

Inventory of methane and nitrous oxide emissions from agricultural soils of India and their global warming potential

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Agricultural soils contribute towards the emission of methane and nitrous oxide, the two important greenhouse gases causing global warming. Due to the diverse soil, land-use types and climatic conditions, there are uncertainties in quantification of greenhouse gas emission from agricultural soils in India. An inventory of the emission of methane and nitrous oxide from different states in India was prepared using the methodology given by the Inter-Governmental Panel on Climate Change. For methane emission, state-specific emission coefficients have been used for all major rice ecosystems. In case of nitrous oxide, both direct and indirect emissions from agricultural soils in different states have been calculated using the emission coefficients derived from the experiments conducted in India. For the base year 1994–95, methane and nitrous oxide emissions from Indian agricultural fields were estimated to be 2.9 Tg (61 Tg CO₂ equivalent) and 0.08 Tg (39 Tg CO₂ equivalent) respectively.

INTERNATIONAL concern for rising anthropogenic greenhouse gas emission and potential dangerous consequences of global climate change has led to the establishment of the United Nations Framework Convention on Climate Change (UNFCCC), following the Earth Summit in June 1992. Most of the countries around the world, with a view to taking positive steps to reduce greenhouse gas emissions and combat climate change adopted the UNFCCC, which requires all parties to compile, periodically update and publish national inventories of greenhouse gas emission sources and sinks using comparable methodologies that have been agreed upon by the Conference of Parties (COP).

Methane (CH₄) and nitrous oxide (N₂O) are the important greenhouse gases contributing 15 and 5% respectively, of the enhanced greenhouse effect. Agricultural and associated sectors produce about 50 and 70%, respectively, of the total anthropogenic emissions of these gases¹. Biological generation of methane in anaerobic environment, including enteric fermentation in ruminants, flooded rice fields, and anaerobic animal waste processing, are the principal sources of methane from agriculture. The pri-

mary sink for methane is oxidation with hydroxyl radicals in the troposphere. Aerobic soils provide an additional sink of 10–20% of annual methane emissions. Agriculture sector contributed over 80% of all-India methane emissions in 1995, including 42% from livestock-related activities, 23% from rice paddy cultivation and 16% from biomass consumption².

Paddy cultivation occupies 42.24 mha in the Indian subcontinent, the largest in Asia, and is one of the major sources of methane emission. Indian rice fields are often blamed to be major contributors of atmospheric methane. According to the United States-Environment Protection Agency (US-EPA) estimate in the early nineties based on extrapolation of measurements in USA and Europe, the annual methane emission from Indian rice paddies was 37.8 Tg (Tg = 10¹² g or million tonne). This estimate was lowered to a great extent after actual measurements were carried out in India. Though the experiments have been conducted at several places, they are too few to be extrapolated to the whole of India for calculation of the methane budget. In 1991, a campaign was carried out for methane measurements across the rice-growing states in India². The data generated from this campaign assigned a methane budget of 4 Tg per annum from Indian paddy fields. Subsequently detailed experiments have been conducted at Indian Agricultural Research Institute, New Delhi; Central Rice Research Institute, Cuttack and at other institutes for measurement of methane emission, and to study the role of water management, cultivars and soil properties on the emission. As a result, methane emission coefficients have been derived for different crop-management practices, which allows better quantification of the fluxes of methane and to assess the mitigation potential of different management options as a guide to policymakers.

Nitrous oxide, with its current concentration of 311 ppbV in the atmosphere, besides being an important greenhouse gas is responsible for the destruction of stratospheric ozone³. Atmospheric concentration of N₂O is increasing at a rate of 0.22 ± 0.02% per year⁴. The concern of N₂O emission is greater because of its long atmospheric lifetime of 166 ± 16 years⁵ and higher global warming potential (310 times that of CO₂). From the agricultural perspective,

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N₂O emission from soil represents a loss of N from the soil system and decreasing N use efficiency⁶. Soil is considered to be one of the major sources, contributing 65% to the global nitrous oxide emission. Annual emission of N₂O–N from agricultural system amounts to 6.3 Tg, which includes the direct emission from agricultural soil and animal system and the indirect emission from agricultural soil through loss of nitrogen to aquatic system and atmosphere⁷. The soil receiving chemical fertilizer and biologically fixed nitrogen contributes to nitrous oxide emission during the processes of nitrification and denitrification. With the advent of modern agriculture, consumption of nitrogenous fertilizer has risen sharply all over the world. This is expected to increase further to meet the food demand of the growing population. Consequently, the emission of nitrous oxide from the soil would also increase.

There are uncertainties in the estimation of methane and nitrous oxide emissions from Indian agriculture because of its diverse soil, climate, land-use types and socioeconomic conditions. Moreover, various crop-management practices, water management for example, play a major role in the emission^{6–8}. What is the real contribution of Indian agriculture to greenhouse gas emissions and subsequent climate change, can only be answered by preparing a national inventory. This will not only improve estimates of emissions and related impact assessments, but also provide a baseline from which we may develop our future emission trajectories to identify and evaluate mitigation strategies.

In an earlier attempt, methane budget of India was estimated exploiting the relationship between biomass production and methane emission⁹. It was observed that the effects of diurnal variation and growth duration on methane emission are ultimately reflected in the biomass production. Thus the total flux of methane could be calculated using the following equation.

$$\text{Total methane flux (mg m}^{-2} \text{ d}^{-1}) = \text{Methane emission area (m}^2) * \text{duration of emission (30 days peak emission)} * \text{methane emission (mg kg}^{-1}) * \text{biomass (kg)}.$$

Accordingly, methane emission from Indian rice fields was estimated to be 1.22 Tg per annum⁹.

For nitrous oxide, a methodology based on the amount of each type of fertilizer N consumed (F_f) and an emission coefficient (E_f) for the fraction of applied N that is released as nitrous oxide for each fertilizer type (f) was developed for preparing national inventories¹⁰.

$$\text{N}_2\text{O emission} = \sum_f (F_f * E_f).$$

Later, OECD/OCDE revised the methodology and included the crop type to which the fertilizer is applied along with the amount of fertilizer.

$$\text{N}_2\text{O emission} = \sum_{fc} (F_{fc} * E_{fc}),$$

where f is the fertilizer type and c is the crop type.

Mosier *et al.*⁷ estimated nitrous oxide emission using the equation

$$\text{N}_2\text{O emission} = \Sigma F * 0.0125,$$

where F is amount of fertilizer consumed and 0.125 is the emission coefficient.

However, both the methods for methane and nitrous oxide are too simplistic to develop an accurate inventory, for which more elaborate and accurate activity data and better validated and calibrated emission coefficients are required. The objective of this article is to estimate the budget for nitrous oxide and methane emission from Indian agricultural soils.

Methodology for emission inventory

Methane

Recently, the Inter-Governmental Panel on Climate Change (IPCC) has outlined a methodology for methane inventory preparation¹¹. Accordingly, the main rice ecosystems are irrigated, rainfed and deepwater. Within each ecosystem are water management systems, which affect the amount of methane emitted during the cropping season.

$$\text{Emission (Tg yr}^{-1}) = \sum_i \sum_j \sum_k EF_{ijk} * A_{ijk} * 10^{-12},$$

where i , j and k are categories under which methane emissions from paddy fields vary such as rice ecosystem, water management, cultivar, organic amendment applied, etc. A_{ijk} is the annual harvested area (m²) under categories i , j and k . For preparing the present inventory, data on area under rice cultivation for the year 1994–95 were obtained from the Fertilizer Association of India (FAI)¹². EF_{ijk} is seasonally integrated emission factor for i , j and k conditions (g m⁻²).

The seasonally integrated emission factors are adjusted according to the category of rice ecosystems as given below.

$$EF_i = EFC * SF_w * SFO * SF_s,$$

where EF_i is adjusted seasonally integrated emission factor for a particular harvested area, EFC is seasonally integrated emission factor for continuously flooded fields without organic amendments, SF_w is scaling factor to account for differences in ecosystem and water-management regime, SFO is scaling factor for different amendment types and SF_s is scaling factor for soil type. The seasonally integrated emission factor for continuously flooded fields for different states was obtained from various studies carried at experimental stations^{13–21}. Where Indian values were not available, IPCC¹¹ scaling factors for water-management regimes have been used for calcu-

lating the methane emission coefficients. Methane emission from the soil is dependent on the soil moisture content. The more the degree of anaerobicity the more is the emission of methane. The coefficients used in the present inventory are listed in Table 1.

Nitrous oxide

The emission of N_2O that results from anthropogenic N input occurs through the direct pathways of nitrification and denitrification from soil and also through a number of indirect pathways, including volatilization losses, leaching and run-off from applied N. The applied N includes synthetic fertilizer, animal manure and sewage sludge applied to soils. Thus, the emission of N_2O has been calculated in two steps: (i) direct N_2O emission from agricultural soils and (ii) indirect N_2O emission from agricultural soils.

Direct N_2O emission

$$N_{2O_{direct}} - N = \{(F_{SN} + F_{AM} + F_{BN} + F_{CR}) * EF1\} + (F_{OS} * EF2),$$

where F_{SN} denotes the annual amount of synthetic fertilizer N applied to soil adjusted to account for the amount that volatilizes as NH_3 and NO_x .

$$F_{SN} = N_{FERT} * (1 - \text{Frac}_{GASF}),$$

where N_{FERT} denotes the total amount of synthetic fertilizer consumed annually. Data on synthetic fertilizer N consumption were obtained from FAI¹². Frac_{GASF} is the fraction of fertilizer that volatilizes as NH_3 and NO_x . Extents of volatilization, however, depend on several of soil, management, plant and climatic factors like the amount of N applied, soil pH, temperature and moisture. Various studies conducted in India estimated the magnitude of

volatilization²²⁻²⁴ to be about 15%. As majority of Indian soils are high in pH and the average annual temperature is also high compared to temperate countries, volatilization losses of N are more. Therefore, in the present calculation we have used this fraction as 15% of the applied N instead of the IPCC default value¹¹ of 10%.

F_{AM} denotes the annual amount of animal manure nitrogen applied to soils adjusted to account for volatilization as NH_3 and NO_x .

$$F_{AM} = \sum_T (N_T * N_{ex(T)}) * (1 - \text{Frac}_{GASM}) [1 - (\text{Frac}_{FUEL} + \text{Frac}_{PRP} + \text{Frac}_{COLLEC} + \text{Frac}_{FEED} + \text{Frac}_{CONST})],$$

where T stands for each defined livestock category/species. In this calculation three categories of livestock, bovine, sheep and goat have been taken. N_T is the number of animals in each category²⁵. $N_{ex(T)}$ is the annual average nitrogen excretion rate per head for each livestock category.

Data on dung produced per animal per year in different categories of livestock were reported by Gaur²⁶. Dry matter content in the fresh dung is 18% in the case of bovine and 32% in the case of sheep and goat²⁷. N content (oven-dry weight basis) is 1.0% in bovine dung and 1.87% in sheep and goat dung²⁸. From these datasets, average N excretion annually for each livestock category has been calculated.

Frac_{GASM} is the fraction of N that volatilizes as NH_3 and NO_x , which is taken to be 15% of the N content of manure^{23,24}. Frac_{FUEL} denotes animal manure that is burnt for fuel, Frac_{PRP} is the fraction of animal manure deposited on soil by grazing livestock, Frac_{CONST} is the fraction of animal manure used as construction²⁶. Frac_{FEED} is the fraction of animal manure used as feed. This fraction has been assumed to be zero in the present estimation, as animal manure is hardly used as animal feed in India. Frac_{COLLEC} is the loss during collection of dung. It has been taken as 30% of the dung produced²⁹.

Table 1. Coefficients used in the present inventory

Parameter	IPCC coefficients	Revised coefficients
<i>EFc</i> , seasonally integrated emission factor for continuously flooded fields	200 kg ha ⁻¹	State-specific coefficients
<i>SFw</i> (scaling factor for different water ecosystems)		
Continuous flooding	1.0	1.0
Rainfed	0.6	0.6
Upland	0.0	0.0
Deepwater	0.8	0.8
<i>EF1</i> (N_2O emission from applied fertilizer; %)	1.25	0.7
<i>EF2</i> (N_2O emission from organic soil; %)	16	16
<i>EF4</i> (N_2O emission from volatilized N from fertilizer and manure; %)	1	0.5
<i>EF5</i> (N_2O emission from leached and run-off N from fertilizer and manure; %)	2.5	0.5
Frac_{GASF} (gas loss through volatilization from inorganic fertilizer; %)	10	15
$\text{Frac}_{GASF-AM}$ (gas loss through volatilization from manure; %)	20	15
Frac_{leach} (leaching loss of N from applied fertilizer and manure; %)	30	10

F_{BN} , the amount of N fixed annually by N-fixing crops is given by

$$F_{BN} = \text{Crop}_{BF} * \text{Frac}_{NCRBF}$$

where Crop_{BF} is seed yield of N-fixing crops¹². Four crops, i.e. gram, arhar, groundnut and soybean were taken into account for the calculation. Frac_{NCRBF} is the N content of grain and straw of legumes²⁸.

F_{CR} , the amount of N in crop residue returned to soil annually, is calculated using the following relationship.

$$F_{CR} = (\text{Crop}_{ST} * \text{Frac}_{NCRST} + \text{Crop}_{SBF} * \text{Frac}_{NCRSBF}),$$

where Crop_{ST} is the amount of straw of non-N fixing crops incorporated to the soil as residue and Crop_{SBF} is the amount of straw of N-fixing crops incorporated to the soil as residue that can be calculated by the following formula.

$$\text{Straw yield} = (\text{Grain yield/harvest index}) - \text{grain yield}.$$

Grain yield data were obtained from FAI¹² and harvest index values from Bandyopadhyay *et al.*³⁰. It is assumed that only 5% of straw produced is incorporated to the soil for all crops. In India, crop residues are used for fuel, feed and other domestic purposes. In Punjab, Haryana and western Uttar Pradesh, for example, rice straw is burnt. Therefore, very little of crop residues are incorporated in the field.

Frac_{NCRST} is the nitrogen content of residue of non-N fixing crops and Frac_{NCRSBF} is the N content of residue of N-fixing crops²⁸. Eleven major crops grown in India were chosen for the calculation.

F_{OS} is the area of organic soil harvested (area of organic soil cultivated annually). Organic soils are those containing more than 12 to 18% of organic carbon depending upon the clay content^{31,32}. Indian soils are generally deficient of organic carbon (contain less than 1%). Only some soils in Kerala and northeast hill regions contain higher organic carbon (about 5%). Therefore, in the present estimation the area under organic soil has been taken as nil.

EF1 is the emission factor (0.7%) for N_2O -N emitted from the various nitrogen additions to the soil. This value is based on studies conducted in India³³⁻³⁵, which showed that emission of N_2O -N from fertilized soil under rice and wheat is about 0.79 kg ha^{-1} , when 120 kg N ha^{-1} was applied. Different coefficients used by IPCC¹¹ and the present inventories are listed in Table 1.

Indirect N_2O emission

The following equation was used for the calculation of indirect emission of N_2O (N_2O_{indirect}).

$$N_2O_{\text{indirect}} = N_2O_{(G)} + N_2O_{(L)},$$

where $N_2O_{(G)}$ is the N_2O produced from volatilization of applied fertilizer and animal manure N and its subsequent

atmospheric deposition as NO_x and NH_4 . This is further calculated as

$$N_2O_{(G)} = [(N_{\text{FERT}} * \text{Frac}_{\text{GASF}}) + (\sum_T (N_{(T)} * N_{\text{ex}(T)} * \text{Frac}_{\text{GASM}}))] * EF4,$$

where N_{FERT} is the amount of fertilizer consumed annually, $\text{Frac}_{\text{GASF}}$ is the fraction (15%) of fertilizer that volatilizes as NH_3 and NO_x , $\sum_T (N_{(T)} * N_{\text{ex}(T)})$ is the amount of N in animal manure excreted annually, T is each defined livestock category, N_T is the number of animals in each category, $N_{\text{ex}(T)}$ is the annual N excretion rate per head for each livestock category. In this calculation, three categories of livestock, i.e. bovine, sheep and goat have been taken into account. $EF4$ is the emission factor for N_2O emission from atmospheric NH_3 and NO_x , which is 1% according to IPCC¹¹ default value. From Indian soils, the factor for N_2O emissions from applied fertilizer is 0.7%; hence emission of N_2O from volatilized N, which has to undergo changes in the atmosphere and then be redeposited in the soil, would be lower than that of direct application of inorganic N in soil. For the present calculation, the coefficient of 0.5% has been used.

Deposited N from leaching and run-off

$$N_2O_{(L)} = N_{\text{FERT}} + \{ \sum_T (N_{(T)} * N_{\text{ex}(T)} * [1 - (\text{Frac}_{\text{FUEL-AM}} + \text{Frac}_{\text{PRP-AM}} + \text{Frac}_{\text{COLLEC}} + \text{Frac}_{\text{FEED-AM}} + \text{Frac}_{\text{CONST-M}})]) \} * \text{Frac}_{\text{LEACH}} * EF5,$$

where $N_2O_{(L)}$ is N_2O produced from leaching and run-off of applied fertilizer and animal manure N, $\text{Frac}_{\text{FUEL-AM}}$ denotes animal manure that is burnt for fuel²⁶, $\text{Frac}_{\text{PRP-AM}}$ is the fraction of animal manure that is deposited onto the soil by grazing livestock. In India, this practice is assumed to contribute negligible amounts of manure to the soil and hence has been taken as nil. $\text{Frac}_{\text{COLLEC}}$ is the loss of dung during collection. $\text{Frac}_{\text{CONST-AM}}$ is the fraction of animal manure that is used as construction²⁶, $\text{Frac}_{\text{FEED-AM}}$ is the fraction of animal manure that is being fed (in the Indian perspective, it is less and assumed to be zero), $\text{Frac}_{\text{LEACH}}$ is the fraction of N lost through leaching, which is 10% of the applied N^{36,37} and $EF5$ is the emission factor for deposited N from leaching and run-off ($\text{kg } N_2O\text{-N kg}^{-1} \text{ N leached and run-off}$), which is taken as 0.5.

$$\text{Total } N_2O\text{-N emission: } N_2O\text{-N}_{\text{TOTAL}} = N_2O\text{-N}_{\text{DIRECT}} + N_2O\text{-N}_{\text{INDIRECT}}$$

Current emission estimates

Methane

The emission of methane from Indian rice fields for the year 1994–95 was estimated to be 2903 Gg ($\text{Gg} = 10^9 \text{ g}$

or thousand tonne; Table 2). Andhra Pradesh emitted the highest amount of CH₄ (529 Gg) followed by West Bengal (448 Gg) and Tamil Nadu (404 Gg). Larger area under rice cultivation in irrigated, continuously submerged water regime (3.45 m ha) in Andhra Pradesh was responsible for higher emission. Though the rice-growing area in irrigated ecosystem in Uttar Pradesh was also high (3.47 m ha), rice fields in most regions are intermittently dried resulting in lower emission of methane (120 Gg). In rainfed ecosystem, the major area under rice cultivation was in Madhya Pradesh and this area is generally drought-prone, resulting in low emissions of methane. The maximum area under deepwater rice was in West Bengal followed by Bihar. In West Bengal, out of total methane emission of 447 Gg, the deepwater rice ecosystem contributed to 109 Gg of methane. The least emission of methane was Andaman and Nicobar islands (0.6 Gg), as the area under rice cultivation was small.

The total area under rice cultivation during the year 1994–95 was 42.24 mha. Among the various rice ecosystems, the largest cultivated area of 14.41 mha was under lowland, rainfed rice and contributed to 0.746 Tg (26%) of methane emission (Figure 1). Maximum emission of 1.379 Tg (47%) was obtained from irrigated, continuously flooded moisture regime (10.97 mha). The area

under irrigated, intermittently flooded rice (10.45 mha) was comparable to rice area under continuous flooded rice, but the emission under this moisture regime was reduced to one-third (17%). Ten per cent emissions of methane were obtained from deepwater rice, as a small area of 2.22 mha was cultivated in this ecosystem. Upland rice grown over 4.2 mha of land did not contribute to methane emission. According to our estimates using IPCC default emission coefficients, Indian paddy soil emitted 4.7 Tg of methane annually (Table 3).

Nitrous oxide

Emission of N₂O–N was estimated to be 79.94 Gg for the year 1994–95 (Table 2). Uttar Pradesh (including Uttarakhand) emitted the highest amount of N₂O–N (15.53 Gg) followed by Andhra Pradesh (9.50 Gg) and Maharashtra (7.50 Gg). Larger area under cultivation, higher use of N fertilizer and greater animal population are responsible for higher emission in these states. Estimates of N₂O–N emission in India from 1980–81 onwards ranged from 32.84 Gg (1980–81) to 93.82 Gg (2000–01) per year (Figure 2). There was a linear increase in emission due to increased area under different crops, higher use of N fertilizers and also increase in animal population. It was observed that inorganic fertilizer is the major contributor (72%) of nitrous oxide (Figure 3). Other sources like crop residues and manure contribute 11 and 3% respectively to the total emission.

Global warming potential of Indian agricultural soil

Global warming potential (GWP) is an index defined as the cumulative radiative forcing between the present and

Table 2. Emission of methane, nitrous oxide and total global warming potential of agricultural soil in different states of India during 1994–95 (current estimates)

State/Union territory	Methane (Gg)	Nitrous oxide (Gg)	Global warming potential (Gg CO ₂)
Andaman and Nicobar Islands	0.6	0.02	18
Andhra Pradesh	528.7	9.50	14,049
Arunachal Pradesh	9.5	0.01	201
Assam	169.6	0.21	3625
Bihar	187.6	3.90	5148
Dadra and Nagar Haveli	1.2	0.01	27
Delhi	0.2	0.10	35
Goa, Daman and Diu	2.6	0.03	63
Gujarat	63.8	4.49	2732
Haryana	71.1	4.38	2850
Himachal Pradesh	1.2	0.26	107
Jammu and Kashmir	19.2	0.32	501
Karnataka	67.0	4.35	2756
Kerala	11.8	0.71	469
Madhya Pradesh	82.7	6.78	3838
Maharashtra	14.5	7.50	2631
Manipur	9.3	0.06	213
Meghalaya	5.0	0.02	110
Mizoram	264.2	0.00	5549
Nagaland	11.0	0.53	394
Orissa	177.4	1.34	4141
Pondicherry	5.5	0.09	144
Punjab	203.2	7.69	6652
Rajasthan	2.3	4.32	1386
Sikkim	2.2	0.01	48
Tamil Nadu	404.4	4.36	9845
Tripura	19.0	0.04	412
Uttar Pradesh	120.2	15.53	7338
West Bengal	447.7	3.38	10,448
Total	2902.7	79.91	85,729

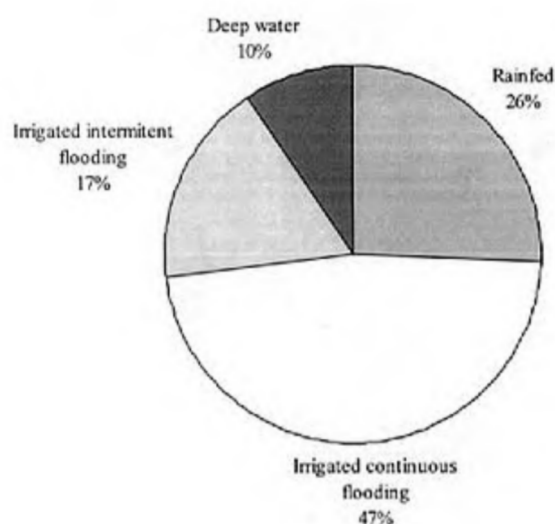


Figure 1. Methane emission from various rice ecosystems under different water-management regimes for the year 1994–95.

some chosen later time 'horizon' caused by a unit mass of gas emitted now. It is used to compare the effectiveness of each greenhouse gas to trap heat in the atmosphere relative to some standard gas, by convention CO_2 . The GWP for CH_4 (based on a 100-year time horizon) is 21, while that for N_2O is 310, when GWP value for CO_2 is taken as 1. GWP of methane and nitrous oxide emitted was calculated using the following equation¹.

$$\text{GWP} = \text{Methane emission} * 21 + \text{Nitrous oxide emission} * 310.$$

Table 3. Emission of CH_4 and N_2O -N in different states of India during 1994–95 using IPCC coefficients

State/Union territory	Methane (Gg)	Nitrous oxide (Gg)
Andaman and Nicobar Islands	1.2	0.033
Andhra Pradesh	701.2	17.282
Arunachal Pradesh	17.6	0.009
Assam	314	0.372
Bihar	375.2	7.114
Dadra and Nagar Haveli	1.2	0.011
Delhi	0.4	0.178
Goa, Daman and Diu	11.2	0.049
Gujarat	106.4	8.185
Haryana	158	7.978
Himachal Pradesh	2	0.471
Jammu and Kashmir	50	0.576
Karnataka	39.6	7.904
Kerala	20.4	1.296
Madhya Pradesh	80.4	12.264
Maharashtra	26.8	13.641
Manipur	17.2	0.104
Meghalaya	9.2	0.030
Mizoram	428.68	0.006
Nagaland	20.4	0.961
Orissa	586	2.439
Pondicherry	6	0.168
Punjab	226.4	14.037
Rajasthan	6.4	7.820
Sikkim	4	0.012
Tamil Nadu	444.4	7.911
Tripura	35.2	0.076
Uttar Pradesh	268.8	28.313
West Bengal	736.4	6.160
Total	4695	144.94

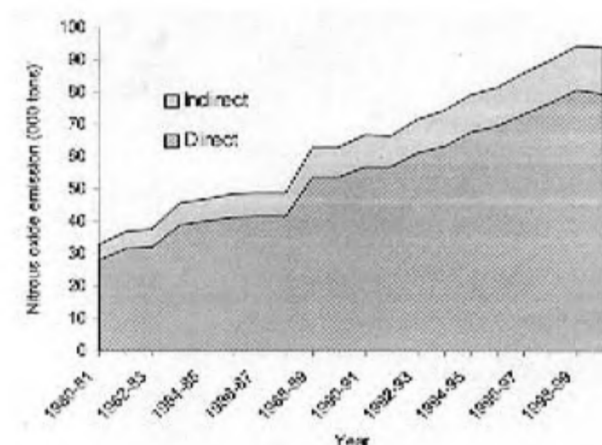


Figure 2. Emission of N_2O -N ('000 tons) in India during 1980–2000.

The contribution of Indian agriculture (current estimates) towards greenhouse gas emissions and its GWP compared to the world agriculture during 1990 is presented in Table 4. According to our estimates, methane and nitrous oxide from Indian agricultural soils are responsible for only about 0.23% and 0.1% respectively, of the global warming caused by world's CO_2 emissions (Table 4). The total global warming potential of Indian agricultural soil is 85,729 Gg equivalents of CO_2 (Table 2).

Indian agriculture as a whole contributed only 3% of the world total methane emissions (375 Tg), of which 25% is from agricultural soils (Table 4). In the agriculture sector livestock is a larger source than rice fields, contributing three times more methane. Among the states, the GWP of Andhra Pradesh was the highest followed by West Bengal and Tamil Nadu (Table 2). Even though the highest nitrous oxide emission was from Uttar Pradesh, it had a lower GWP because of lower methane emission from predominantly intermittently irrigated rice.

In terms of nitrous oxide emission, the contribution of Indian agriculture as a fraction of the world agriculture is miniscule. In an earlier estimate³⁸, emission of 243 Gg of N_2O was ascribed to Indian agriculture (Table 4). Out of this, 240 Gg was contributed by Indian agricultural soil and 3 Gg was due to burning of agricultural residues. For the year 1994–95 using the IPCC default emission coefficients, the value of nitrous oxide emissions was found to be 145 Gg (Table 3). Our present estimates using indigenous emission coefficients have shown that the Indian agricultural soil is contributing only 79.94 Gg of nitrous oxide. Based on these estimates, the contribution of Indian agriculture will be revised to 120 Gg of N_2O -N annually.

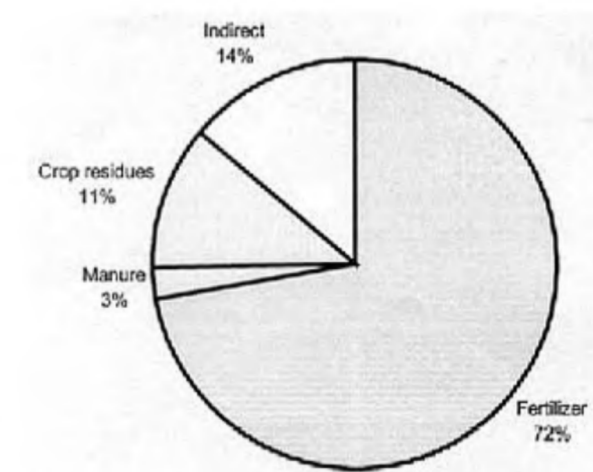


Figure 3. Contribution of different sources towards total nitrous oxide emission.

Table 4. Methane and nitrous oxide emissions from agriculture and their global warming potential

	CO ₂ (Tg)	CO ₂ (% of the world)	CH ₄ (Tg)	CH ₄ (% of the world)	[†] GWP of CH ₄	% GW caused by CO ₂	N ₂ O (Tg)	N ₂ O (% of GWP of N ₂ O the world)	% GW caused by CO ₂
World ³⁸	26400	100	375	100	7875	29.8	8.96	100	2776.7
India ³⁸	585	2.1	17.7	4.7	371.7	1.4	0.26	2.8	79.1
World agriculture ¹	—	—	167.5	44.7	3517.5	13.3	3.5	39.1	1085.0
Indian agriculture ³⁸	—	—	11.8	3.2	223.4	0.85	0.24	2.7	75.3
Agricultural soil [†]	—	—	2.9	0.77	60.9	0.23	0.08	0.88	24.5

[†]Current estimates.[†]CO₂ equivalents are based on GWP of 1 for CO₂, 21 for CH₄ and 310 for N₂O.

Conclusion

This study has shown that the contribution of Indian agricultural soil to greenhouse gas emissions and its GWP is small compared to earlier estimates. Emission of methane as well as nitrous oxide is several times higher when default emission coefficients given by IPCC are used for calculation. IPCC gives the same coefficients for a particular rice ecosystem irrespective of soil conditions and production system management. Using the IPCC default emission coefficients, the annual methane emission from paddy cultivation was estimated to be 4.1 Tg¹⁸ and annual emission of nitrous oxide from Indian agricultural soil was estimated to be 145 Gg³⁹. Therefore, GWP of Indian agriculture as estimated by the IPCC default values is considerably higher and needs revision. In the present article we have used emission coefficients for methane that are based on specific experiments carried out at various rice-growing regions across the country under different moisture regimes. In case of nitrous oxide, the methodology accounts for emission of nitrous oxide not only from fertilizer application, but also takes into account other sources like crop residue and animal manure incorporation in the soil. The indirect sources of nitrous oxide emission, i.e. fertilizer leached as nitrate and volatilized as ammonia are also accounted for in the present inventory. Accordingly, methane and nitrous oxide from Indian agricultural soils are responsible for only about 0.23 and 0.1% respectively, of the global warming caused by the world's CO₂ emissions. Thus overall greenhouse gas emission from Indian agriculture, especially from the soil is a small fraction of the total world greenhouse gas emission.

- IPCC, *Climate Change (1995): Scientific Technical Report Analysis*, Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change (eds Watson, R. T. *et al.*) Cambridge University Press, Cambridge, 1996, p. 880.
- Bhattacharya, S. and Mitra, A. P., Greenhouse gas emissions in India for the base year 1990. *Global Change*, 1998, **11**, 30–39.
- Rodhe, A. L., A comparison of the contribution of various gases to the greenhouse effect. *Science*, 1990, **248**, 1217–1219.
- Battle, M., *et al.* Atmospheric gas concentrations over the past century measured in air from firm at the south pole. *Nature*, 1996, **383**, 231–235.
- Prinn, R. D. *et al.*, Atmospheric emissions and trends of nitrous oxide deduced from 10 years of ALE–GAGE data. *J. Geophys. Res.*, 1990, **95**, 18369–18385.
- Pathak, H., Emissions of nitrous oxide from soils. *Curr. Sci.*, 1999, **77**, 359–369.
- Mosier, A. R., Duxbury, J. M., Freney, J. R., Heinemeyer, O. and Minami, K., Assessing and mitigating N₂O emissions from agricultural soils. *Climatic Change*, 1998, **40**, 7–38.
- Aulakh, M. S., Khera, T. S., Doran, J. W. and Bronson, K. F., Denitrification, N₂O and CO₂ fluxes in rice-wheat cropping system as affected by crop residues, fertilizer N and legume green manure. *Biol. Fertil. Soils*, 2002, **34**, 375–389.
- Sinha, S. K., Global methane emission from rice paddies: Excellent methodology but poor extrapolation. *Curr. Sci.*, 1993, **68**, 643–646.
- OCED/OECD (1991): Estimation of greenhouse gas emissions and sinks. Final report from OECD experts meeting prepared for IPCC, 18–21 February 1991.
- Inter-Governmental Panel on Climate Change, *IPCC Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*, Cambridge University Press, New York, 1996.
- Fertilizer Statistics (1995–96)*, Fertilizer Association of India, New Delhi.
- Pathak, H., Bhatia, A., Prasad, S. and Singh, J., Final report on reduction of uncertainties in methane and nitrous oxide emission from agricultural soils, submitted to Winrock International India on behalf of the Ministry of Environment and Forest, Govt. of India, 2003.
- Pathak, H., Shiv Prasad, Bhatia, A., Singh, S., Kumar, S., Jain, M. C. and Kumar, U., Emission of methane from rice wheat systems of Indo-Gangetic plains of India. *Agric. Ecosyst. Environ.*, 2003, **97**, 309–316.
- Jain, M. C. *et al.*, Methane emissions from irrigated rice fields in Northern India (New Delhi). *Nutr. Cycl. Agroecosyst.*, 2000, **58**, 75–83.
- Singh, J. S., Raghubanshi, A. S., Reddy, V. S., Singh, S. and Kashyap, A. K., Methane flux from irrigated paddy and dryland rice fields, and from seasonally dry tropical forest and savanna soils of India. *Soil Biol. Biochem.*, 1998, **30**, 135–139.
- Adhya, T. K., Bharti, K., Mohanty, S. R., Ramakrishnan, B., Rao, V. R., Sethunathan, N. and Wassmann, R., *Nutr. Cycl. Agroecosyst.*, 2000, **58**, 95–106.
- Mitra, A. P., Methane budget estimates from rice fields based on data available up to 1995. *Global Change*, 1996, **10**, 8–19.
- Rath, A. K., Mohanty, S. R., Mishra, S., Kumaraswamy, S., Ramakrishnan, B. and Sethunathan, N., Methane production in unamended and rice-straw-amended soil at different moisture levels. *Biol. Fertil. Soils*, 1999, **28**, 145–149.

20. Barauh, K. K., Project report of Department of Science and Technology funded project on methane emission from rice fields in different agro-climatic zones of Assam, 2002.
21. Chakraborty, D., Ph D thesis, Bidhan Chand Krishi Viswavidyalaya, Kalyani, 2003.
22. Parashar, D. C., Kulshreshtha, U. C. and Sharma, C., Anthropogenic emissions of NO_x , NH_3 and N_2O in India. *Nutr. Cycl. Agroecost.*, 1998, **52**, 255–259.
23. Aggarwal, R. K. and Kaul, P., Loss of nitrogen as ammonia volatilization from urea on loamy sand soil of Jodhpur. *Ann. Arid Zone*, 1978, **17**, 242–245.
24. Sarkar, M. C., Banerjee, N. K., Rana, D. S. and Uppal, K. S., Field measurements of ammonia volatilization losses of N from urea applied to wheat. *Fert. News*, 1991, **33**, 25–29.
25. Planning Commission of India, Agro-climatic regional planning: recent development. ARPU Paper No. 10, Agro-climatic Regional Planning Unit, Ahmedabad, 1998, p. 220.
26. Gaur, A. C., In *Bulky Organic Manures and Crop Residues* (ed. Tandon, H. L. S.), FDCO, New Delhi, 1995.
27. Chawla, O. P. Use of other inputs. In *Advances in Biogas Technology*, ICAR, New Delhi, 1986, p. 77.
28. Subrian, P., Annadurai, K. and Palaniappan, S. P. (eds), *Agriculture Facts and Figures*, Kalyani Publishers, New Delhi, 2000, pp. 133–134.
29. TERI, *The Energy Research Institute – Energy Data Directory and Year Book*, 2000–01.
30. Bandyopadhyay, S. K. *et al.*, Estimation and Agro-technical Description of Production Systems. In *Land Use Analysis and Planning for Sustainable Food Security: With an Illustration for the State of Haryana, India*, ICAR, New Delhi and IIRI, Philippines, 2001, p. 85.
31. Brady, N. C., *The Nature and Properties of Soils*, Macmillan Publishing Co., 1984, 9th edn, p. 750.
32. Klemetsson, L. A., Klemetsson, K., Escala, M. and Kulmala, A., Inventory of N_2O emission from farmed European peatlands. In *Approaches to Greenhouse Gas Inventories of Biogenic Sources in Agriculture* (eds Freibauer, A. and Kaltschmitt, M.), Proceedings of the Workshop at Lokeberg, Sweden, 9–10 July 1998, pp. 79–91.
33. Kumar, U., Jain, M. C., Kumar S., Pathak, H. and Majumdar, D., Effects of moisture levels and nitrification inhibitors on N_2O emission from a fertilized alluvial clay loam soil. *Curr. Sci.*, 2000, **79**, 224–228.
34. Majumdar, D., Kumar, S., Pathak, H., Jain, M. C. and Kumar, U., Reducing nitrous oxide emission from rice field with nitrification inhibitors. *Agric. Ecosyst. Environ.*, 2000, **81**, 163–169.
35. Pathak, H., Bhatia, A., Prasad, S., Jain, M. C., Kumar, S., Singh, S. and Kumar, U., Emission of nitrous oxide from soil in rice-wheat systems of Indo-Gangetic plains of India. *Environ. Monit. Assess.*, 2002, **77**, 163–178.
36. Singh, B., Singh, Y., Khind, C. S. and Meelu, O. P., Leaching losses of urea-N applied to permeable soils under lowland. *Fert. Res.*, 1991, **28**, 179–184.
37. Patel, S. K., Panda, B. and Mohanty S. K., Relative ammonia loss from urea based fertilizers applied to rice under different hydrological situations. *Fert. Res.*, 1989, **19**, 113–119.
38. ALGAS, National report on Asia least cost greenhouse gas abatement strategy, Ministry of Environment and Forest, Government of India, New Delhi, 1998.
39. Aggarwal, P. K., Pathak, H., Bhatia, A. and Kumar, S., Final report on inventory of nitrous oxide emission from agricultural soils, submitted to Winrock International India on behalf of Ministry of Environment and Forest, Govt. of India, 2003.

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