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

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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 182807 to 242298 ha of paddy field in the first crop season ranged from 8062 to 12066 ton, and it was between 16261 and 25007 ton for 144178–211968 ha in the second crop season with local measurement. The value ranged from 12132 to 17465 ton, and from 16046 to 24762 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 77593–112095 ton of nitrogen-fixing crops, from 991 to 1859 ton for 3259731–6183441 ton of non-nitrogen-fixing crops, and from 1.77 to 2.22 Gg for 921169–1172594 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 26421–37914 ton, and nitrous oxide emission was 9810–11649 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).
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 aeration 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 were 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 (mg m\(^{-2}\) h\(^{-1}\)), \( V \) is the volume of chamber above soil (m\(^3\)), \( A \) is the cross-section of chamber (m\(^2\)), \( \Delta C \) is the concentration difference between time zero and time \( t \) (mg m\(^{-3}\)), and \( \Delta t \) 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
stated by the IPCC guidelines (IPCC, 1997a,b). Nitrous oxide emission from crop residue was calculated as follows:

$$\text{N}_2\text{O emission} = 2 \times \left[ \text{Crop}_0 \times \text{Frac}_{\text{NCRBF}} + \text{Crop}_{\text{BF}} \times \text{Frac}_{\text{NCRBF}} \right] \times (1 - \text{Frac}_R) \times \text{EF} \times \text{Conversion ratio}$$

where Crop$_0$ = production of non-nitrogen-fixing crops in country, Frac$_{\text{NCRBF}}$ = fraction of nitrogen in nitrogen-fixing crops, Frac$_R$ = fraction of nitrogen in non-nitrogen-fixing crops, Frac$_{\text{BF}}$ = fraction of crop residue that is removed from the field as crop, Frac$_{\text{BURN}}$ = fraction of crop residue that is burned rather than left on field, Crop$_{\text{BF}}$ = 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):

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

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

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

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

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

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

<table>
<thead>
<tr>
<th>Location</th>
<th>CH(_4) emission coefficient (mg m(^{-2}) h(^{-1}))</th>
<th>N(_2)O emission coefficient (mg m(^{-2}) h(^{-1}))</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>First crop</td>
<td>Second crop</td>
</tr>
<tr>
<td>Taipei</td>
<td>2.12</td>
<td>4.85</td>
</tr>
<tr>
<td>I-lan</td>
<td>0.69</td>
<td>8.93</td>
</tr>
<tr>
<td>Taoyuan, Hsinchu</td>
<td>0.89</td>
<td>4.15</td>
</tr>
<tr>
<td>Miaoli</td>
<td>2.92</td>
<td>13.70</td>
</tr>
<tr>
<td>Taichung, Changhua, Nantou</td>
<td>2.84</td>
<td>2.54</td>
</tr>
<tr>
<td>Yulin, Chiayi, Tainan</td>
<td>1.21</td>
<td>3.53</td>
</tr>
<tr>
<td>Kaohsiung, Pingtung</td>
<td>0.82</td>
<td>2.94</td>
</tr>
<tr>
<td>Hualien, Taitung</td>
<td>2.11</td>
<td>4.21</td>
</tr>
</tbody>
</table>
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 aeration treatments 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 decrease 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 aeration (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>
<thead>
<tr>
<th>Year</th>
<th>First crop season</th>
<th>Second crop season</th>
<th>Total</th>
<th>Cultiv. CH$_4$ emission (ton)</th>
<th>N.O emission (ton)</th>
<th>Local IPCC cont. CH$_4$ emission (ton)</th>
<th>IPCC single aeration CH$_4$ emission (ton)</th>
<th>IPCC multiple aeration CH$_4$ emission (ton)</th>
<th>Total CH$_4$ emission (ton)</th>
<th>N.O emission (ton)</th>
<th>Local IPCC cont. CH$_4$ emission (ton)</th>
<th>IPCC single aeration CH$_4$ emission (ton)</th>
<th>IPCC multiple aeration CH$_4$ emission (ton)</th>
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<tr>
<td>1990</td>
<td>242 298</td>
<td>12 096</td>
<td>254 394</td>
<td>126 806</td>
<td>24 662</td>
<td>150 212</td>
<td>149 372</td>
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<td>1991</td>
<td>227 474</td>
<td>10 498</td>
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<td>1993</td>
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<td>1995</td>
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<td>1997</td>
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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 \( \text{gm}^{-2} \)) for seven locations, \(-0.40 \) to 1.00 (average was 0.24 \( \text{gm}^{-2} \)) for eight locations, \(-0.46 \) to 0.59 (average was 0.43 \( \text{gm}^{-2} \)) for five locations, and \(-0.62 \) to 0.44 (average was \(-0.17 \text{gm}^{-2} \)) for three locations) \( \text{gm}^{-2} \) 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, 6206–10973, 8646–10641, and 7717–117893 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 \( \text{gm}^{-2} \) in banana cultivation (average was \(-0.46 \text{gm}^{-2} \)) and between \(-1.80 \) and 3.80 \( \text{gm}^{-2} \) in mango cultivation (average was 0.22 \( \text{gm}^{-2} \)). 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 \( \text{gm}^{-2} \)) for seven locations, 0.36 and 2.81 (average was 1.04 \( \text{gm}^{-2} \)) for eight locations, 0.56 and 2.23 (average was 1.14 \( \text{gm}^{-2} \)) for five locations, and 0.21 and 0.77 (average was 0.49 \( \text{gm}^{-2} \)) for three locations) \( \text{gm}^{-2} \), 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 522 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 \( \text{gm}^{-2} \) for banana cultivation and from 0.10 to 1.16 \( \text{gm}^{-2} \) 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-
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 emission 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 615,307 ton in 1990 to 325,973 ton in 2000. Annual nitrous oxide emission from non-nitrogen-fixing crops also decreased from 1847 ton in 1990 to 991 ton in 2000.
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 5
Nitrous oxide emission from chemical nitrogen fertilizers, nitrogen-fixing and non-nitrogen-fixing crops

<table>
<thead>
<tr>
<th>Year</th>
<th>Chemical nitrogen fertilizer</th>
<th>Nitrogen-fixing crops</th>
<th>Non-nitrogen-fixing crops</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Application (ton)</td>
<td>N₂O emission (ton)</td>
<td>Yield (ton)</td>
</tr>
<tr>
<td>1990</td>
<td>1060.917</td>
<td>2039.5</td>
<td>89,840</td>
</tr>
<tr>
<td>1991</td>
<td>1135.096</td>
<td>2160.8</td>
<td>104,592</td>
</tr>
<tr>
<td>1992</td>
<td>1105.114</td>
<td>2087.6</td>
<td>95,399</td>
</tr>
<tr>
<td>1993</td>
<td>1140.480</td>
<td>2118.6</td>
<td>99,562</td>
</tr>
<tr>
<td>1994</td>
<td>1156.835</td>
<td>2132.8</td>
<td>104,041</td>
</tr>
<tr>
<td>1995</td>
<td>1140.412</td>
<td>2175.8</td>
<td>112,095</td>
</tr>
<tr>
<td>1996</td>
<td>1172.594</td>
<td>2216.9</td>
<td>102,785</td>
</tr>
<tr>
<td>1997</td>
<td>1004.616</td>
<td>1914.3</td>
<td>101,117</td>
</tr>
<tr>
<td>1998</td>
<td>982.082</td>
<td>1862.2</td>
<td>79,985</td>
</tr>
<tr>
<td>1999</td>
<td>966.679</td>
<td>1805.2</td>
<td>77,593</td>
</tr>
<tr>
<td>2000</td>
<td>921.169</td>
<td>1768.3</td>
<td>87,377</td>
</tr>
</tbody>
</table>

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, tabacco, sugar cane, sesame, rapeseed and perfume plants.

### Table 6
Methane and nitrous oxide emissions from crop residue burning

<table>
<thead>
<tr>
<th>Year</th>
<th>Rice yield (ton)</th>
<th>Rice hull CH₄ emission (ton)</th>
<th>N₂O emission (ton)</th>
<th>Corn yield (ton)</th>
<th>Corn stalk CH₄ emission (ton)</th>
<th>N₂O emission (ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990</td>
<td>2283.670</td>
<td>23.9</td>
<td>21.3</td>
<td>398,875</td>
<td>4.1</td>
<td>3.7</td>
</tr>
<tr>
<td>1991</td>
<td>2311.638</td>
<td>24.2</td>
<td>21.5</td>
<td>374,810</td>
<td>3.9</td>
<td>3.5</td>
</tr>
<tr>
<td>1992</td>
<td>2069.880</td>
<td>21.6</td>
<td>19.3</td>
<td>389,869</td>
<td>4.1</td>
<td>3.6</td>
</tr>
<tr>
<td>1993</td>
<td>2232.933</td>
<td>23.3</td>
<td>20.8</td>
<td>405,999</td>
<td>4.2</td>
<td>3.8</td>
</tr>
<tr>
<td>1994</td>
<td>2061.403</td>
<td>21.5</td>
<td>19.2</td>
<td>397,118</td>
<td>4.2</td>
<td>3.7</td>
</tr>
<tr>
<td>1995</td>
<td>2071.968</td>
<td>21.7</td>
<td>19.3</td>
<td>375,571</td>
<td>3.9</td>
<td>3.5</td>
</tr>
<tr>
<td>1996</td>
<td>1930.897</td>
<td>20.2</td>
<td>18.0</td>
<td>395,412</td>
<td>4.1</td>
<td>3.7</td>
</tr>
<tr>
<td>1997</td>
<td>2041.843</td>
<td>21.3</td>
<td>19.0</td>
<td>337,617</td>
<td>3.5</td>
<td>3.2</td>
</tr>
<tr>
<td>1998</td>
<td>1859.157</td>
<td>19.4</td>
<td>17.3</td>
<td>243,792</td>
<td>2.6</td>
<td>2.3</td>
</tr>
<tr>
<td>1999</td>
<td>1916.305</td>
<td>20.0</td>
<td>17.9</td>
<td>201,195</td>
<td>2.1</td>
<td>1.9</td>
</tr>
<tr>
<td>2000</td>
<td>1843.227</td>
<td>19.9</td>
<td>17.8</td>
<td>138,315</td>
<td>1.4</td>
<td>1.3</td>
</tr>
</tbody>
</table>
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 37914 and 11649 ton in 1990, respectively, and the value decreased to 26421 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.

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