4.3 Methane Emissions from Rice Cultivation: Flooded Rice Fields

4.3.1 Overview

Anaerobic decomposition of organic material in flooded rice fields produces methane (CH_4), which escapes to the atmosphere primarily by diffusive transport through the rice plants during the growing season. Upland rice fields, which are not flooded and therefore do not produce significant quantities of CH_4, account for approximately 10 per cent of the global rice production and about 15 per cent of the global rice area under cultivation. The remaining area is grown for wetland rice, consisting of irrigated, rainfed, and deepwater rice. The global wetland rice area harvested annually in the early 1980s was about 123.2 million hectares (total harvested area including upland rice is 144 Mha), over 90 per cent of which was in Asia (Neue et al., 1990).[14]

Of the wide variety of sources of atmospheric CH_4, rice paddy fields are considered one of the most important. The Intergovernmental Panel on Climate Change (IPCC, 1996) estimated the global emission rate from paddy fields at 60 Tg/yr, with a range of 20 to 100 Tg/yr. This is about 5-20 per cent of the total emission from all anthropogenic sources. This figure is mainly based on field measurements of CH_4 fluxes from paddy fields in the United States, Spain, Italy, China, India, Australia, Japan and Thailand.

The measurements at various locations of the world show that there are large temporal variations of CH_4 fluxes and that the flux differs markedly with soil type and texture, application of organic matter and mineral fertiliser (Neue and Sass, 1994). The wide variations in CH_4 fluxes also indicate that the flux is critically dependent upon several factors including climate, characteristics of soils and paddy, and agricultural practices, particularly water regime. The parameters that affect methane emissions vary widely both spatially and temporally. Multiple year data sets near the same location and under similar conditions can lead to substantial differences in seasonal methane emission levels, making it difficult to establish a single number as the methane emission level from a field, let alone at a regional or country level. Thus, at the current level of understanding, a reported range in methane emission levels for a country is more realistic than a single number.

Methane production processes

The major pathways of CH_4 production in flooded soils are the reduction of CO_2 with H_2, with fatty acids or alcohols as hydrogen donor, and the transmethylation of acetic acid or methanol by methane-producing bacteria (Takai, 1970; Conrad 1989). In paddy fields, the kinetics of the reduction processes are strongly affected by the composition and texture of soil and its content of inorganic electron acceptors. The period between flooding of the soil and the onset of methanogenesis can apparently be different for the various soils. However, it is unclear if soil type also affects the rates of methanogenesis and CH_4 emission when steady state conditions have been reached (Conrad, 1989).

---

[14] The term "harvested area" has a different meaning from "cultivated area" in that the former accounts for double and triple cropping. For example, if a country has 10 million hectares of land under rice cultivation, all of which are double-cropped (i.e., two crops of rice are grown on each hectare each year), then this country has 20 million hectares of rice area harvested annually.

The redox[15] potential is one important factor for production of CH_4 in soils. The Eh, or electron activity, of the soil gradually decreases after flooding. Patrick (1981) demonstrated that the redox potential of a soil must be below approximately -150 mV in order to have CH_4 production. Yamane and Sato (1964) also showed that the evolution of CH_4 from flooded paddy soils did not commence until the Eh fell below -150 mV.

Carbon substrate and nutrient availability are also important factors. Application of rice straw to paddy fields significantly increases the CH_4 emission rate compared with application of compost prepared with rice straw or chemical fertiliser.

Soil temperature is known to be an important factor in affecting the activity of soil micro-organisms. This is to a certain extent related to the soil moisture content because both the heat capacity and the heat conductivity are lower for a dry soil than for a wet soil. Yamane and Sato (1961) have already found that CH_4 formation reached a maximum at 35°C in waterlogged alluvial soils. The rate of methane formation was very small below 20°C.

Because the conversion rate of substrate to CH_4 depends on the temperature, it is generally observed that the momentary local emission of CH_4 from the soil to the atmosphere depends on the temperature. However, the dependence of the seasonally integrated emissions of CH_4 on temperature is much weaker. That emission depends primarily on the total input of organic substrate: although the temperature determines the time it takes to convert the substrate to CH_4, that time is generally short compared to a season. Thus the methodology proposed here will be based on the seasonally integrated CH_4 emission, whose temperature dependence can be neglected in first approximation.

It is generally recognised that CH_4 formation is only efficient in a narrow pH range around neutrality (pH from 6.4 to 7.8). The effect of flooding is to increase the pH in acid soil, while it decreases the pH in alkaline soil. The increase of pH in acid soils is mainly due to the reduction of acidic Fe^{3+} to Fe^{2+} which simultaneously reduces the Eh. The addition of nitrate as chemical fertiliser to flooded soils may suppress the production of CH_4, because nitrate acts, as well as Fe^{3+}, Mn^{4+}, as a terminal electron acceptor in the absence of molecular oxygen during anaerobic respiration, and poises the redox potential of soils at values such that the activity of strict anaerobes is prevented. The addition of sulphate may also inhibit methane production for similar reasons as nitrate.

There are three processes of CH_4 release into the atmosphere from rice fields. Diffusion loss of CH_4 across the water surface is the least important process. Methane loss as bubbles (ebullition) from paddy soils is a common and significant mechanism, especially if the soil texture is not clayey. During land preparation and initial growth of rice, ebullition is the major release mechanism. The third process is CH_4 transport through rice plants, which has been reported as the most important phenomenon (Seiler et al., 1984; Schütz et al., 1989b).

Many researchers reported that more than 90 per cent of total CH_4 emitted during the cropping season is released by diffusive transport through the aerenchyma system of the rice plants and not by diffusion or ebullition. Emission through rice plant, may be expected to show great seasonal variations as a function of changes in soil conditions and variations in plant growth.

---

[15] Redox (Eh) refers to oxidation-reduction, two processes that take place simultaneously. Oxidation is the loss of an electron by an atom, and reduction is the gain of an electron by an atom.

Methane emission rates are also a function of the partial pressure of CH_4 in the soil. Part of the CH_4 produced in the soil is consumed in the oxidised rhizosphere of rice roots or in the oxidised soil-floodwater interface. It is known that soil methanotrophic bacteria can grow with CH_4 as their sole energy source, and other soil bacteria, such as *Nitrosomonas* species are also able to consume CH_4 (Conrad, 1993). Methane is also leached to ground water, as a small part dissolves in water. Therefore a reduction in soil methane does not necessarily mean that all this CH_4 has been emitted into the atmosphere.

Global emissions from rice fields

The total harvested area of rice has increased from 86 Mha in 1935 to 144 Mha in 1985, which means an annual average increase of 1.05 per cent. The average annual increase was 1.23 per cent between 1959 and 1985. However, in the last few years, the rate of expansion of the total rice acreage has decreased (Minami, 1994).

Table 4-9 provides a summary of measured emissions at a number of specific research sites around the world. It should be noted that methane fluxes from paddy rice fields vary substantially from day to day, and during a day (e.g., day and night). The data presented here are based on frequent measurements which capture the diurnal variations, and variations over the growing season. Based on area and production statistics, with average emission values, a number of researchers have estimated global emissions from rice.

TABLE 4-9
REPRESENTATIVE METHANE EMISSIONS FROM RICE PADDY FIELDS IN VARIOUS LOCATIONS OF THE WORLD

Country	Location	Range of CH_4 flux mg/m^2/hr	Season total g/m^2	Experimental Treatment	Reference
Australia	Griffith	2.8	10	-	NGGIC, 1996
China	Beijing	14.6 - 48.9	27 - 91	OM, WM	Chen et al., 1993
	Beijing	9.4 - 26.8	12 - 39	MF, OM, WM	Yao and Chen, 1994a, 1994b
	Beijing	1.9 - 48.9	5.3 - 100.9	MF, OM, SO, WM	Shao, 1993
	Hangzhou, Zhejiang	6.9 - 50.6	14 - 82	MF, OM, SE	Wassmann et al., 1993a
	Nanjing, Jiangsu	2.6 - 14.3	6 - 34	MF, OM, WM	Chen et al., 1993
	Taoyuan, Hunan	6.5 - 56.2	12 - 115	MF, OM, SE	Wassmann et al., 1993b
	Tuzhu, Sichuan	58.0	167		Khalil et al., 1991
	Wuxian, Jiangsu	3.2 - 6.2	10 - 19	CU, MF, OM, SE, WM	Cai et al., 1994
India	Allahabad, Uttar Pradesh	0.2	0.5	NAV	Mitra, 1992
	Barrackpore, West Benegal	0.7, 20.2	1.8, 6.3	NAV	Mitra, 1992
	Cuttack, Orissa	2.7-7.2	7-19	CU	Mitra, 1992
	Faizabad, Uttar Pradesh	0.8	2	NAV	Mitra, 1992
	Garagacha, West Benegal	11	29	NAV	Mitra, 1992
	Jorhat, Assam	18.1	46	NAV	Mitra, 1992
	Kalyani, West Bengal	4.1	10.8	NAV	Mitra, 1992
	Koirapur, West Bengal	6.1	19	NAV	Mitra, 1992
	Madras, Tamil Nadu	5.8	11	NAV	Mitra, 1992
	New Delhi	0.02-0.21	0.06-0.58	MF	Mitra, 1992
	Purulia, West Bengal	4.2	11	NAV	Mitra, 1992
	Trivandrum, Kerala	5.1	9	NAV	Mitra, 1992
Indonesia	Taman Bogo, Lampung	18.0 - 27.1	31 - 47	MF, OM	Nugroho et al., 1994a
	Taman Bogo, Lampung	17.9 - 31.7	30 - 50	MF, OM	Nugroho et al., 1994b
	Sukamandi, West Java	8.7 - 20.2	19 - 44	WM, CU	Husin et al., 1995
Italy	Vercelli	5 - 28	18 - 75	MF, OM	Schütz et al., 1989a

TABLE 4-9 (CONT.)
REPRESENTATIVE METHANE EMISSIONS FROM RICE PADDY FIELDS IN VARIOUS LOCATIONS OF THE WORLD

Country	Location	Range of CH_4 flux mg/m^2/hr	Season total g/m^2	Experimental Treatment	Reference
Japan	Kawachi	16.3	45		Yagi and Minami, 1990a; Minami, 1994
	Mito	1.2 - 4.1	4 - 13	MF, OM	Yagi and Minami, 1990a; Minami, 1994
	Ryugasaki	2.8 - 15.4	11 - 28	MF, OM	Yagi and Minami, 1990a; Minami, 1994,
	Ryugasaki	1.9 - 7.9	7 - 12	WM	Yagi and Minami, 1990a; Minami, 1994
	Taya	7.0	26		Yagi and Minami, 1990a; Minami, 1994
	Tsukuba	0.2 - 0.4	<1.1	OM	Yagi and Minami, 1990a; Minami, 1994
Korea	Suwon	0.66 - 4.55	9 - 60	OM, WM	Shin et al., 1995
Philippines	Los Banos	0.8 - 18.5	2 - 42	MF, OM	Neue et al., 1994
	Los Banos	3.3 - 7.9	7 - 19	SE	Wassmann et al., 1994
Spain	Savilla	4	12		Seiler et al., 1984
Thailand	Ayutthaya	3.3 - 7.9	13 - 20	CU, OM, WM	Siriratpiraya, 1990
	Bang Khen	4.3 - 21.7	16 - 55	SE	Minami, 1994; Yagi et al., 1994b
	Chai Nat	1.6	4		Minami, 1994 Yagi et al., 1994b
	Chiang Mai	3.7 - 5.5	9 - 13	MF, OM	Jermsawatdipong et al., 1994
	Chiang Mai	9.0 - 9.5	20 - 21	CU	Siriratpiriya et al 1995
	Khlong Luang	3.8	8		Minami, 1994 Yagi et al., 1994b
	Khon Kaen	23.0	76		Minami, 1994; Yagi et al., 1994b

TABLE 4-9 (CONT.)
REPRESENTATIVE METHANE EMISSIONS FROM RICE PADDY FIELDS IN VARIOUS LOCATIONS OF THE WORLD

Country	Location	Range of CH_4 flux mg/m^2/hr	Season total g/m^2	Experimental Treatment	Reference
Thailand (cont.)	Nakompathom	9.4-12.0	25-32	SE	Tomprayoon et al., 1991
	Pathumthani	1.9 - 4.6	5 - 11	MF, OM	Jermsawatdipong et al., 1994
	Phitsanulok	6.6 - 7.2	17 - 18	SE	Katoh et al, 1995
	Phrae	16.6 - 22.2	51 - 69	SE	Minami, 1994; Yagi et al., 1994b
	Ratchaburi	3.2 - 42.5	9 - 117	MF, OM	Jermsawatdipong et al., 1994
	San Pa Tong	10.4 - 16.1	25 - 40	SE	Minami, 1994; Yagi et al., 1994b
	Surin	15.0 - 24.5	41 - 66	MF, OM	Jermsawatdipong et al., 1994
	Surin	13.3	41		Jermsawatdipong et al., 1994
	Suphan Buri	19.5 - 32.2	51 - 75	SE	Minami, 1994; Yagi et al., 1994b
USA	Beaumont, Texas	2.5 - 23.5	5 - 36	OM, SO	Sass et al., 1990, 1991a, 1991b
	Beaumont, Texas	0.6 - 6.3	1 -15	WM	Sass et al., 1992
	Crowley, Louisiana	10.2 - 17.9	21 - 37	MF	Lindau et al., 1991
	Crowley, Louisiana	12.6 - 85.0	22 - 149	MF, OM, SE	Lindau and Bollich, 1993
	Crowley, Louisiana	27 - 99	60 - 220	MF	Lindau, 1994
	Davis, California	3.4 - 10.4	18		Cicerone et al., 1983, 1992
	Knights Landing, California	0.5 - 18.8	1 - 58	MF, OM	Cicerone et al., 1992

Experimental treatment: CU - cultivars, MF - fertilisers, OM - organic matters, SE - seasons (early and late rices, or dry and rainy seasons), SO - soil types, WM - water management.

NAV = not available

Source: Modified from K Minami (1995)

Global emissions of CH_4 from rice paddies reported by several researchers are summarised in Table 4-10. Extrapolation of emission rates to a global scale is very difficult, because the effects of variations in agricultural practices, number of crops per year, soil types and other factors discussed above are uncertain.

The IPCC (IPCC, 1996) presented a candidate list of CH_4 sources to the atmosphere as annual release rates. The total annual source is constrained by the observed rate of atmospheric increase of concentrations and by the estimated atmospheric lifetime to be 535 Tg CH_4/yr. Rice paddies are listed as a source of 60 ± 40 Tg CH_4/yr.

TABLE 4-10
REPRESENTATIVE GLOBAL ANNUAL METHANE EMISSIONS FROM RICE FIELDS AS ESTIMATED BY DIFFERENT AUTHORS

Reference	Estimate (Tg CH_4/yr)
Koyama (1964)	190
Ehhalt and Schmidt (1978)	280
Cicerone and Shetter (1981)	59
Khalil and Rasmussen (1983)	95
Seiler et al (1984)	35-59
Blake and Rowland (1988)	142-190
Crutzen (1985)	120-200
Holzapfel-Pschorn and Seiler (1986)	70-170
Cicerone and Oremland (1988)	60-170
Schütz et al. (1989a)	50-150
Aselman and Crutzen (1989)	60-140
Schütz et al. (1990)	50-150
Wang et al. (1990)	60-120
Neue et al. (1990)	25-60
Bouwman (1990)	53-114
Yagi and Minami (1990b)	22-73
IPCC (1990)	25-170
Minami(1994)	12-113
Sass (1994)	25-54
Parashar et al (1994)	20
IPCC (1996)	20-100

Source: Modified from K. Minami (1994)

4.3.2 Methods For Estimating Emissions

Emissions of methane from rice fields can be represented as follows:

EQUATION 1

$$F_C = EF \times A \times 10^{-12}$$

where:

F_C = estimated annual emission of methane from a particular rice water regime and for a given organic amendment, in Tg per year;

EF = methane emission factor integrated over integrated cropping season, in g/m^2;

A = annual harvested area cultivated under conditions defined above. It is given by the cultivated area times the number of cropping seasons per year, i.e., in m^2/yr.

The seasonally integrated emission factor is evaluated from direct field measurements of methane fluxes for a single crop.

In practice, it will be necessary to calculate the total annual emissions from a country as a sum of the emissions over a number of conditions. Total rice production can be divided into subcategories based on different biological, chemical and physical factors that control methane emissions from rice fields. In large countries, this may include different geographic regions. To account for the different conditions, F is defined as the sum of Fc (see Equation 1). This approach to emissions estimation can be represented as follows:

EQUATION 2

$$F = \Sigma_i \Sigma_j \Sigma_k EF_{ijk} \times 10^{-12}$$

where:

- ijk: are categories under which methane emissions from rice fields may vary.

For instance, i may represent water levels in the rice fields such as fields inundated for the duration of the growing season (flooded regime) or fields under water only intermittently. This occurs either under managed irrigation when water is not readily available or when rains do not maintain flooded conditions throughout the growing season (intermittent regime) as given in Table 4-12. j, k, may represent water regimes modified by other factors like organic inputs, soil textures, fertilisation regimes under each of the conditions represented by the index i, and so on. As more factors are identified, more categories need to be included. Inclusion of additional parameters should lead to an improvement of the estimate of the total emissions. The summation should include all cropping seasons.

The factors clearly identified by field experiments as being most important are (1) water regime with inorganic fertilisers (except sulphate-containing inorganic fertilisers which inhibit CH_4 production); (2) organic fertiliser applications; (3) soil type, and soil texture; (4) cultivar; and (5) agricultural practices such as direct seeding or transplanting. Data show that in continuously flooded fields, some types of organic fertilisers and certain cultivars lead to higher emissions compared to rice grown without organic amendments or intermittent or managed irrigation in which the fields are not continuously inundated and only where chemical fertilisers are used.

At present there are insufficient data to incorporate most of these factors. Nonetheless, the estimates can be improved substantially by incorporating the current knowledge on water regimes, organic amendments and soil types etc. For some countries the effects of organic fertiliser can be included.

4.3.3 Summary of Recommended Method

Basic Method

Data on rice cultivation under different water management techniques should be available from most of the important rice-producing countries. Therefore, the basic method for estimating emissions from each country includes estimates based on rice ecosystems (Kush,1984; Neue, 1989) relating to water regime (Table 4-12), namely:

- **Upland**: Fields are never flooded for a significant period of time.
- **Lowland**: Fields are flooded for a significant period of time.
    - **Irrigated**: Water regime is fully controlled.
        - **Continuously flooded:** Fields have standing water throughout the rice growing season and may only dry for harvest.
        - **Intermittently flooded :** Fields have at least one aeration period of more than 3 days during the cropping season.
            - **Single aeration:** Fields have a single aeration during the cropping season at any growth stage.
            - **Multiple aeration:** Fields have more than one aeration period during the cropping season.
    - **Rainfed**: Water regime depends solely on precipitation.
        - **Flood prone:** The water level may rise up to 50 cm during the cropping season.
        - **Drought prone**: Drought periods occur during every cropping season.
    - **Deep water rice**: Floodwater rises to more than 50 cm for a significant period of time during the cropping season.
        - Fields inundated with water depth from 50-100 cm.
        - Fields inundated with water depth > 100 cm.

The discussion refers to a single inventory (or base) year, (e.g., 1990) but an average over three years around the base year (e.g., 1989-1991) is recommended for the activity data, if possible.

For the inventory year, a number of input data are required.

- Area of rice cultivation by water management regime in square metres (m^2). As discussed above, that area is multiplied by the number of crops per year. This includes areas counted for each crop.
- Seasonally integrated flux (EF) emission values for areas of different rice ecosystems (water regimes) without organic amendments.
- of enhancement factors for organic amendments.

The result is methane emissions for each category. The total emissions for the country is the sum of the individual results for each category.

Default data

In many cases, especially at the beginning of the process, there will be important rice-growing areas for which specific fluxes will not be available. In such cases the regional and country-specific default data provided in Tables 4-12 and 4-13 can be used to carry out first order estimates. These data may also be used by national experts for comparison. Several ongoing activities to improve comparable measurement data have been identified. See Appendix for further information.

Area Statistics

Table 4-11 contains information on harvested area of rice according to statistics from the FAO Yearbook (UN, 1992), China Agricultural Yearbook (1990), IRRI RICE Almanac (IRRI, 1994) and World Rice Statistics (IRRI, 1993). Allocation of areas to categories, e.g., irrigated, rainfed (flood prone and lowland rainfed) and upland rice for main rice-producing countries were based on the IRRI Rice Almanac (IRRI, 1994) and for other rice-producing countries these categories were based on IRRI (1990), Huke (1982) and Grist (1986). Actual percentage of the irrigated, rainfed, and flood prone areas which are continuously flooded or have an aeration period greater than 3 days or multiple aerations, are to be obtained from the country specific data.

Seasonally Integrated flux values

Tables 4-12 and 4-13 provides default EF values for various categories of water regimes and multiplication factors for organic amendments. Emissions from upland rice are assumed to be 0 and ignored in the emission calculations.

For continuously flooded rice, a “model” average seasonally integrated emissions for rice-growing countries of the world was estimated from existing data (Table 4-13) to be 20 g/m^2. These flux values are representative of flooded rice fields where organic fertiliser is not used.

For intermittently flooded rice, a simple correction is applied. Fluxes are taken to be 50 per cent of the flooded (non-organic) value of 20 g/m^2 for single aeration and 20 per cent for multiple aeration. For other water regimes new default values are given in Table 4-2. For irrigated and continuously flooded, lowland rice ecosystems, the default seasonally integrated methane emission is 20 g/m^2 (see Table 4-13) for soils ‘without organic amendments’. For conversion to methane emissions from soils ‘with organic amendments’, a default correction factor of 2 (Range 2-5) is applied to the corresponding rice ecosystems for the ‘without organic amendment’ category. This is because organic amendments of flooded rice paddies increase methane emission to the atmosphere (Yagi and Minami, 1990a; Sass et al., 1991a, 1991b; Neue et al., 1994). A comprehensive review of methane flux measurements over the past decade from a variety of countries and with different organic amendments and inorganic fertiliser treatments, is presented by Minami (1995). The amount of methane that is emitted as a result of organic soil amendments depends greatly on the amount and condition of readily available decomposable carbon contained in the treatment. Schütz et al (1989a) observed increases from a control value of 28.6 g CH_4 m^2/yr to 68.4 g CH_4 m^2/yr with added rice straw, (a factor of 2.4). Cicerone et al. (1992) observed increases from a control value of 1.4 g CH_4 m^2/yr to up to 58.2 g CH_4 m^2/yr with added straw, a factor of over 40 times higher. In field studies in the Philippines, Denier van der Gon and Neue (1995) found that fields treated with green manure applied at a rate of 22 tonnes/ha emitted over twice as much methane as fields in which the application rate was 11 tonnes/ha.

Methane emission rates are highly sensitive to water management. Periodic drainage of irrigated rice paddies results in a significant decrease in methane emissions. Yagi and Minami (1990a) reported a decrease in methane emission rates as a result of a mid-season drainage in Japanese rice fields. Sass et al. (1992) found that a single midseason drain reduced seasonal emission rates by 50 per cent (from 9.27 g/m^2 to 4.86 g/m^2). In addition, multiple short periods of drainage (2-3 days) approximately every three weeks during the growing season reduced methane emissions to an insignificant amount (1.15 g/m^2) without decreasing rice grain yield. Yagi et al. (1996) compared a continuously flooded plot with constant irrigation with an intermittently drained plot with short-term draining periods several times during the rice growing season. Total seasonal methane emission rates during the cultivation period were 14.8 g/m^2 and 8.6 g/m^2 for 1991 and 9.5 g/m^2 and 5.2 g/m^2 for 1993 in the continuously flooded and intermittently drained plots, respectively. Scaling factors in Table 4-12 have been developed using the data from the literature.

Default values in Tables 4-12 and 4-13 can be used for initial calculation where local measurements are not adequate. However, national experts are encouraged to use locally available data if available. If this is done it is important to ensure that these coefficients are based on a sufficient number of measurements to capture the variability and produce a representative seasonal average value, which is needed for inventory calculations (see Appendix).

Possible Refinements

National experts are encouraged to go beyond the basic method, and add as much detail as can be scientifically justified, based on laboratory and field experiments on various amendments and theoretical calculations, to arrive at the estimate of emissions from rice cultivation in their country. These details should be incorporated into subcategories (indices j,k in Equation 2) under each of the main water management categories in Equation 2 so that they can be compared at that level with data from other countries.

> For example:
>
> Where emission data are available for different fertiliser types, this may be incorporated into the calculations. Each category, (e.g., continuously flooded) would be further divided as follows:

F (continuously flooded) = F (flooded chemical) + F (flooded/organic amendment)

This procedure would then be repeated for as many separate subcategories as have been defined. Each amendment may be incorporated in the same manner.

In all cases, the emission inventory must be fully documented. The documentation has two aspects. First, method of calculation must be specified as in Equation 2. Matrices of amendments must be delineated. Second, all data and original sources must be referenced, if not included explicitly as part of the inventory report. It is desirable in all cases to rely on published information, whether from the county's government/scientific institutions an international organisation such as the UN-FAO, or the scientific literature.

TABLE 4-11

DEFAULT ACTIVITY DATA - HARVESTED RICE

Country or Region	1990 Area (1000s ha)	Irrigated[a] (%)	Upland Rice (%)	Rainfed[b] (%)
Americas				
USA	1114	100	0	0
Belize	2	10	90	0
Costa Rica	53	10	90	0
Cuba	150	100	0	0
Dominican Rep	93	98	2	0
El Salvador	15	10	90	0
Guatemala	15	10	90	0
Haiti	52	40	60	0
Honduras	19	10	90	0
Jamaica	0	40	60	0
Mexico	123	41	59	0
Nicaragua	48	10	90	0
Panama	92	5	95	0
Puerto Rico	0	75	25	0
Trinidad & Tobago	5	45	55	0
Argentina	103	100	0	0
Bolivia	110	25	75	0
Brazil	3945	19	75	6 (0 + 6)
Chile	35	79	21	0
Columbia	435	67	23	10 (0 + 10)
Ecuador	266	40	10	50
Guyana	68	95	5	0
Paraguay	34	50	50	0
Peru	185	84	16	0
Surinam	58	100	0	0
Uruguay	108	100	0	0
Venezuela	119	90	10	0

TABLE 4-11 (CONT.)
DEFAULT ACTIVITY DATA - HARVESTED RICE

Country or Region	1990 Area (1000s ha)	Irrigated[a] (%)	Upland Rice (%)	Rainfed[b] (%)
Asia				
Brunei	1	79	21	0
Hong Kong	0	100	0	0
Syria	0	100	0	0
Turkey	52	100	0	0
India	42321	53 (16 + 37)	15	32 (16 + 16)
Pakistan	2113	100	0	0
Bangladesh	10435	22	8	70 (23 + 47)
Myanmar	4760	18	6	76 (24 + 52)
Nepal	1445	23	3	74 (8 + 66)
Afghanistan	173	100	0	0
Bhutan	25	50	4	46 (42 + 4)
China [3]	33265	93	2	5 (0 + 5)
Indonesia	10502	72 (22 + 50)	11	17 (10 + 7)
Iran	570	100	0	0
Iraq	78	100	0	0
Japan	2074	99 (2 + 97)	1	0
Malaysia	639	66	12	22 (1 + 21)
Philippines	3319	61	2	37 (2 + 35)
Sri Lanka	828	37	7	56 (3 + 53)
Taiwan	700	97	3	0
Thailand	9650	7	1	92 (7 + 85)
Kampuchea	1800	8	2	90 (42 + 48)
Laos	638	2	37	61 (0 + 61)
Vietnam	6028	53	8	39 (11 + 28)
Democratic Republic of Korea	670	67	13	20
Republic of Korea	1242	100 (9 + 91)	0	0

TABLE 4-11 (CONT.)
DEFAULT ACTIVITY DATA - HARVESTED RICE

Country or Region	1990 Area (1000s ha)	Irrigated[a] (%)	Upland Rice (%)	Rainfed[b] (%)
Europe				
Albania	2	100	0	0
Bulgaria	11	100	0	0
France	20	100	0	0
Greece	15	100	0	0
Hungary	11	100	0	0
Italy	208	100	0	0
Portugal	33	100	0	0
Romania	37	100	0	0
Spain	81	100	0	0
Former USSR	624	100	0	0
Former Yugoslavia	8	100	0	0
Pacific				
Australia	102	100	0	0
Fiji	13	50	50	0
Africa				
Algeria	1	100	0	0
Angola	18	100	0	0
Benin	7	10	90	0
Burkina Faso	19	89	11	0
Burundi	12	25	75	0
Cameroon	15	25	75	0
C African Rep	10	25	75	0
Chad	39	25	75	0
Comoros	13	100	0	0
Congo	4	25	75	0
Egypt	436	100	0	0
Gabon	0	25	75	0
Gambia	14	90	10	0
Ghana	85	24	76	0
Guinea Bissau	57	25	75	0
Guinea	608	8	47	45

TABLE 4-11 (CONT.)
DEFAULT ACTIVITY DATA - HARVESTED RICE

Country or Region	1990 Area (1000s ha)	Irrigated[a] (%)	Upland Rice (%)	Rainfed[b] (%)
Ivory Coast	583	6	87	7
Kenya	15	25	75	0
Liberia	168	0	94	6
Madagascar	1160	10	14	76 (2 + 74)
Malawi	29	25	75	0
Mali	222	25	75	0
Mauritania	14	100	0	0
Morocco	6	100	0	0
Mozambique	109	25	75	0
Niger	29	35	65	0
Nigeria	1567	16	51	33 (33 + 0)
Rwanda	3	25	75	0
Senegal	73	25	75	0
Sierra Leone	339	1	67	32
Somalia	5	50	50	0
South Africa	1	100	0	0
Sudan	1	50	50	0
Swaziland	0	25	75	0
Tanzania	375	3	22	75 (0 + 75)
Togo	21	4	96	0
Uganda	37	25	75	0
Zaire	393	5	90	5
Zambia	11	25	75	0
Zimbabwe	0	25	75	0

[a] Numbers in brackets indicate continuously flooded and intermittently flooded respectively.

[b] Numbers in brackets indicate continuously flood-prone and drought-prone respectively.

[c] Values are currently being updated.

Sources: DeDatta (1975), Huke, (1982), Grist (1986), IRRI (1990), NGGIC (1996).

Notes: Areas were taken from FAO Yearbook (UN, 1992), China Agricultural Yearbook (1990), World Rice Statistics (IRRI, 1990) and IRRI Rice Almanac 1993-1995 (IRRI, 1993).

TABLE 4-12
SCALING FACTORS FOR METHANE EMISSIONS FOR RICE ECOSYSTEMS RELATIVE TO CONTINUOUSLY FLOODED FIELDS (WITHOUT ORGANIC AMENDMENTS)

Category	Sub-Category[a]			Scaling Factors (relative to emission factors for continuously flooded fields)
Upland	None			0
Lowland	Irrigated	Continuously flooded		1.0
		Intermittently flooded[b]	Single aeration	0.5 (0.2-0.7)
			Multiple aeration	0.2 (0.1-0.3)
	Rainfed	Flood prone		0.8 (0.5-1.0)
		Drought prone		0.4 (0-0.5)
	Deep water	Water depth 50-100 cm		0.8 (0.6-1.0)
		Water depth > 100 cm		0.6 (0.5-0.8)

[a] Other rice ecosystem categories, like swamps and inland, saline or tidal wetlands may be discriminated within each sub-category according to local emisson measurements.

[b] Defined as > 3 days aeration during the vegetative period.

Note: For irrigated and continuously flooded, lowland rice ecosystems, the default seasonally integrated methane emission is 20 g/m^2 (see Table 4-13) for soils 'without organic amendments'. For conversion to methane emissions from soils 'with organic amendments', apply a default correction factor of 2 (Range 2-5) to the corresponding rice ecosystem for the 'without organic amendment' category.

TABLE 4-13
SEASONALLY INTEGRATED METHANE EMISSION FACTORS FOR CONTINUOUSLY FLOODED RICE WITHOUT ORGANIC FERTILISER IN VARIOUS LOCATIONS OF THE WORLD

Country	Seasonally Integrated Emission Factor, EF[a] (g/m^2)	Literature/Remarks
Australia	22.5	NGGIC, 1996
China	13 (10-22)	Wassman et al., 1993a
India	10 (5 - 15)	Mitra, 1996 Parashar et al., 1996
Indonesia	18 (5 - 44)	Nugroho et al., 1994a,b
Italy	36 (17-54)	Schütz et al., 1989a
Japan	15	Minami, 1995
Republic of Korea	15	Shin et al., 1995
Philippines	(25 - 30)	Neue et al., 1994; Wassman et al., 1994
Thailand	16 (4 - 40)	Towpryaoon et al., 1993
USA (Texas)	25 (15 - 35)	Sass and Fisher, 1995
Arithmetic Mean [b]	20 (12-28)	-

[a] It is recognised that the emission factors presented in Table 4-13 will need to be periodically updated as better data become available. However, this dataset represents the best available information at the time of compilation.

[b] The arithmetic mean of the seasonally integrated emission factor, EF, is derived from the values shown in Table 4-13. The range of emission factors is defined as the standard deviation about the mean.

Appendix

Intercomparability of Methane Emission Data from Rice Cultivation

Chamber measurements

Each laboratory should provide a standardised emission program of control flux measurements to ensure the intercomparibilty and intercalibration of extended data sets.

An emission standardisation programme will consist of a specified experimental plan for seasonal and annual flux measurements along with specific accompanying data on location and climate, soil, water management, plant characteristics, fertiliser treatment and a detailed cropping calendar.

- Methane flux measurements should be recorded at least twice per week over an entire season. Experiments should be continued during fallow and/or alternate cropping times as well as during the entire normal local rice growing season including land preparation. In areas where double or triple cropping is practised, data should be collected for all growing seasons.
- Since emissions are strongly influenced by daily temperature changes, the diel pattern of emission (6-12 flux rates within a 24 hour period) should be determined at least three times during the season.
- A data log of all agricultural events should be kept., e.g., transplant date, panicle initiation, heading, anthesis, harvest, etc. as well as fertilisation, water management schedule, weeding schedule, herbicide and pesticide treatments.
- At the time of each flux measurement, one should also collect the air temperature, flood water temperature, and the soil temperature.
- Fertilisation treatment in the standardisation (continuous irrigation) plots should be according to local practices, but limited to inorganic fertiliser. The application rate as kg N ha^{-1} and number and timing of applications should be reported.
- Fertilisation treatment in other experimental areas, including organic fertilisers, should reflect local practices. Amounts, type, and timing of applications should be reported for each phase of the cropping sequence at all scales.
- Standardisation chamber plots are to be kept flooded from shortly before transplanting until maturity. During flood, the water should be kept at a 5 cm minimum constant depth. A daily log should be kept of the amount of water added and when.

  Other water management regimes should be investigated when they are practised locally. A daily log should be kept of times and durations of draining, the amounts of water added and other applicable data.

For further information, *see 'Global Measurements Standards of methane emissions for irrigated rice cultivation'*, IGAC (1994).

4.4 Greenhouse Gas Emissions from Agricultural Burning

4.4.1 Introduction

Where there is open burning associated with agricultural practices, a number of greenhouse gases (GHGs) are emitted from combustion. All burning of biomass produces substantial CO_2 emissions. However, in agricultural burning, the CO_2 released is not considered to be **net** emission. The biomass burned is generally replaced by regrowth over the subsequent year. An equivalent amount of carbon is removed from the atmosphere during this regrowth, to offset the total carbon released from combustion. Therefore the long term net emissions of CO_2 are considered to be zero. Agricultural burning releases other gases in addition to CO_2 which are by-products of incomplete combustion: methane, carbon monoxide, nitrous oxide, and oxides of nitrogen, among others. These non-CO_2 trace gas emissions from biomass burning are net transfers from the biosphere to the atmosphere. It is important to estimate these emissions in national inventories.[16]

There are two major types of agricultural burning addressed in this section – savanna burning and field burning of crop residues. The approach is essentially the same as that used for non-CO_2 trace gases for all burning of unprocessed biomass, including traditional biomass fuels and open burning of cleared forests. For all these activities, there is a common approach in the proposed methodology, in that crude estimates of non-CO_2 trace gas emissions can be based on ratios to the total carbon released. The carbon trace gas releases (CH_4 and CO) are treated as direct ratios to total carbon released. Non-methane volatile organic compounds (NMVOCs) can be treated in a similar way. However, no default values for NMVOC are provided in this version of the *Guidelines*. To handle nitrogen trace gases, nitrogen to carbon ratios are used to derive total nitrogen released and then emissions of N_2O and NO_x are estimated based on ratios of these gases to total nitrogen released. Tables 4-15 and 4-16 provide suggested default values for non-CO_2 trace gas emission ratios. These are presented with ranges, which

---

[16] For biomass combustion, CO_2 emissions are frequently not considered **net** emissions, and this is the case for agricultural burning. One could argue, in such cases, that this burning could be considered a short term sink of CO_2. That is, a portion of carbon in biomass is being released as **net** emissions of CH_4 and CO, while regrowth is removing the full amount of the original carbon from the atmosphere in the next cycle. Each year plants take up a certain amount of carbon from the atmosphere. When they are burned some of that carbon is converted to CO, and CH_4, so that an amount less than the total CO_2 which was taken up by the plants is re-emitted as CO_2. See Howden et al. (1996), for a more detailed discussion of this proposal. Treating emissions of CO and CH_4 to the atmosphere, as a sink for atmospheric CO_2, however, is inconsistent with the proposed IPCC emissions methodology. In particular, the other carbon compounds emitted are converted back into CO_2 in the atmosphere over periods of days up to a decade or so. Thus, over the time horizons of interest for CO_2, (i.e. more than 100 years) there is no sink of CO_2.

emphasise their uncertainty. However, the basic calculation methodology requires that users select a best estimate value.[17]

The calculation of immediate trace gas emissions, based on the default emission ratios provided in Tables 4-15 and 4-16, produces relatively crude estimates with substantial uncertainties.[18] Use of specific emission ratios which vary by type of burning, region, etc. may allow for more precise calculations. The calculations described here ignore the contemporary fluxes associated with past burning activities. These delayed releases are known to exist, but are poorly understood at present. This and other possible refinements are discussed at the end of this section.

4.4.2 Prescribed Burning of Savannas

Background

The term savanna refers to tropical and subtropical vegetation formations with a predominantly continuous grass cover, occasionally interrupted by trees and shrubs (Bouliere and Hadley 1970). These formations exist in Africa, Latin America, Asia, and Australia. The growth of vegetation in savannas is controlled by alternating wet and dry seasons: most of the growth occurs during the wet season; man-made and/or natural fires are frequent and generally occur during the dry season. The global area of savannas is uncertain, in part due to lack of data and in part due to differing ecosystem classifications. Estimates of the areal extent of savannas range from 1300-1900 million hectares world-wide, about 60 per cent of which are humid savannas (annual rainfall of 700 mm or more) and 40 per cent are arid savannas (annual rainfall of less than 700 mm) (Bolin et al., 1979; Whittaker and Likens, 1975; Lanly, 1982; Lacey et al., 1982; and Hao et al., 1990). Large-scale burning takes place primarily in the humid savannas because the arid savannas lack sufficient grass cover to sustain fire. Humid savannas are burned every one to four years on average with the highest frequency in the humid savannas of Africa (as cited in Hao et al., 1990).

---

[17] Emissions inventory developers are encouraged to provide estimates of uncertainty along with these best estimate values where possible or to provide some expression of the level of confidence associated with various point estimates provided in the inventory. Procedures for reporting this uncertainty or confidence information are discussed in *Volume 1: Reporting Instructions*.

[18] Emission ratios used in this section and presented in the tables are derived from Crutzen and Andreae (1990), Delmas (1993), Delmas and Ahuja (1993) and Lacaux, et al. (1993). They are based on measurements in a wide variety of fires, including forest and savanna fires in the tropics and laboratory fires using grasses and agricultural wastes as fuel. In many cases these ratios are general averages for all biomass burning. Research will need to be conducted in the future to determine if more specific emission ratios, e.g., specific to the type of biomass and burning conditions, can be obtained. Also, emission ratios vary significantly between the flaming and smouldering phases of a fire. CO_2, N_2O, and NO_x are mainly emitted in the flaming stage, while CH_4 and CO are mainly emitted during the smouldering stage (Lobert et al., 1990). The relative importance of these two stages will vary between fires in different ecosystems and under different climatic conditions, and so the emission ratios will vary. As inventory methodologies are refined, emission ratios should be chosen to represent as closely as possible the ecosystem type being burned, as well as the characteristics of the fire.

Savannas are intentionally burned during the dry season primarily for agricultural purposes such as ridding the grassland of weeds and pests, promoting nutrient cycling, and encouraging the growth of new grasses for animal grazing. Savanna burning may be distinguished from other biomass burning activities like open forest clearing because there is little net change in the ecosystem biomass in the savanna after the vegetation regrows during the wet season. Consequently, while savanna burning results in instantaneous gross emissions of CO_2, it is reasonable to assume that the net carbon dioxide released to the atmosphere is essentially zero because the vegetation typically regrows between burning cycles.[19] Savanna burning does release several other important trace gases: methane (CH_4), carbon monoxide (CO), nitrous oxide (N_2O), oxides of nitrogen (NO_x, i.e., NO and NO_2) and non-methane volatile organic compounds (NMVOCs).

Estimates of global emissions of these gases due to savanna burning have been based on estimates of the annual instantaneous gross release of carbon from this activity and on ratios of the other trace gases released from burning to the total carbon released by burning. Estimates of the annual instantaneous gross release of carbon from savanna burning are highly uncertain because of lack of data on:

- the aboveground biomass density of different savannas;
- the savanna area burned annually;
- the fraction of aboveground biomass which actually burns; and
- the fraction which oxidises.

The methodology that is proposed in the next section, although conceptually quite simple, takes these factors into account. The approach allows for estimation of non-CO_2 trace gases released by savanna burning, based on default data sets and on assumptions from average literature values for various regions and types of savannas. It also allows for more accurate national estimates if data and assumptions can be developed to reflect national average conditions accurately. Nonetheless, a wide variety of technical details and open scientific issues remain important research topics.

Calculations

There are two basic components to the calculation. First, it is necessary to estimate the total amount of carbon released to the atmosphere from savanna burning. These are not considered to be net emissions, but are needed to derive non-CO_2 trace gas emissions, which are net emissions. What is required is the annual area burned for the various types of savannas, where type is based primarily upon above and below ground biomass, and perhaps climatological conditions and nutrient status. It is generally recommended for all emissions from agriculture that three-year averages of activity data (e.g., hectares burned) be used instead of a single year's data where possible. This is especially important for savanna burning which is highly variable from year to year. This variability should also be taken into account by national experts in planning data collection programmes to provide more accurate inputs to national inventory calculations. If data are not directly available, estimates can be derived based on total savanna area[20] and

---

[19] If grazing pressure coupled with burning too often reduces biomass (i.e., degrades the quality of savannas), then this needs to be considered as a carbon dioxide source. This is not assumed in the basic calculations but could be included as a refinement if considered important.

[20] Most countries with significant savanna area should have national statistics on the total area, but FAO publications (e.g. FAO, 1993) also provide country-specific estimates.