558.3
1992	1 105 114	2087.6	95 399	112.4	6 183 441	1859.4
1993	1 140 480	2118.6	99 562	117.3	5 097 723	1545.7
1994	1 156 835	2132.8	104 041	122.6	5 797 750	1751.8
1995	1 140 412	2175.8	112 095	132.1	5 155 242	1569.6
1996	1 172 594	2216.9	102 785	121.1	4 698 543	1430.1
1997	1 004 616	1914.3	101 117	119.1	4 444 101	1355.2
1998	982 082	1862.2	79 985	94.3	4 057 935	1230.5
1999	966 679	1805.2	77 593	91.4	3 597 715	1094.1
2000	921 169	1768.3	87 377	103.0	3 259 731	991.3

Chemical nitrogen fertilizer include ammonium sulfate, urea, calcium ammonium nitrate and combined fertilizer.

Nitrogen-fixing crops include soybean, peanut, common bean, adzuki bean, and mung bean.

Non-nitrogen-fixing crops include sweet potato, cassava, potato, tea, tobacco, sugar cane, sesame, rapeseed and perfume plants.

3.7. Methane and nitrous oxide emission from crop residues burning

The ratio of crop residue to crop (or grain) depends on the variety of crop. The ratio of crop residue to crop is low (0.2) in sugar beet and high (2.1) in mung bean and soybean. The relative coefficients of greenhouse gas emission from crop residue burning are not available in local measurement, and all of these coefficients are adapted by the IPCC guidelines (IPCC, 1997a,b). Rice and corn are the major crops in Taiwan; therefore, methane and nitrous oxide emissions from the burning of rice hull and corn stalk are calculated and presented in Table 6. Methane and nitrous oxide emissions from rice hull burning were in the range from 19.4 to 24.2 ton, and from 17.2 to 21.5 ton, respectively. In the case of corn stalk burning, methane and nitrous oxide emissions

was between 2.1 and 4.2 ton and between 1.8 and 3.8 ton, respectively.

From the mention results, methane and nitrous oxide emissions from paddy fields and uplands during 1990–2000 in Taiwan are summarized in Fig. 1. Methane emission is higher than those of nitrous oxide in paddy fields. Annual methane and nitrous oxide emissions were 37 073 and 1029 ton in 1990, respectively, and the values decreased gradually to 25 678 and 762 ton in 2000. Methane emission from paddy fields in local measurement with intermittent irrigation is lower than those calculated by the IPCC guidelines with continuous flooding, and the value was consistent with continuous flooding for multiple aerations. While in the uplands, nitrous oxide emission is higher than those of methane emission. Annual methane and nitrous oxide emissions were 813 and 6602 ton in 1990, respectively. They had

Table 6

Methane and nitrous oxide emissions from crop residue burning

Year	Rice yield (ton)	Rice hull		Corn yield (ton)	Corn stalk	
		CH ₄ emission (ton)	N ₂ O emission (ton)		CH ₄ emission (ton)	N ₂ O emission (ton)
1990	2 283 670	23.9	21.3	398 875	4.1	3.7
1991	2 311 638	24.2	21.5	374 810	3.9	3.5
1992	2 069 880	21.6	19.3	389 869	4.1	3.6
1993	2 232 933	23.3	20.8	405 999	4.2	3.8
1994	2 061 403	21.5	19.2	397 118	4.2	3.7
1995	2 071 968	21.7	19.3	375 571	3.9	3.5
1996	1 930 897	20.2	18.0	395 412	4.1	3.7
1997	2 041 843	21.3	19.0	337 617	3.5	3.2
1998	1 859 157	19.4	17.3	243 792	2.6	2.3
1999	1 916 305	20.0	17.9	201 195	2.1	1.9
2000	1 843 227	19.9	17.8	138 315	1.4	1.3

Fig. 1. Methane and nitrous oxide emissions from agriculture sector during 1990–2000 in Taiwan. (a) Methane emission and (b) nitrous oxide emission. (□–□) Total emission, (●–●) paddy fields, (▲–▲) uplands, (△–△) chemical nitrogen fertilizers, (■–■) nitrogen-fixing crops, (▼–▼) non-nitrogen-fixing crops, (○–○) rice hull burning, (▽–▽) corn stalk burning.

the maximum value in 1993, and then decreased to 721 and 6167 ton in 2000. Total annual methane and nitrous oxide emissions from the agriculture sector were 37 914 and 11 649 ton in 1990, respectively, and the value decreased to 26 421 and 9810 ton in 2000. Methane emission is high from paddy fields, while nitrous oxide emission is high from uplands and chemical nitrogen fertilizer application. Intermittent irrigation and appropriate application of fertilizer might reduce methane and nitrous oxide emissions from agriculture practices.

Acknowledgements

The authors thank Professors Y.P. Wang, L.P. Lin, C.C. Young, C.C. Chao, S.N. Huang and R.S. Chung for their helpful assistances and comments, National Science Council and Environmental Protection Administration of Republic of China for financial supports.

References

- Abao Jr., E.B., Bronson, K.F., Wassmann, R., Singh, U., 2000. Simultaneous records of methane and nitrous oxide emis-

- sions in rice-based cropping systems under rainfed conditions. *Nutr. Cycl. Agroecosyst.* 58, 131–139.
- Battle, M., Bender, M., Sowers, T., Tans, P.P., Buter, J.H., Elkins, J.W., Ellis, J.T., Conway, T., Zhang, N., Lang, P., Clarke, A.D., 1996. Atmospheric gas concentrations over the past century measured in air from firn at the South Pole. *Nature* 383, 231–235.
- Chang, H.L., Yang, S.S., 1997. Measurement of methane emission from soil. *J. Chin. Agric. Chem. Soc.* 35, 475–484.
- Chang, T.C., Luo, Y.C., Yang, S.S., 2000. Determination of greenhouse gases by open-path gas-type FTIR spectroscopy. *Food Sci. Agric. Chem.* 2, 7–14.
- Chao, C.C., 1997. Nitrous oxide emission from paddy field, upland, wetland, forest and slopeland in central and southern Taiwan and their effect factors. In: Lu, S.C., Liu, C.M., Yang, S.S. (Eds.), *Research on Atmospheric Environments of Taiwan Area*. Global Change Research Center and Department of Agricultural Chemistry, National Taiwan University, Taipei, Taiwan, pp. 173–194.
- Chung, R.S., Liao, C.H., Lo, C.S., 1997. Methane emission from upland soils and effect of organic matter on the methane emission. In: Lu, S.C., Liu, C.M., Yang, S.S. (Eds.), *Research on Atmospheric Environments of Taiwan Area*. Global Change Research Center and Department of Agricultural Chemistry, National Taiwan University, Taipei, Taiwan, pp. 79–98.

- Cicerone, R.J., Setter, J.D., Delwiche, C.C., 1983. Seasonal variation of methane flux from a California rice paddy. *J. Geophys. Res.* 88, 11022–11024.
- Council of Agriculture/ROC, 2001. Agriculture Yearbook 2000. Council of Agriculture, Executive Yuan, Taipei, Taiwan.
- Davidson, E.A., Swank, W.T., Perry, T.O., 1986. Distinguishing between nitrification and denitrification as sources of gaseous nitrogen production in soil. *Appl. Environ. Microbiol.* 52, 1280–1286.
- Denier van der Gon, H.A.C., Neue, H.U., 1995. Influence of organic matter incorporation on the methane emission from a wetland rice field. *Global Biogeochem. Cycles* 9, 11–22.
- Department of Agriculture and Forest, Provincial Taiwan Government, 1991–2000. Agriculture Yearbook 1990–1999. Department of Agriculture and Forest, Provincial Taiwan Government, Nantou, Taiwan.
- Holzapfel-Pschorn, A., Seiler, W., 1986. Methane emission during a cultivation period from an Italian rice paddy. *J. Geophys. Res.* 91, 11803–11814.
- Huang, S.N., Liu, R.M., Lee, S.R., 1999. Methane emission and mitigation of paddy fields in southern Taiwan. In: Yang, S.S. (Ed.), *Flux and Mitigation of Greenhouse Gases*. Department of Agricultural Chemistry and Global Change Research Center, National Taiwan University, Taipei, Taiwan, pp. 74–83.
- Intergovernment Panel on Climate Change (IPCC), 1997a. Guidelines for National Greenhouse Gas Inventories: Workbook, Chapter 4.3, Agriculture: Rice cultivation. OECD, Paris, France.
- Intergovernment Panel on Climate Change (IPCC), 1997b. Guidelines for National Greenhouse Gas Inventories: Reference Manual, Chapter 4.3, Agriculture: Methane Emission from Rice Cultivation. OECD, Paris, France.
- Isermann, K., 1994. Agriculture's share in the emission of trace gases affecting the climate and some cause-oriented proposals for sufficiently reducing this share. *Environ. Pollut.* 83, 95–111.
- Lai, C.M., 1998. Nitrous oxide emissions from upland, forest soil and landfill in the northern Taiwan area and their affecting factors. In: Lu, S.C., Liu, C.M., Yang, S.S. (Eds.), *Research on Atmospheric Environments of Taiwan Area (III)*. Global Change Research Center and Department of Agricultural Chemistry, National Taiwan University, Taipei, Taiwan, pp. 105–117.
- Lai, C.M., 2000. Mitigation strategies of nitrous oxide emission from agricultural soils (II). In: Yang, S.S. (Ed.), *Flux and Mitigation of Greenhouse Gases (II)*. Department of Agricultural Chemistry and Agricultural Exhibition Hall, National Taiwan University, Taipei, Taiwan, pp. 110–126.
- Lindau, C.W., Bollich, P.K., DeLaune, R.D., Mosier, A.R., Bronson, K.F., 1993. Methane mitigation in flooded Louisiana rice fields. *Biol. Fertil. Soils* 15, 174–178.
- Lindau, C.W., Bollich, P.K., DeLaune, R.D., 1995. Effect of rice variety on methane emission from Louisiana rice. *Agric. Ecosyst. Environ.* 54, 109–114.
- Liu, C.M., Yang, S.S., Hong, C.C., 1996. Emission of methane and nitrous oxide in Taiwan in 1990. *J. Biomass Energy Soc. China* 15, 1–8.
- Minami, K., Neue, H.U., 1994. Rice paddies as a methane source. *Climatic Change* 27, 13–26.
- Perng, D.C., Huang, S.N., 1998. Methane emission and its affected factors in eastern Taiwan paddy. In: Lu, S.C., Liu, C.M., Yang, S.S. (Eds.), *Research on Atmospheric Environments of Taiwan Area (III)*. Global Change Research Center and Department of Agricultural Chemistry, National Taiwan University, Taipei, Taiwan, pp. 314–332.
- Rasmussen, R.A., Khalil, M.A.K., 1986. Atmospheric trace gases: trends and distribution over the last decade. *Science* 32, 1623–1624.
- Rolston, D.E., 1986. Gas flux. In: Klute, A. (Ed.), *Methods of Soil Analysis*, second ed. In: *Agronomy Monograph No. 9*. ASA and SSSA, Madison, Wisconsin, pp. 1103–1119.
- Sass, R.L., Fisher, F.M., Wang, Y.B., Turner, F.T., Jund, M.F., 1992. Methane emission from rice fields: the effect of floodwater management. *Global Biogeochem. Cycles* 6, 249–262.
- Schutz, H., Holzapfel-Pschorn, A., Conard, R., Rennenberg, H., Seiler, W., 1989. A three-year continuous record on the influence of daytime, season, and fertilizer treatment on methane emission rates from an Italian rice paddy. *J. Geophys. Res.* 94, 16405–16416.
- Shin, Y.K., Lee, Y.S., Yun, S.H., Park, M.E., 1995. A simplified closed static chamber method for measuring methane flux in paddy soils. *J. Korean Soil Sci. Soc.* 28, 183–190.
- Wang, Y.P., Shieh, S.W., 1997. Emission and environmental conditions of paddy soil, wetland, dryland, upland soil and forest soil in the central and southern Taiwan area. In: Lu, S.C., Liu, C.M., Yang, S.S. (Eds.), *Research on Atmospheric Environments of Taiwan Area*. Global Change Research Center and Department of Agricultural Chemistry, National Taiwan University, Taipei, Taiwan, pp. 99–121.
- Watson, R.T., Meira Filho, L.G., Sanhueza, E., Janetos, A., 1992. Greenhouse gases: sources and sinks. In: Intergovernment Panel on Climate Change (IPCC). IPCC Supplement, pp. 29–42.
- Yang, S.S., 1998. Methane production in river and lake sediments in Taiwan. *Environ. Geochem. Health* 20, 245–249.
- Yang, S.S., Chang, E.H., 1997. Effect of fertilizer application on methane emission/production in the paddy soils of Taiwan. *Biol. Fertil. Soils* 25, 245–251.
- Yang, S.S., Chang, H.L., 1998. Effect of environmental conditions on methane production and emission from paddy soil. *Agric. Ecosyst. Environ.* 69, 69–80.
- Yang, S.S., Chang, H.L., 1999. Diurnal variation of methane emission from paddy fields at different growth stages on rice cultivation in Taiwan. *Agric. Ecosyst. Environ.* 76, 75–84.
- Yang, S.S., Chang, H.L., 2001a. Effect of green manure amendment and flooding on methane emission from paddy fields. *Chemosphere: Glob. Change Sci.* 3, 41–49.
- Yang, S.S., Chang, H.L., 2001b. Methane emission from paddy fields in Taiwan. *Biol. Fertil. Soils* 33, 157–165.
- Yang, S.S., Wei, C.B., Koo, K., Tsai, S.S., 1991. Food and agricultural wastes produced in Taiwan area. *J. Biomass Energy Soc. China* 10, 70–87.
- Yang, S.S., Lin, C.C., Chang, E.H., Chung, R.S., Huang, S.N., 1994. Effect of fertilizer, soil type, growth season on methane production and emission in the paddy soils of Taiwan. *J. Biomass Energy Soc. China* 13, 68–87.

- Yang, S.S., Liu, C.M., Liu, Y.L., 2001. Estimation of methane and nitrous oxide emission from animal husbandry industry on Taiwan. *J. Agric. Assoc. China* 2, 450–463.
- Young, C.C., 1997. Uptake and emission of greenhouse effect gases in orchard and forest soils. In: Lu, S.C., Liu, C.M., Yang, S.S. (Eds.), *Research on Atmospheric Environments of Taiwan Area*. Global Change Research Center and Department of Agricultural Chemistry, National Taiwan University, Taipei, Taiwan, pp. 122–141.
- Yu, K.W., Wang, Z.P., Vermoesen, A., Patrick Jr., W.H., Van Cleemput, O., 2001. Nitrous oxide and methane emissions from different soil suspensions: effect of soil redox status. *Biol. Fertil. Soils* 34, 25–30.