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Development of methane emission factors for Indian paddy fields and estimation of national methane budget

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ABSTRACT

A state-wise assessment of methane (CH_4) budget for Indian paddies, based on a decadal measurement data across India is presented for the calendar year (CY) 1994, the base year for India's Initial National Communication (NATCOM) to the United Nations Framework Convention on Climate Change (UNFCCC), along with national trend from CY 1979 to 2006. The NATCOM CH_4 emission factors (EFs) for Indian paddy cultivation areas, generally having less than 0.7% of soil organic carbon (SOC), have been estimated as 17.48 ± 4 g m^{-2} for irrigated continuously flooded (IR-CF), 6.95 ± 1.86 g m^{-2} for rain-fed drought prone (RF-DP), 19 ± 6 g m^{-2} for rain-fed flood prone (RF-FP) and deep-water (DW), 6.62 ± 1.89 g m^{-2} for irrigated intermittently flooded single aeration (IR-IF-SA) and 2.01 ± 1.49 g m^{-2} for IR-IF multiple aeration (MA) paddy water regimes. The state-wise study for 1994 has indicated national CH_4 budget estimate of 4.09 ± 1.19 Tg y^{-1} and the trend from 1979 to 2006 was in the range of 3.62 ± 1 to 4.09 ± 1.19 Tg y^{-1}. Four higher emitting or "hot spot" states (West Bengal, Bihar, Madhya Pradesh and Uttar Pradesh) have accounted for 53.9% of total CH_4 emission with RF-FP paddy water regime as the major contributor. CH_4 emissions were enhanced by factors such as SOC (~1.5 times due to increase in SOC by ~1.8 times), paddy cultivars (~1.5 times), age of seedlings (~1.4 times), and seasons (~1.8 times in Kharif or monsoon than in Rabi or winter season).

1. Introduction

Paddy fields are considered to be one of the important anthropogenic sources of atmospheric methane (CH_4). Methane emissions from paddy fields, which depend on many factors (Schutz et al., 1989; Yagi and Minami, 1990; Parashar et al., 1991, 1993; Sass et al., 1991; Cicerone et al., 1992; Adhya et al., 1994; Baruah et al., 1997; Satpathy et al., 1997; Khalil et al., 1998), arises due to the anaerobic decomposition of organic materials in the flooded soil and escapes to the atmosphere mainly by diffusive transport through the paddy plants (Nouchi et al., 1990) during the growing season. 15% of the 150 Mha global paddy harvest area (HA) are upland paddy fields which are not flooded and therefore do not emit CH_4. Other paddy fields consisting of irrigated, rain-fed and deep-water paddy water regimes constitute an area of nearly 127 Mha of which over 90% is in Asia (Huke, 1982; Gupta et al., 2002) with maximum HA in India (42.2 Mha). Amount of global CH_4 emitted from paddy fields is 60 ± 40 Tg y^{-1} (Houghton et al., 1997).

National Physical Laboratory (NPL) had estimated (Mitra, 1991) a value of 3 Tg y^{-1} for CH_4 emission in India on the basis of measurements done upto 1990 at various paddy-growing regions in the country (Parashar et al., 1991). Methane campaign 1991 (MC-1991) observations had indicated CH_4 emission budget estimate of around 4 ± 2 Tg y^{-1} for Indian paddy fields. MC-1991, methane Asia campaign (MAC-1998) reports and several other papers (Mitra, 1991, 1992, 1996; Parashar et al., 1994a; Gupta and Mitra, 1999; Gupta et al., 2002) have so far documented the CH_4 budget estimate of 3.64 ± 1.26 Tg y^{-1}, based on the flux data available upto 1999 from Indian paddy fields. This paper presents our study to

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Table 1
Details of CH_4 measurement data at various stations/sites from the period post MAC-1998 up to NC-2002

Stations	No. of observations	Year of observation	Paddy variety, fertilizer/manure applied	Paddy water regimes and E_{sif} (g m^{-2})	Reference
West Bengal-IRPE					
Gabberia, Lakshmi-kantapur, 24 Pgs. (South)	2	2002	IET; Urea 160 Kg ha^{-1}, Oil cake 300 Kg ha^{-1}, Superphosphate 90 Kg ha^{-1}, Potash 60 Kg ha^{-1}, DAP 120 Kg ha^{-1}	IR-CF; Rabi: 12.98*, Kharif: 23.04*	NC-2002
Orissa					
CRRI farms, Cuttack	4	1999	cv Gayatri; Control Prilled urea (60 kg N ha^{-1}) GM (60 kg N ha^{-1}) Prilled urea (30 kg N ha^{-1}), green manure (30 kg N ha^{-1})	IR-CF; 15.51** 32.81** 29.91*** 44.84***	Rath et al., 1999
CRRI research farms, Cuttack	6	2002	 CV. Lalat CV. K-39 CV. IR-64 CV. Ratna CV. Lalat -35 d seedling CV. Lalat -20 d seedling N: Urea @120 Kg ha^{-1} in 3 equal split, P: SSP @ 60 Kg ha^{-1} at basal, K: MoP @ 60 Kg ha^{-1} at basal	IR-CF; 29.33* 29.73* 45.39*** 30.91* 38.43* 54.34***	
Actual farmer's rice field, Balianta –Near Bhubaneshwar (RRLB)	1	2002	Padmini (traditional), FYM @ 400 Kg ha^{-1} and Urea @ 49 Kg ha^{-1}	RF-DP; 5.90***	NC-2002
Assam					
Titabar Farms – AAU, Jorhat (Upper Brahmaputra valley zone)	2	2002	Bishnu prashad Jaya and Chilarai; Urea, SSP and MoP @ 40, 20, 20 Kg ha^{-1}	IR-CF; 9.18* RF-DP; 7.14*	NC-2002
Jharkhand-CFRI					
Farmer's field, village- Parghabad, Patherdih, Dhanbad	2	2002	IR 36; NPK (60, 30, 30) Kg ha^{-1} (Urea, Super phosphate, Potash)	IR-CF (Peat soil);100.14***, 94.89***	NC-2002
Delhi-NPL	1	2002	Pusa basmati 1; NPK (150, 75, 75); 150 kg N ha^{-1} as Urea in three split doses, 75 Kg ha^{-1} P as DAP and 75 Kg ha^{-1} K as MoP	IR-IF-MA; 1.08 ± 0.08#*	NC-2002
Delhi-IARI	8	2002	Pusa 44; Control - PK (26, 50) Urea Urea + Hydroquinone Urea + Neem cake Urea + Thiosulphate, Urea + Neem oil Urea + DCD Urea + Karanj cake [NPK (120, 26, 50), 12 kg N ha^{-1}]	IR-IF-MA; 0.47* 0.47* 0.39* 0.47* 0.42* 0.48* 0.50* 0.50*	NC-2002
Uttar Pradesh					
Varanasi, Experimental field, Inst. of Ag. Sc.-Banaras Hindu University (BHU)	2	1998	Pant. Dhan-4; Control Urea @ 40 Kg ha^{-1}; (Basal treatment of KCl, P_2O_5, FYM @ 60, 60, 1000 Kg ha^{-1})	IR-CF; 15.43** 26.12***	Singh et al., 1998
Farmer's field- Dungrauli, Meerut	5	2002	 Saket-4, NPK (120, 40, 20) Saket-4, NPK (115, 40, 25) Saket-4, NPK (110, 40, 20) PB-1, NPK (100, 40) Saket-4, NPK (110, 40)	IR-IF-MA; 0.55* 0.68* 0.47* 0.56* 0.45*	NC-2002
Tamil Nadu-AU					
Mangadu and Mangadupattu near Chennai	4	2002	ADT 43; Rabi Site 1 NPK @ 120, 40, 40 Kg ha^{-1} as Urea, SSP, MoP; Ammo.chloride, ammo.sulphate @ 60.5, 60.5 Kg ha^{-1} Site 2 NPK @ 25, 0, 25 Kg ha^{-1} as Urea, SSP, MoP Kharif Site 1 Neem cake @ 25 Kg ha^{-1}, NPK @ 110, 25, 30 Kg ha^{-1} in the form of Urea, Super phosphate, MoP and 17, 17, 17 complex, Ammonium Chloride @ 99 Kg ha^{-1} Site 2 Neem cake @ 25 Kg ha^{-1}, NPK @ 120, 30, 40 Kg ha^{-1} in the form of Urea, super phosphate, MoP and 17,17,17 complex, Ammonium Chloride @99 Kg ha^{-1}	 IR-IF-SA; 3.38* IR-IF-MA; 1.43* IR-CF; 18.15* IR-CF; 11.06*	NC-2002

(continued on next page)

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Table 1 (*continued*)

Stations	No. of observations	Year of observation	Paddy variety, fertilizer/manure applied	Paddy water regimes and E_{sif} (g m^{-2})	Reference
Kerala					
RRL, Trivandrum	1	2002	Kanchana; NPK (70, 38, 35)	IR-IF-MA; 3.27*	NC-2002
Andhra Pradesh					
NRSA, Hyderabad	2	2002	MTU-1010; NPK (155, 95, 70), $ZnSo_4$ @ 5 L ha^{-1}, Quinolphos @ 2.5 L ha^{-1} on 7 DAT	IR-IF-SA; 8.95* IR-IF-MA; 1.09*	NC-2002

DAP = di-ammonium phosphate; SSP = single super phosphate; MoP = muriate of potash; GM = green manure (*Sesbania rostrata*); FYM = farmyard manure; AAU = Assam agricultural university; NPK = nitrogen phosphorous potassium; IARI- Indian agriculture research institute; DCD = dicyandiamide; DAT = day after transplantation.
* These values are considered in calculating NC-2002 EF values given in Table 2.
** These values are considered in calculating year 1999 EF value given in Table 2.
*** These values are not considered in calculating NC-2002 EF values given in Table 2.
# It is 'Mean ± Standard Deviation' in the value (** ± **).

develop national communication (NATCOM) CH_4 emission factors (EFs) for Indian paddy fields and evolve trend of national CH_4 emission inventory from 1979 to 2006 with detailed state-wise analysis for the year 1994, which was the base year for reporting in the Initial National Communication to United Nations Framework Convention on Climate Change (UNFCCC).

2. Methodology adopted for methane emission inventory

The annual CH_4 emission from paddy fields has been estimated, using Inter-governmental Panel on Climate Change (IPCC) 1996 guidelines, as the product of the HA under different paddy water regimes as classified by IPCC with the corresponding seasonally integrated CH_4 flux (E_{sif}) (Houghton et al., 1997). The total budget is the sum of resulting CH_4 emission from each paddy water regimes and can be formulated as:

$$F_c = \sum_i \sum_j \sum_k \cdots (E_{sif})_{ijk\ldots} \times A_{ijk\ldots} \times 10^{-12}$$

where, F_c is the total estimated emission of CH_4 in Tg y^{-1} for different paddy water regimes *i*, *j*, *k*...[like, irrigated continuously flooded (IR-CF), rain-fed drought prone (RF-DP), rain-fed flood prone (RF-FP), deep-water (DW), irrigated intermittently flooded single aeration (IR-IF-SA) and IR-IF- multiple aeration (MA)], E_{sif} is the seasonally integrated CH_4 flux for these corresponding water regimes under a paddy-cropping season in g m^{-2} and A_{ijk} is the annual paddy HA in m^2 under such water regimes.

2.1. Emission factors for IPCC paddy water regimes

Emission data generated in the country mainly involved manual sampling using static box or chamber technique over the entire paddy-cropping season, in major paddy-growing regions of the country apart from some data generated at Delhi and Cuttack utilizing automatic sampling systems of International Rice Research Institute (IRRI). The Indian data of CH_4 E_{sif} from paddy cultivation, post MAC 1998, has been updated upto year 2002 (Table 1), which includes measurement data obtained under

Table 2
Updated NATCOM methane EFs (g m^{-2}) from Indian paddy water regimes* and its comparison with MAC-1998 and IPCC-1996 default values

Water regimes	RF-FP	RF-DP	IR-CF	IR-IF-SA	IR-IF-MA	DW
1991	19 ± 6.0# Koirapur	5 ± 3.2# Devoke,Cuttack	12.7 ± 1.6# Bhubaneswar, Cuttack, Chennai	5 ± 3.2# Devoke, Cuttack	0.56 ± 0.23# Allahabad, Faizabad, NPL	19 ± 6.0# Koirapur
1992			18.6 ± 9.3# Bhubaneswar			
1993					1.64 NPL	
1994					2.39 ± 0.8# IARI and NPL New Delhi	
1995			13.7 ± 2# Maruteru		1.82 ± 0.76# IARI and NPL New Delhi	
1996					2.05 IARI, New Delhi	
1997					1.48 IARI, New Delhi	
1998		8.7 ± 2.4# Pant Nagar and Karnal	16.1 ± 2.2# Chennai	8.7 ± 2.4# Pant Nagar and Karnal	5.36 Pant Nagar	
1999			21.25 ± 10.01# CRRI, BHU			
NC-2002		7.14 AAU	22.53 ± 10.26# IRPE, CRRI, AAU, AU	6.17 AU, NRSA	0.78 ± 0.70# NPL, IARI, Meerut, AU, RRLT, NRSA	
NATCOM EFs	19 ± 6#	6.95 ± 1.86#	17.48 ± 4#	6.62 ± 1.89#	2.01 ± 1.49#	19 ± 6#
IPCC-1996 default values	16	8	20	10	4	16
MAC-1998 EFs	19 ± 6#	6.9 ± 4.3#	15.3 ± 2.6#	6.9 ± 4.3#	2.2 ± 1.5#	19 ± 6#

* Low soil organic carbon and without organic amendments.
# It is 'mean ± standard deviation' in the value (** ± **).

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recent national campaign-2002 (in NC-2002, an extensive study was conducted in a coordinated network mode involving 10 institutes/universities in India covering the widest possible representative paddy areas) under India's NATCOM project and also data published in scientific papers (Singh et al., 1998; Rath et al., 1999). The quality and accuracy of the methane data generated during NC-2002 by the participating institutes has been ensured by calibrating the gas chromatographs methane analysis of the participating institutes by using methane gas standards 'BND 1601 methane in nitrogen' (a certified Indian Reference material) having national (NPL-India) traceability. As a measure of quality assurance/quality control (QA/QC) of the data generated by the participating institutes, a round robin inter-comparison for methane standard sample (BND 1601 methane in nitrogen) was also organized. The values of the institutes were found to be within the acceptable range of 2 *Z*-score. The *Z*-score, based on robust statistics, is a normalized value, which gives a score to each result relative to the other numbers in the group and is proposed by the National Association of Testing Authorities, Australia in 1996 (NATA, 1996). Table 1 provides the details of the study stations, number and year of seasonal flux observations, paddy variety, fertilizer/manure applied, paddy water regimes, E_{sif} and the corresponding references. The NC-2002 results, average of its participating institutes' E_{sif} from respective IPCC defined paddy water regimes without any organic amendments and representative of actual farmer field's soil and practices (Table 1), when integrated with earlier decadal data from 1991 to 1999 (Table 2) (Singh et al., 1998; Rath et al., 1999; Gupta et al., 2002), have yielded the new CH_4 E_{sif} values which are termed as NATCOM EFs (Fig. 1 and Table 2). Indian paddy cultivation areas, which consist of mainly low to medium levels (<0.7%) of soil organic carbon (SOC) (Velayutham et al., 2000; Gupta et al., 2002), indicated for different paddy water regimes without any organic amendments, NATCOM EFs of $17.48 \pm 4\ g\ m^{-2}$ for IR-CF, $6.95 \pm 1.86\ g\ m^{-2}$ for RF-DP, $19 \pm 6\ g\ m^{-2}$ for RF-FP and DW, $6.62 \pm 1.89\ g\ m^{-2}$ for IR-IF-SA and $2.01 \pm 1.49\ g\ m^{-2}$ for IR-IF-MA (Table 2). A comparison of NATCOM EFs with MAC-1998 and IPCC-1996 default values is given in Table 2.

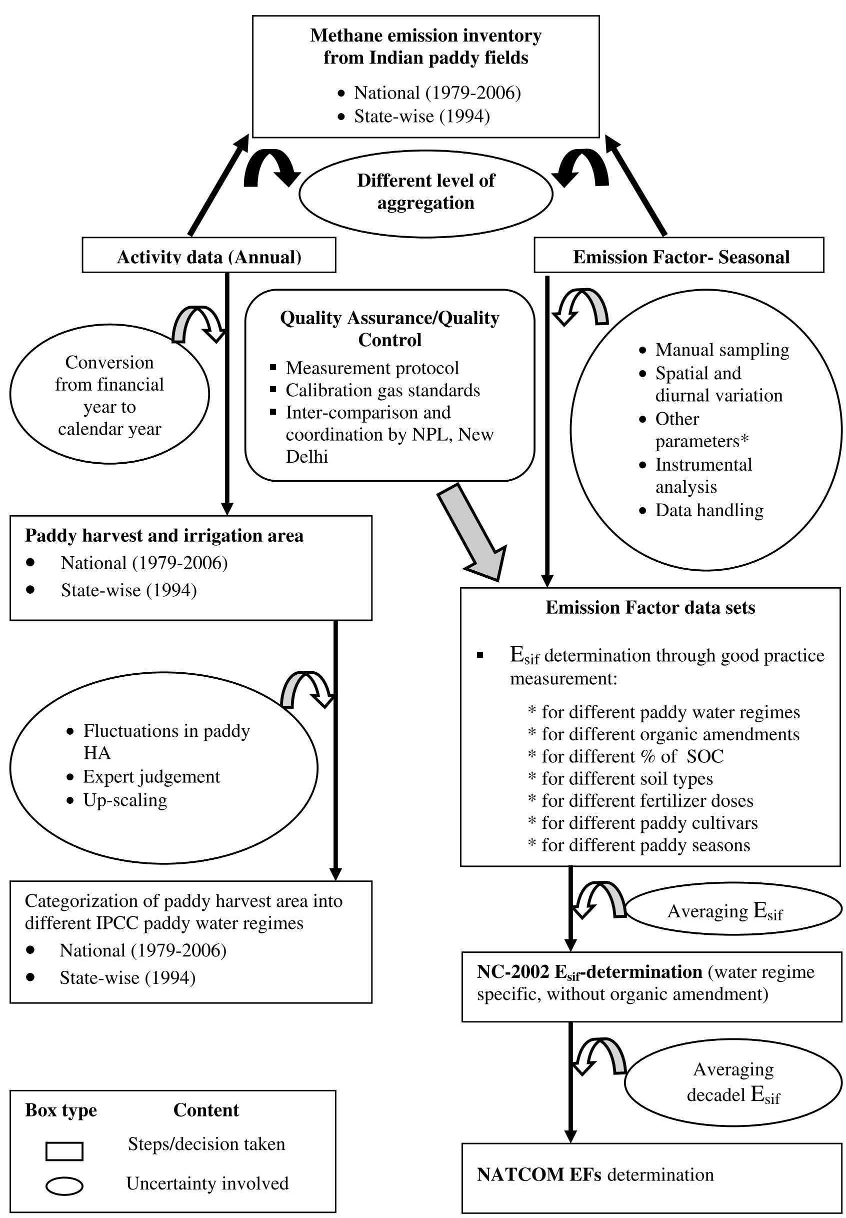

Fig. 1. Flow diagram of the methodology adopted for methane emission inventory from Indian paddy fields.

2.2. Harvest area activity data under IPCC paddy water regimes

Published government documents and reports have been used for activity data input values to the extent possible, as a measure of QA/QC practice. National (1979–2006) and state-wise (1994) financial year paddy HA statistics (CMIE, 2001; Agricultural Statistics at a Glance, 2002; Agricultural Statistics at a Glance, 2006) have been converted to calendar year (CY), which were then classified into 15% upland and the remaining 85% lowland (Table 3A and B) which has been further sub-categorized into 32% rain-fed and 53% irrigated HA. These have been further sub-classified according to available country and states area statistics (WRI, 1991; Bolin, 1995; IRRI, 1995; Parashar et al., 1996; Houghton et al., 1997; Parashar et al., 1997; CMIE, 2001; Agricultural Statistics at a Glance, 2002; Gupta et al., 2002; Agricultural Statistics at a Glance, 2006). Out of the total area under rain-fed category, 16% has been assigned to FP that includes 6% under deep-water regime (Khush, 1984) and remaining 16% to DP. The irrigated areas (IA) (CMIE, 2001; Agricultural Statistics at a Glance, 2002; Agricultural Statistics at a Glance, 2006) are divided into 16% CF and 37% IF of the total HA (Houghton et al., 1997). Intermittently flooded paddy HA is further classified into SA and MA, which are prevalent in the

Table 3
Time series Indian paddy and state level 1994 HA activity data in '000 ha, along with methane emission

CY	HA	IA	HA under IPCC paddy water regimes							Total methane emission ($Tg\ y^{-1}$)
			Upland	RF-FP	RF-DP	IR-CF	IR-IF-SA	IR-IF-MA	DW	
(A) From 1979 to 2006										
1979	39681	16862	5952	3968	10518	6349	9127	1386	2381	3.68 ± 1.02[#]
1980	39968	16474	5995	3997	11104	6395	9193	886	2398	3.73 ± 1.03[#]
1981	40569	16756	6085	4057	11237	6491	9331	934	2434	3.79 ± 1.05[#]
1982	38874	16276	5831	3887	10547	6220	8941	1115	2332	3.62 ± 1.00[#]
1983	40499	17226	6075	4050	10718	6480	9315	1431	2430	3.75 ± 1.05[#]
1984	41180	17893	6177	4118	10522	6589	9471	1832	2471	3.80 ± 1.06[#]
1985	41143	17732	6171	4114	10656	6583	9463	1687	2469	3.80 ± 1.06[#]
1986	41160	18028	6174	4116	10372	6586	9467	1976	2470	3.79 ± 1.06[#]
1987	39396	17228	5909	3940	9955	6303	9061	1864	2364	3.63 ± 1.02[#]
1988	41004	18566	6151	4100	9726	6561	9431	2575	2460	3.75 ± 1.05[#]
1989	42059	19358	6309	4206	9663	6729	9674	2955	2524	3.83 ± 1.08[#]
1990	42557	19427	6384	4256	9938	6809	9788	2829	2553	3.88 ± 1.09[#]
1991	42658	19985	6399	4266	9449	6825	9811	3349	2559	3.86 ± 1.09[#]
1992	41993	20082	6299	4199	8893	6719	9658	3705	2520	3.78 ± 1.08[#]
1993	42348	20519	6352	4235	8702	6776	9740	4003	2541	3.80 ± 1.08[#]
1994	42745	21159	5576	6367	7260	6894	9355	4910	2383	4.09 ± 1.19[#]
1995	42831	21362	6425	4283	8191	6853	9851	4658	2570	3.82 ± 1.09[#]
1996	43284	21957	6493	4328	7909	6925	9955	5076	2597	3.84 ± 1.10[#]
1997	43443	22091	6516	4344	7885	6951	9992	5148	2607	3.85 ± 1.11[#]
1998	44463	23091	6669	4446	7588	7114	10227	5751	2668	3.92 ± 1.13[#]
1999	45070	24114	6761	4507	6985	7211	10366	6536	2704	3.93 ± 1.14[#]
2000	44823	24059	6723	4482	6869	7172	10309	6578	2689	3.91 ± 1.14[#]
2001	44853	23906	6728	4485	7042	7176	10316	6414	2691	3.92 ± 1.14[#]
2002	42110	21476	6317	4211	7580	6738	9685	5053	2527	3.73 ± 1.07[#]
2003	42238	21970	6336	4224	7174	6758	9715	5497	2534	3.72 ± 1.07[#]
2004	42080	22302	6312	4208	6733	6733	9678	5891	2525	3.68 ± 1.07[#]
2005	43223	22908	6483	4322	6916	6916	9941	6051	2593	3.78 ± 1.10[#]
2006	43690	23156	6554	4369	6990	6990	10049	6117	2621	3.82 ± 1.11[#]
States	HA 1994	IA 1994	HA under IPCC paddy water regimes							Total Methane Emission ($Tg\ y^{-1}$)
			Upland	RF-FP	RF-DP	IR-CF	IR-IF-SA	IR-IF-MA	DW	
(B) For 1994										
West Bengal (WB)	5798	1530	883	1047	1661	486	816	228	677	0.59 ± 0.17[#]
Bihar (BR)	4821	1890	531	1230	498	605	879	406	672	0.57 ± 0.17[#]
Madhya Pradesh (MP)	5317	1219	1300	1930	868	390	469	360	0	0.53 ± 0.16[#]
Uttar Pradesh (UP)	5525	3310	495	550	937	1059	1539	712	233	0.52 ± 0.15[#]
Orissa (OR)	4481	1619	691	696	1325	739	399	481	150	0.42 ± 0.12[#]
Andra Pradesh (AP)	3615	3426	0	0	0	1096	1593	737	189	0.35 ± 0.10[#]
Assam	2469	532	215	850	772	170	247	114	100	0.28 ± 0.09[#]
Tamil Nadu (TN)	2248	2082	0	64	102	666	968	448	0	0.21 ± 0.06[#]
Punjab (PJB)	2253	2224	0	0	28	712	1034	478	0	0.20 ± 0.06[#]
Maharashtra (MAH)	1541	413	369	0	437	132	192	89	322	0.13 ± 0.04[#]
Karnataka (KAR)	1315	879	436	0	0	281	409	189	0	0.08 ± 0.02[#]
Haryana (HR)	785	783	0	0	2	250	364	168	0	0.07 ± 0.02[#]
Gujarat (GJ)	607	390	0	0	217	125	181	84	0	0.05 ± 0.01[#]
Others	957.5	156	349	0	413	50	72	33	40	0.05 ± 0.01[#]
Kerala	504	257	247	0	0	82	120	55	0	0.02 ± 0.01[#]
Rajasthan (RAJ)	155	155	0	0	0	50	72	33	0	0.01
Jammu and Kashmir (J&K)	272	244	28	0	0	0	0	244	0	0.01
Himachal Pradesh (HP)	83	51	32	0	0	0	0	51	0	0
TOTAL	42745	21159	5576	6367	7260	6894	9355	4910	2383	4.09 ± 1.19[#]
NATCOM CH_4 EFs ($g\ m^{-2}$)			0	19 ± 6[#]	6.95 ± 1.86[#]	17.48 ± 4[#]	6.62 ± 1.89[#]	2.01 ± 1.49[#]	19 ± 6[#]	
Total Methane emission ($Tg\ y^{-1}$)			0	1.21 ± 0.38[#]	0.50 ± 0.14[#]	1.21 ± 0.28[#]	0.62 ± 0.18[#]	0.10 ± 0.07[#]	0.45 ± 0.14[#]	
Total emission (%)				29.6	12.2	29.6	15.2	2.4	11	

[#] It is 'Mean ± standard deviation' in the value (** ± **).

northern and western regions of India. MA occurs due to high water percolation rates of sandy-loam soils (Mitra, 1992; Baruah et al., 1997; Parashar et al., 1997) and non-availability of timely irrigation, making it highly variable. In the absence of documentation of paddy HA under these water regimes, the apportionment of IF paddy HA to 23% SA and 14% MA involved bottom-up approach and expert judgement for base year 1994, by using district level HA for major CH_4 emitting states, which considerably reduced the uncertainty. The national HA activity data from 1979 to 2006 and state-wise HA activity data for 1994 are presented in Table 3A and B, respectively. The flow diagram of the methodology adopted for CH_4 emission inventory from Indian paddy fields is presented in Fig. 1.

2.3. Experimental design for development of enhancement factors

The experimental setups at the participating institutes under NC-2002 were designed with the aim to develop enhancement factors (the ratio of the maximum emission to the minimum emission) for different parameters affecting methane emission. To

Table 4
Effect of SOC, cultivar variety, rice seasons (Kharif and Rabi), organic amendments, and paddy water regime on CH_4 emissions i.e. E_{sif}

(A) Effect of SOC on E_{sif} during NC-2002

SOC (%)	N applied (kg ha^{-1})	E_{sif} g m^{-2}	Enhancement Factor[$]
Station: farmer's field-Meerut- IARI; paddy water regime: IR-IF-MA; cultivar: Pusa 44			
1.14	52.90	0.68	1.5
0.79	50.60	0.47	
0.75	55.20	0.55	
0.64	50.60	0.45	

(B) Effect of cultivar variety on E_{sif} during NC-2002

Cultivars	E_{sif} g m^{-2}	Enhancement factor[$]
(i) Station: CRRI, Cuttack, Orissa; amendment: N: urea @ 120 Kg ha^{-1} in 3 equal split, P: SSP @ 60 Kg ha^{-1} at basal, K: MoP @ 60 Kg ha^{-1} at basal; paddy water regime: IR-CF; SOC: 0.87%		
Lalat	29.33	
K-39	29.73	
Ratna	30.91	
IR-64	45.39	1.5

Cultivars	SOC (%)	E_{sif} g m^{-2}	Enhancement factor[$]
(ii) Station: CRRI, Cuttack, Orissa; amendment: N: urea @ 120 Kg ha^{-1}, P: SSP @ 60 Kg ha^{-1}, K: MoP @ 60 Kg ha^{-1}; paddy water regime: IR-CF			
Lalat-20 d seedling	0.86	54.34	1.4
Lalat-35 d seedling	0.86	38.43	

(C) Effect of seasons: Rabi and Kharif on E_{sif} during NC-2002

Seasons	SOC (%)	E_{sif} g m^{-2}	Enhancement factor[$]
Station: IRPE, West Bengal; amendment: urea 160 Kg ha^{-1}, oil cake 300 Kg ha^{-1}, super phosphate 90 Kg ha^{-1}, potash 60 Kg ha^{-1}, DAP 120 Kg ha^{-1}; paddy water regime: IR-CF; cultivar: IET			
Rabi	1.08	12.98	
Kharif	0.92	23.04	1.8

(D) Effect of paddy water regime and organic amendments on E_{sif} during MAC-1998

	E_{sif} g m^{-2}(IF)	E_{sif} g m^{-2}[CF (SA)]	Enhancement factor[$]
(i) Station: Pant Nagar, UP; amendment: NPK-60, 50, 40 Kg ha^{-1}, FYM @ 50% N; cultivar: Pant-4; season: Kharif, 1998			
With organic amendment	7.15	12.5	1.8
Without organic amendment	5.36	7.07	1.3
Enhancement factor[$]	1.3	1.8	
(ii) Station: NPL, New Delhi; amendment: FYM @ 10000 Kg ha^{-1}; cultivar: P-169; season: Kharif, 1998			
With organic amendment	2.0	12.05	6

(E) Effect of organic amendments on E_{sif} during MAC-1998

Water regime	E_{sif} g m^{-2}(no organic amendment)	E_{sif} g m^{-2}(with organic amendment)	Enhancement factor[$]
(i) For low organic carbon soils, <0.7%			
RF-FP	19 ± 6 (15)[*#]		
RF-DP	7 ± 4 (7)[*#]	13 (13)[*]	1.9 (1.9)[*]
IR-CF	15 ± 3 (12)[*#]	12 ± 4 (16)[*#]	0.8 (1.3)[*]
IR-IF-SA	7 ± 4 (9)[*#]	13 (13)[*]	1.9 (1.4)[*]
IR-IF-MA	2 ± 1 (2)[*#]	5 (8)[*]	2.5 (4)[*]
DW	19 ± 6 (19)[*#]	(26)[*]	(1.4)[*]
(ii) For high organic carbon soils, >0.7%			
RF-FP		(30)[*]	
RF-DP	8 ± 2 (8)[*#]		
IR-CF	26 ± 7 (29)[*#]	63 ± 17 (60)[*#]	2.4 (2)[*]
IR-IF-SA	8 ± 2 (8)[*#]	(19)[*]	(2.4)[*]
IR-IF-MA	(6)[*]	(21)[*]	(3.5)[*]

[$] It is the ratio of the maximum emission (E_{sif} g m^{-2}) to the minimum emission.
[*] MAC-1998 synthesized values for Asia.
[#] It is 'Mean ± standard deviation' in the value (** ± **).

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study the effect of SOC on E_{sif}, experiments were planned at farmers' field at Dungrauli, Meerut (Uttar Pradesh). Similarly, to study the effect of rice cultivars and seedling age on E_{sif}, experiments were carried out at CRRI research farms, Cuttack (Orissa) and the effect of growth season on E_{sif} has been studied at Lakshmi-kantapur, IRPE (West Bengal) (Table 1). The enhancement factor results are presented in Table 4 and discussed in Section 3.2.

3. Results and discussion

3.1. Methane emission inventory and "hot spots"

Using NATCOM EFs, the trend of national CH_4 emission inventory from paddy fields during 1979 to 2006 has indicated emission estimates and the variability in the range of 3.62 ± 1 to 4.09 ± 1.19 Tg y^{-1} (Table 3A and Fig. 2A-i), with an insignificant growth rate of 0.004 Tg y^{-1} (Fig. 2A-i). Uncertainty ranges in the methane emission estimates under different paddy water regimes for the period 1979–2006 are shown in Fig. 2A-ii. For the year 1994, state-wise CH_4 emission estimates along with their uncertainty ranges have indicated, using NATCOM EFs, a total national budget estimate of 4.09 ± 1.19 Tg y^{-1} (Table 3B and Fig. 2B-i) which is more precise with reduced uncertainty compared to the previous estimates (Gupta et al., 2002), because of the detailed classification of paddy HA under different water regimes, down to district level for major CH_4 emitting states. 1994 CH_4 emission estimate shows an increase compared to the other years (Table 3A and Fig. 2A-i) because of the up-scaling of district level HA activity data to state level for various paddy water regimes, whereas for other years state level HA activity data has been used. Using IPCC-1996 EFs, the 1994 CH_4 budget estimate was estimated to be 4.49 Tg y^{-1}. The states in India have been ranked according to their cumulative emissions in descending order (Fig. 2B-ii) and the relatively high emitting (>0.5 Tg y^{-1}) states were termed as "hot spots" (Fig. 2B-i). Cumulative CH_4 emissions and their variability from various paddy water regimes for various states for the year 1994 are shown in Fig. 2B-ii. The results indicated that the four "hot spot" states (CH_4 emission >0.5 Tg y^{-1}) namely West Bengal, Bihar, Madhya Pradesh and Uttar Pradesh, accounted for nearly 53.9% of national CH_4 budget for 1994 (4.09 ± 1.19 Tg y^{-1}) The RF-FP water regime in these four states is the major contributor with 41% share (Fig. 2B-iii). However, at national level for the year 1994, maximum emissions are contributed from irrigated paddy water regimes with similar emission contribution (29.6%) from both RF-FP and IR-CF paddy water regimes (Table 3B).

3.2. Enhancement factors

High SOC content increases CH_4 production and emission by providing more carbon substrate. Since Indian paddy soils consist of mainly low to medium levels of SOC (Gupta et al., 2002), high SOC soils are not taken into account for Indian CH_4 budget estimates. However, during the NATCOM studies, influence of SOC variation on CH_4 flux has been studied for similar paddy cultivars,

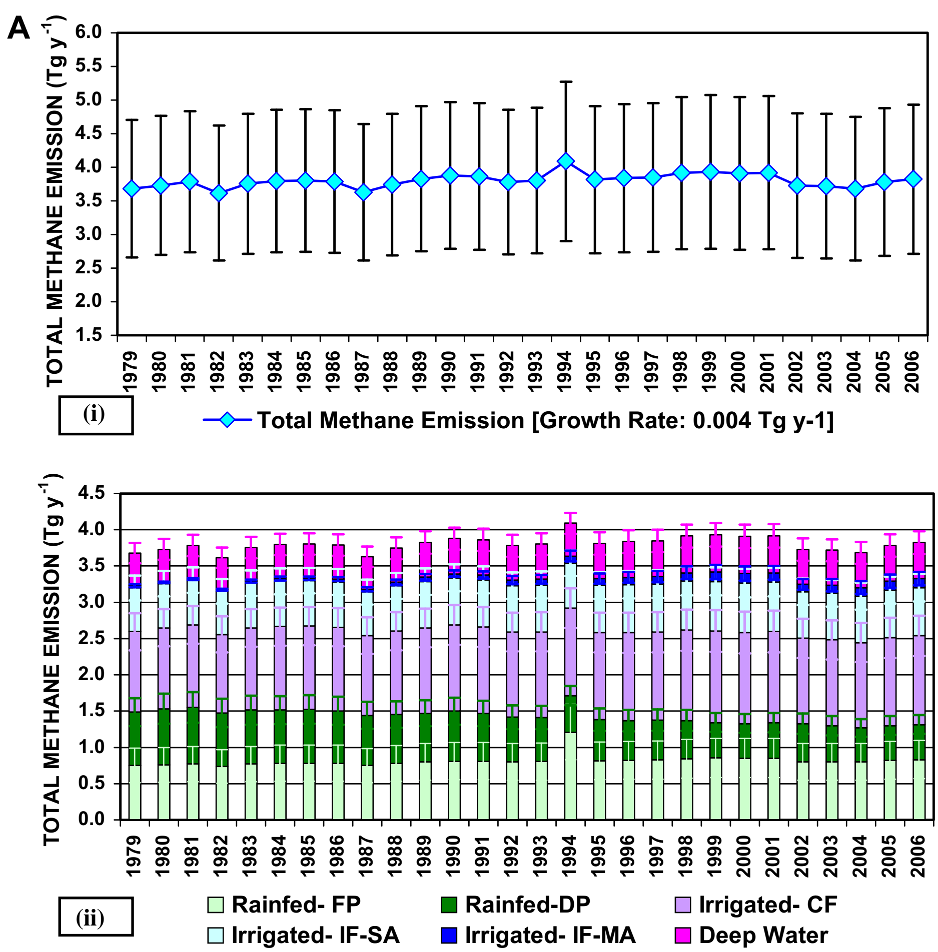

Fig. 2. (A) Methane emissions from Indian paddy fields from 1979 to 2006. (i) Variability in methane emissions, (ii) variability in cumulative methane emissions from Indian paddy water regimes. (B) Methane emissions from Indian states' paddy fields for the year 1994. (i) Methane emissions map showing the "hot spots" in red, (ii) variability in cumulative methane emissions from Indian states' paddy water regimes, (iii) % methane contribution by each paddy water regime of "hot spots".

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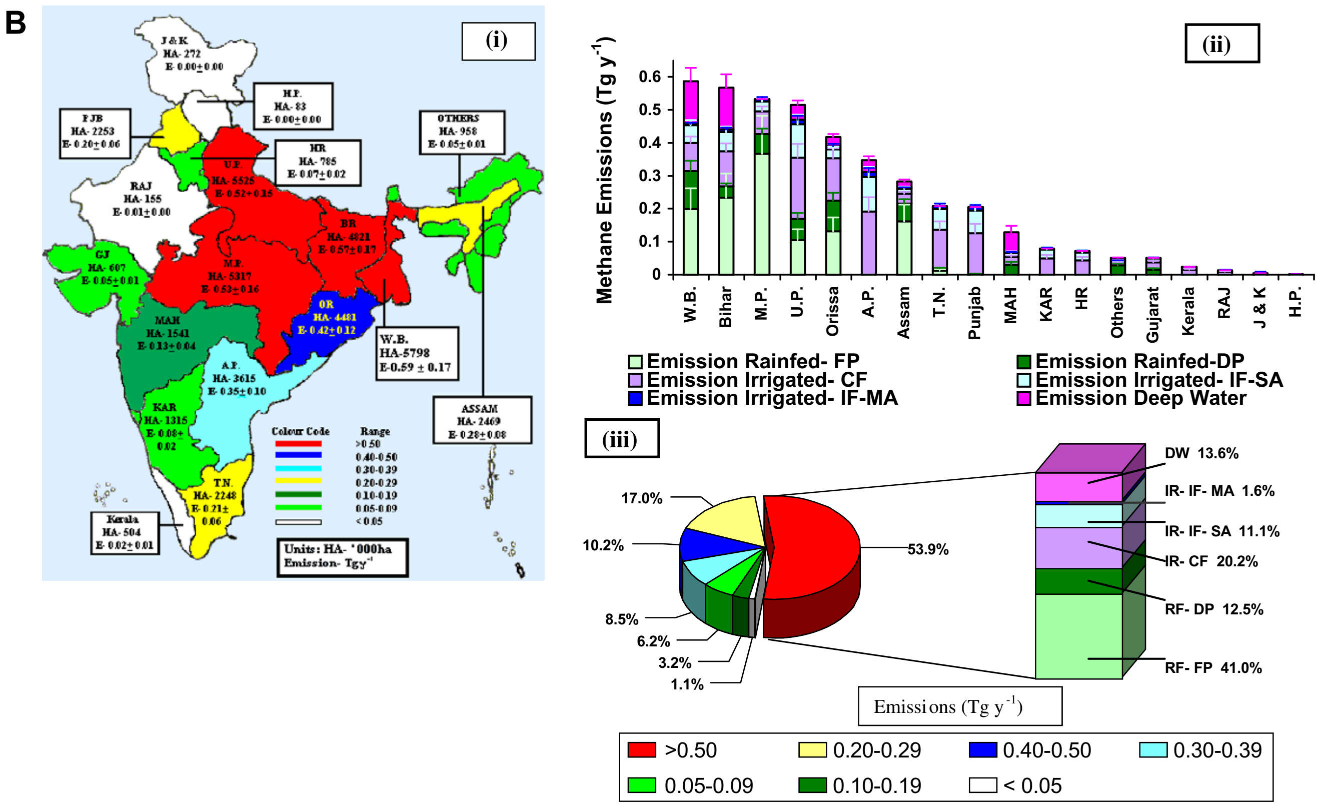

Fig. 2 (*continued*)

paddy water regimes and different doses of N applied as fertilizer supplements and have indicated that difference of ~1.8 times in SOC may result in ~1.5 times increase in CH_4 emissions (Table 4A). Cultivars also affect CH_4 emissions due to differences in root exudation and oxidation power as well as the gaseous exchange between atmosphere and anaerobic soil (Nouchi et al., 1990; Sethunathan, 1995). Studies have shown that rice cultivars could influence the CH_4 emissions by ~1.5 times (Table 4B-i), and different age of seedlings for same cultivar could influence the CH_4 emissions by ~1.4 times (Table 4B-ii), when planted under the same conditions. For the eastern part of country where two rice crops are cultivated in Kharif and Rabi seasons, it has been observed that CH_4 emissions during Kharif (July–November) or monsoon season is more as compared to Rabi (January–April) or winter season, by a factor of ~1.8 (Table 4C), when other factors were kept same.

Effect of IR-CF or IR-IF conditions for the same cultivar and soil regime in the presence of organic amendments can influence the CH_4 emissions (Gupta et al., 2002) by a factor of 1.3–6 (Table 4D-i and D-ii). As-per IPCC-1996 guidelines, organic amendments in flooded soils can increase CH_4 production and emission by a factor of 2 by providing more carbon substrate (Houghton et al., 1997). Limited Indian studies for the effect of organic amendment under different paddy water regimes have shown an enhancement in CH_4 emissions, for low organic carbon soils (Mitra et al., 2002), by a factor of 0.8–2.5 (Table 4E-i); and for high organic carbon soils, by a factor of 2.4 for IR-CF water regime (Table 4E-ii). CH_4 emissions from low and high organic carbon paddy soils for Asia have been given in Table 4E (Mitra et al., 2002).

4. Conclusions

The present study helps in the development of refined country specific CH_4 EFs from rice paddy fields along with emission estimates and trend for India. The CH_4 EFs with reduced uncertainty were 17.48 ± 4 g m^{-2} for IR-CF, 6.95 ± 1.86 g m^{-2} for RF-DP, 19 ± 6 g m^{-2} for RF-FP and DW, 6.62 ± 1.89 g m^{-2} for IR-IF-SA and 2.01 ± 1.49 g m^{-2} for IR-IF-MA paddy water regimes. The Indian CH_4 budget for the base year 1994 was 4.09 ± 1.19 Tg y^{-1} and the trend in estimates from 1979 to 2006 was in the range of 3.62 ± 1–4.09 ± 1.19 Tg y^{-1}. The "hot spot" states in India have been found to be West Bengal, Bihar, Madhya Pradesh and Uttar Pradesh with RF-FP paddy water regimes, which are the largest contributors. The HA activity data for IR-IF-SA and IR-IF-MA water regimes and for different enhancement factors like organic amendments and SOC, need to be surveyed and documented upto district level, for further refining and reducing the uncertainties in the CH_4 emission budget estimates from rice paddy fields in India.

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