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Regional and sectoral assessment of greenhouse gas emissions in India

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Abstract

In this paper the authors have estimated for 1990 and 1995 the inventory of greenhouse gases CO_2, CH_4 and N_2O for India at a national and sub-regional district level. The district level estimates are important for improving the national inventories as well as for developing sound mitigation strategies at manageable smaller scales. Our estimates indicate that the total CO_2, CH_4 and N_2O emissions from India were 592.5, 17, 0.2 and 778, 18, 0.3 Tg in 1990 and 1995, respectively. The compounded annual growth rate (CAGR) of these gases over this period were 6.3, 1.2 and 3.3%, respectively. The districts have been ranked according to their order of emissions and the relatively large emitters are termed as hotspots. A direct correlation between coal consumption and districts with high CO_2 emission was observed. CO_2 emission from the largest 10% emitters increased by 8.1% in 1995 with respect to 1990 and emissions from rest of the districts decreased over the same period, thereby indicating a skewed primary energy consumption pattern for the country. Livestock followed by rice cultivation were the dominant CH_4 emitting sources. The waste sector though a large CH_4 emitter in the developed countries, only contributed about 10% the total CH_4 emission from all sources as most of the waste generated in India is allowed to decompose aerobically. N_2O emissions from the use of nitrogen fertilizer were maximum in both the years (more than 60% of the total N_2O). High emission intensities, in terms of CO_2 equivalent, are in districts of Gangetic plains, delta areas, and the southern part of the country. These overlap with districts with large coal mines, mega power plants, intensive paddy cultivation and high fertilizer use. The study indicates that the 25 highest emitting districts account for more than 37% of all India CO_2 equivalent GHG emissions. Electric power generation has emerged as the dominant source of GHG emissions, followed by emissions from steel and cement plants. It is therefore suggested, to target for GHG mitigation, the 40 largest coal-based thermal plants, five largest steel plants and 15 largest cement plants in India as the first step.

Keywords: Greenhouse gas (GHG); Carbon dioxide; Methane; Nitrous oxide; CO_2 equivalent; Disaggregated emissions; Mitigation flexibility.

1. Introduction

The national greenhouse gas (GHG) emission inventories, besides meeting the communications requirements of the United Nations Framework Convention on Climate Change (UNFCCC), serve as benchmarks for assessing mitigation policies. While estimates at the national scale provide general guidelines for assessing mitigation alternatives, significant regional variability exists within the country. Estimates of source magnitudes on a regional site-specific scale allow more focused and efficient mitigation strategies by exploiting this variability. In addition, since emissions from some sources are influenced by climate variables, more accurate

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region-specific models should result in improved national estimates. A regional inventory is also relatively easy to update periodically, which is a critical step in assessing progress towards achieving the goals of reduction/stabilization of the spiralling GHG emissions.

For assessing country level and global emissions, gridded inventories by source have been reported by several authors (Lerner et al., 1988; Andreae et al, 1996; Subak et al., 1993; Marland et al., 1994; Olivier et al., 1993, 1997, Visschedijk et al., 1999). In India, though it is easy to estimate the emissions from large point sources such as thermal power and steel plants, it is very difficult to assess the same from dispersed sources such as from vehicular population by type, animals by type, as well as emissions from biomass used as fuel, etc. Districts can reasonably capture the diversity of Indian emission patterns due to different resources use and agriculture practices. Above 80% of Indian districts are smaller than $1^\circ \times 1^\circ$ resolution, with 60% being smaller than even $\frac{1}{2} \times \frac{1}{2}^\circ$. The largest district is about $2 \times 2^\circ$ size but the larger districts have much lower population densities and consequently lower emissions as well. District level emissions thus represent a very finely gridded inventory information by international standards. Moreover, districts in India have well-established administrative and institutional mechanisms which will be useful for implementing and monitoring mitigation measures. This paper, therefore, makes an attempt to estimate the national GHG emissions and their sectoral contributions by estimating these values for the 466 districts in the country. The district level emissions data have been linked to the district topology available with the Space Application Center, India. These data were then converted into per unit area for each of the 466 districts and plotted, except for the state of Jammu and Kashmir where state level average per unit emissions have been plotted.

The whole exercise has enabled us to rank the 466 Indian districts in descending order of their individual CO_2, CH_4 and N_2O emissions for each source category for 1990 and 1995. The largest 25-emitter districts in each source category have been termed as hot spot districts. Such a study is useful for the policy makers to identify the specific regions and sources that require attention. The district level analysis is also expected to lead to the formation of more accurate gridded GHG inventories for the country. Energy, industry, transport, agriculture and waste disposal sectors have been considered for emission estimates. Diverse data sources have been made use of and cross verifications have been made as much as possible. Most of these are published documents of the government of India. Wherever year-specific data were not available, growth trends of the previous years were applied. Mainly emission coefficient relevant to the Indian conditions have been used and wherever not available, appropriate IPCC default emission factors applied.

2. Methodology and emission factors

Sources considered for emission estimates include combustion of coal (MoC, 1993, 1998), oil products and natural gas combustion, oil and natural gas extraction/refining/processing (MoPNG, 1992, 1996; CMIE, 1996; IPD, 1996; SAKET, 1998; TEDDY, 1998), coal mining (DGMS, 1997), transport – road and rail, electric power generation (CMIE, 1996, IBC, 1996; CEA, 1997; TEDDY, 1997; CMIE, 1998a), steel (CII, 1996; SAIL, 1996), biomass burning (CMIE, 1995; FAI, 1996, 1997; Ravindranath et. al., 1995; TERI, 1997). The industrial sector emission sources include manufacturing of cement (ICRA, 1995; CIER, 1998), brick (Shukla, 1994; CMIE, 1996) and nitric acid (GoI, 1989; CMIE, 1998b). The agriculture sector includes GHG emissions from rice cultivation (CMIE, 1995, 1998c; FAI, 1996), livestock-related emissions (CMIE, 1995; ALGAS, 1998; MoA, 1998), use of nitrogen fertilizers (CMIE, 1995; FAI, 1995, 1996, 1997) and burning of crop residue (TERI, 1997). Lastly, the waste sector includes emissions from the landfills (TEDDY, 1997, 1998) and wastewater disposal (CPCB, 1997). The sector identification of emission source categories is important since emission coefficients for non-CO_2 gases are highly sector specific.

The basic methodology to estimate the total emissions of a particular gas from the country uses following formula, which is in line with the IPCC methodology (1996):

$$\text{Total emissions} = \sum_{\text{Districts}} \sum_{\text{Source}} \sum_{\text{Sectors}} [\text{activity level} * \text{emission coefficient}].$$

Table 1 lists the emission factors for CO_2 emission estimates. The emission factors are based on the carbon content of fuels. The net calorific values (NCV) are specific to Indian fuels. Coking coal is mainly used by the iron

Table 1
CO_2 emission coefficients[a]

Source categories	Emission coefficients	
	ton ton^{-1}	Gg PJ^{-1}
Coal combustion	1.76	94.7
Coking coal combustion (steel sector)	2.05	108.9
High-speed diesel combustion	3.18	74.0
Motor spirit combustion	3.16	68.8
Kerosene combustion	2.94	68.2
Light diesel oil combustion	3.18	74.0
Fuel oil combustion	3.13	78.0
Naphtha combustion	2.57	57.0
Low sulfur heavy stock combustion	3.13	78.0
Aviation turbine fuel combustion	2.94	68.2
Natural gas combustion	1.98[b]	52.6
Cement production	0.5	—

[a] ALGAS (1998).
[b] Ton/Billion Cubic Meter.

Table 2
Methane emission coefficients

(a) *Enteric fermentation in animals* (Mitra, 1992)

Source category	Methane emissions from different age groups (kg head^{-1} yr^{-1})		
	Up to 12 months	12–30 months	> 30 months
Cattle	8.5	16.3	23.2
Buffalo	9.1	20.3	25.8
Sheep	4.6	5.8	5.8
Goat	4.6	5.8	5.8
Others	6.08	6.08	6.08

(b) *Livestock manure management* (IPCC, 1996)

Source category	Methane emission (kg head^{-1} yr^{-1})
Cattle (dairy)	5.5
Cattle (non –dairy)	2
Buffalo	4.9
Sheep	0.16
Goat	0.17
Others	1

(c) *Biomass burning* (IPCC, 1996)

Source category	Methane emissions (kg kg^{-1})
Fuel wood consumption	0.006
Dung cake consumption	0.008
Charcoal consumption	0.001
Charcoal production[a]	0.2

(d) *Paddy cultivation* (Parashar et al., 1997)

Type of water regime				Methane emissions (ton km^2)
Upland	—		—	
Low land	Rainfed	Flood prone		19.0 ± 6.0
		Drought prone		6.0 ± 1.5
	Irrigated	Continuously flooded		25.1 ± 8.4
		Intermittently flooded	Single aeration	6.0 ± 1.5
			Multiple aeration	1.36 ± 0.57
	Deep water	Water depth 50–100 cm		19.0 ± 6.0

(e) *Coal production* (Mitra, 1992)

Mine type	Methane emissions (ton ton^{-1})
Open cast	0.00073
Degree I	0.00073
Degree II	0.00743
Degree III	0.01579

(f) *Municipal solid waste disposal (only urban population considered) generates 0.045 kg methane per kg waste* (IPCC, 1996)

Year	Methane (kg head^{-1} yr^{-1})
1990	4.9275
1995	5.7488

(*continued on next page*)

Table 2 (*continued*)

(g) *Municipal waste water disposal:*
Generates 0.48 kg methane per urban head per year

(h) *Industrial waste water disposal:*
Generates 1.46 kg methane per urban head per year

(i) *Oil and natural gas* (IPCC, 1996)

Source categories	Emission coefficient (ton/MT)
Oil production	13.04
Natural gas production[b]	1730.6
Oil refining	3.91
Natural gas processing, transport & distribution[b]	4439.27

(j) *Burning of agricultural crop residue:* (IPCC, 1996)
0.864 kg methane per ton of agricultural crop residue

[a]On the basis of charcoal consumed (6 kg charcoal produced per kg charcoal consumption).
[b]In tons of methane per billion cubic meter of gas.

Table 3
N_2O emission coefficients (kg per ton of source category)[a]

Source categories	N_2O Emission coefficients (kg/ton^{-1})
Coal combustion	0.03
Oil products consumption	0.08
Natural gas consumption	0.003
Burning of agriculture residue	0.25
Use of nitrogen fertilizers	17.68
Livestock excretions (Non-dairy cattle)	0.04[b]
Livestock excretions (Swine)	0.25[b]
Biological N_2 fixations	0.05
Nitric acid production	6

[a]All IPCC (1996), except nitric acid production (ALGAS, 1998).
[b]In Kg per head of livestock.

and steel industry and has a higher NCV and therefore a higher emission coefficient (2.05 CO_2 per ton of coal consumed), while all the other coal have an average CO_2 emission coefficient of 1.76 ton CO_2 per ton of coal consumed (ALGAS, 1998). CO_2 emission from biomass burning in energy and agriculture sector has not been considered in this paper as most of the biomass are produced sustainably, in which case the actual net emissions are zero (IPCC, 1996).

The IPCC tier-II methodology (1996) has been adopted for estimating methane emissions from enteric fermentation in animals and Tier-I for emissions from animal manure management. The methodology for enteric fermentation takes into account age distribution and hence the weight of the animals. The Indian domestic livestock population increased from 456 million in 1987 to 467 million in 1992 and its expected to increase to 625 millions by 2020 (ALGAS, 1998). The emission factors used for each age group are appropriate to the Indian conditions (ALGAS, 1998). CH_4 emission from animals is influenced by the factors such as the breed of animal reared and the type of feed provided to it. Domestic animals in India are mostly raised in rural areas, in small holdings, and the animals have relatively low body weights and feed intake compared to their European or American counterparts and therefore emit less methane (Mitra, 1992b; Singh and Mohini, 1996). In fact, the feed availability and consumptions are low during summer and winter periods and a large proportion of bovine stock starve at these times of the year. Almost 50% of the dung produced is converted to dungcakes (IPCC, 1996) used as fuel and the rest is assumed to decompose anaerobically leading to CH_4 emission.

Average default IPCC (1996) emission factors have been applied to calculate the amount of non-CO_2 greenhouse gases emitted from crop residues burnt in India. They are burnt mainly to clear the remaining straw and stubble after the harvest in order to prepare the field for the next cropping cycle. The main crop residue that contributes maximum to the net emissions of non-CO_2 emissions in India is wheat followed by rice straw.

Methane emissions from disposal and treatment of industrial and municipal solid waste (MSW) are not a prominent source in India, except in large urban centers. About 30.3 Tg solid waste was produced in India in 1995. As per the IPCC guidelines for developing countries, we have considered solid waste generation only from urban population as the rural waste is not systematically collected and therefore not anaerobically decomposed. The average per capita solid waste generation has

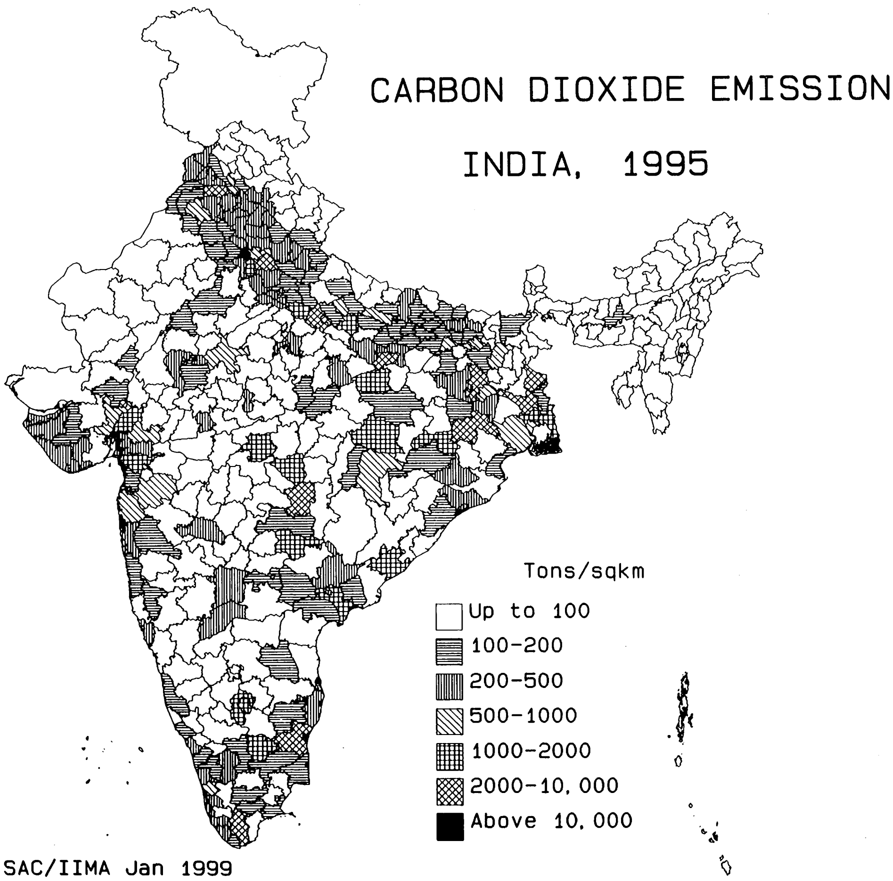

Fig. 1. CO_2 emissions from Indian districts in 1995.

been taken as 300 and 350 g for 1990 and 1995, respectively. Moreover we have used the specific waste generation estimates for 30 big cities (TEDDY, 1999). CH_4 emission from the industrial wastewater are based on Central Pollution Control Board's published data (CPCB, 1997) on generation of wastewater from big cities. The amount of waste water generated in India in the domestic sector was 135 litres per capita per day and industrial waste water produced for the same period was around 8% of this.

The paddy area of 42.32 Mha in India, being the largest in Asia, is of special concern as it is double and at times triple cropped in a year to increase production. For estimating methane emitted from this source, the methodology documented in the revised IPCC guidelines (IPCC, 1996) has been adopted. The emission factors used are for upland, continuously flooded, intermittently flooded and deep-water eco-systems. The intermittently flooded have been sub-classified into single- and multiple-aerated, and deep-water into fields with water level between 50–100 cm and 100–150 cm. The emission factors used in each of the water regimes are based on actual measurement carried out in the country (Parashar et al., 1997). Though cultivar type, fertilizer used, and organic amendment (Baruah et al., 1997; Parashar et al., 1991; Ramakrishnan et al., 1995; Rath et al., 1998) also play a role in methane emission but flooding of the fields whether continuous or intermittent create anaerobic conditions leading to emission of methane from this source. Therefore wetness of the soil and hence the water regimes are the overriding factor in methane emission from paddy fields. Recent methane Asia campaign including India (Gupta and Mitra, 1999) has revealed that for India, average enhancement factors of methane emission factors for organically amended soils submerged in water vary from 2 (for low soil organic carbon <0.7) to 4 (for high soil organic carbon >0.7), this includes observations from continuously flooded as well as intermittently flooded fields.

In case of CH_4 emission from coal mining and handling activities, coal production has been multiplied with the CH_4 emission factor [the conversion factor of $1.49\times10^9\,m^3$ as equivalent to 1 Tg of CH_4] to arrive at the total CH_4 emission from this source (Mitra, 1992a, b;

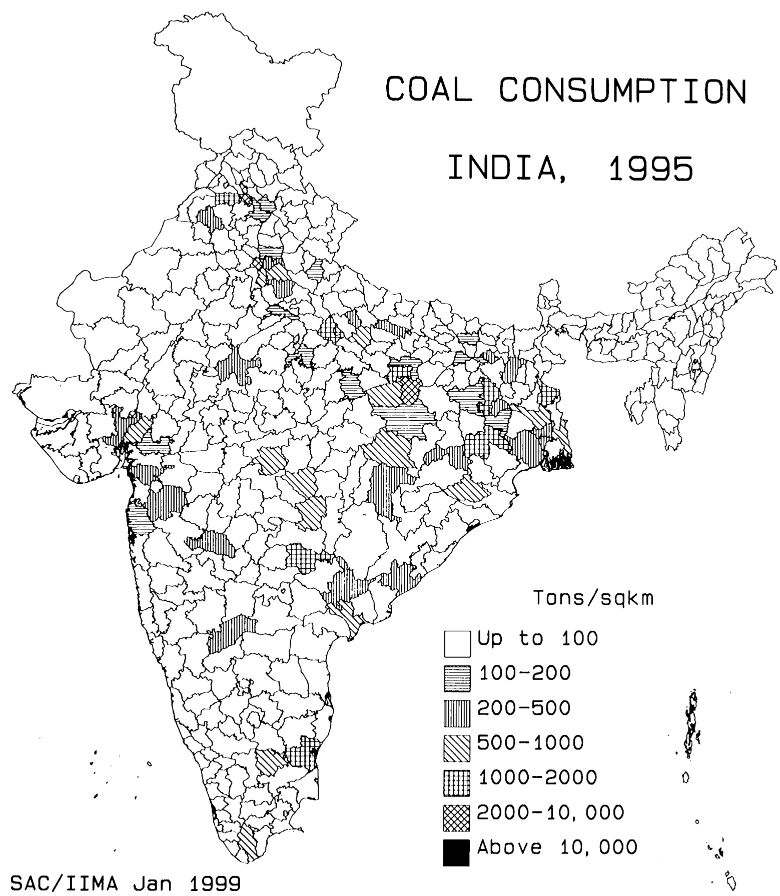

Fig. 2. Distribution of coal consumption in India.

Banerjee, 1994). In India monitoring of all coal mines is mandatory under the auspices of Directorate General of Mine Safety (DGMS, 1967) and all the states have mines identified and classified under various degree of gassiness degree I, II, and III instead of sizes. Degree I seam represents methane emission rate $<1\,m^3/t$, degree II seam represents emission rate between $1–10\,m^3/t$ and degree III seam represents emission rates $>10\,m^3/t$ (DGMS, 1997). Table 2 lists the methane emission coefficients used for this study.

In this study N_2O emissions from the agricultural system have been estimated from burning of fossil fuel, crop residue burnt, use of nitrogen fertilizers, livestock, biological N_2 fixation, indirect emission from atmospheric depositing of NH_3 and NO_x. N_2O emission estimates additionally have been made from coal, oil products and natural gas combustion and from industrial activities namely production of nitric acid. IPCC (1996) default emission factors have been used except for emissions from nitric acid production. The emission factor for nitric acid, used mainly as feedstock in fertilizer production, depends on technology and operating conditions. An emission factor of 6 Kg of N_2O for per ton of nitric acid production is considered appropriate for Indian conditions (ALGAS, 1998). Table 3 lists the emission coefficients used for nitrous oxide emission estimates.

3. Inventory assessment

3.1. CO_2 emissions

The total CO_2 emissions from the country due to anthropogenic activities have increased from 592 Tg in 1990 to 778 Tg in 1995. Fig. 1 depicts the CO_2 emissions from Indian districts in 1995. Dark spots indicate high emission areas. Thermal power plants (high coal consumption), large cities (high oil product consumption) and industrial towns constitute most of these dark spots. Coal is the mainstay of the Indian energy sector and contributes almost 73% of total CO_2 emissions. Coal consumption varies across regions (Fig. 2) and CO_2 emissions reflect this pattern. Uttar Pradesh (UP),

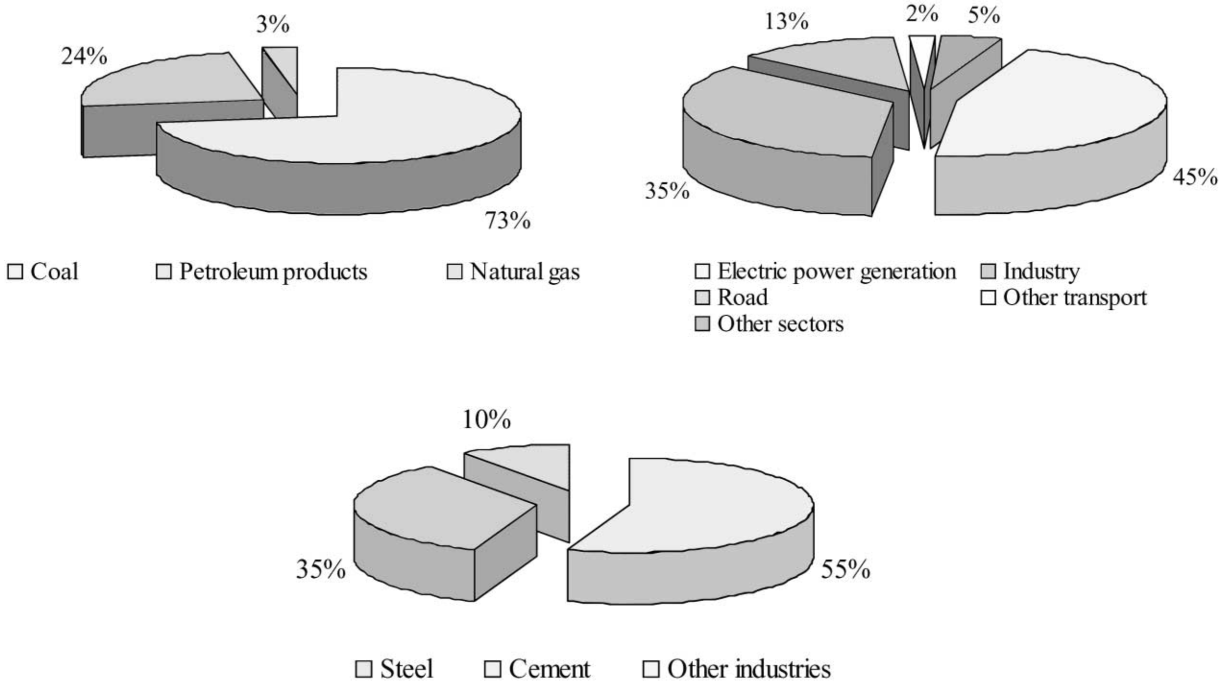

Fig. 3. (a) Fuel share of CO_2 emissions in 1995. (b) Sector distribution of CO_2 emissions in 1995. (c) Share of industrial CO_2 emissions in 1995.

Table 4
Distribution of CO_2 emission from Indian districts

No. of largest emitter districts	Percentage of total emission		Percentage CAGR
	1990	1995	
1–5	16.7	16.1	10.3
1–15	35.4	36.7	8.7
1–25	46.8	50.3	8
1–47	62.7	67.4	8
1–233	93	95.3	6.1
All India	100	100	5.6

Madhya Pradesh (MP), Andhra Pradesh (AP), Maharashtra and Tamil Nadu (TN) states are the largest coal-consuming states. Their CO_2 emission were also in the same order except for Maharashtra which was the fourth largest state in overall coal consumption in 1995 but third in total CO_2 emissions. This was due to its high oil-products-related CO_2 emission as well (15.3% of all India). Greater Mumbai and Thane (Mumbai suburb) districts of Maharashtra together accounted for 6.6% of all India oil products consumption in 1995.

Figs. 3a–c show the composition of fuel, sectoral and industrial sub-sector level CO_2 emissions in 1995 on a national scale. These indicate that electric power generation contributes almost half of India's CO_2 emissions and majority of it comes from coal and lignite consumption. It is interesting to note that CO_2 emission due to coal consumption in the electric power generation sector has increased by 60% and in the industrial sector by 19% between 1990 and 1995. However, coal-related CO_2 emission from the transport sector (namely, railways) has decreased from 10 to 0.5 Tg mainly due to phasing out of steam traction in the railway sector. But the overall CO_2 emission from railway has increased by 18% from 1990 to 1995 due to almost 50%.

There were 12 districts emitting more than 10 Tg CO_2 each in 1990 and their number almost doubled in next five years. These top emitters accounted for 30% of total national emissions in 1990 and 35% in 1995. Ten percent of total Indian districts contributed 67% of India's total CO_2 emissions in 1995 indicating a high concentration of emissions (Table 4). The national average CO_2 emissions per district rose to 1.67 MT from 1.27 MT during 1990–1995. The standard deviation of district level CO_2 emissions has increased by 38%. These indicate that there is a clear upward shift in CO_2 emissions from individual districts. However, there appears to be a clear distinction in emission growth patterns from hotspot districts and other districts. While the former are growing in leaps and bounds, the cumulative emissions from the latter are almost stagnant. The largest 10% emitters (as per 1995 emissions) increased their emissions by

Table 5
Largest CO_2 emitter districts in India in 1995 (Tg)

District	Total CO_2 (Gg)		Emission per capita (T)		(%) CAGR (1990–1995)
	1990	1995	1990	1995	
Bilaspur (MP)	26.7	30.0	7.04	7.24	2.4
Sonbhadra (UP)	20.5	29.7	19.04	25.02	7.7
South Arcot (TN)	1.2	23.0	0.25	4.42	81.3
Giridih (Bih)	18.5	21.2	8.31	8.59	2.8
Chandrapur (Mah)	9.9	21.2	5.61	11.05	16.3
Raipur (MP)	15.8	20.1	4.05	4.70	4.8
Delhi	17.4	18.6	1.84	1.62	1.3
All India	592	778	0.7	0.84	5.6

Table 6
Largest CO_2 emitting districts in different sectors in 1995

Sector	Largest	Second	Third	Fourth	Fifth
Electric power	Sonbhadra	Bilaspur	South Arcot	Karimnagar	Chandrapur
Transport	Delhi	Greater Mumbai	Bangalore	Pune	Thane
Steel	Raipur	Giridh	Visakhapatnam	Bardhaman	Purbi Singhbhum
Cement	Gulbarga	Satna	Chandrapur	Chittaurgarh	Raipur
Brick	Kanpur	Puri	Calcutta	Cuttak	Lucknow
Other industries	Dhenkanal	Mirzapur	Bilaspur	Greater Mumbai	Delhi
Overall	Bilaspur	Sonbhadra	South Arcot	Giridh	Chandrapur

one-third during 1990–1995 showing an annual growth rate of 8.1%. These patterns indicate skewed primary energy consumption patterns for the country.

Table 5 captures the highest CO_2 emitter districts in India as per 1995 levels. South Arcot district was the fourth CO_2 emitting districts in 1995 but was at 95th place in 1990. The large increase in its emissions was due to commissioning of Neyveli Thermal power plant but its annual growth rate will now stabilize around 4–5%. Delhi slipped four places since 1990 to occupy seventh place in 1995. This is due to the reduced coal consumption, 5.42 Tg in 1990 to 5.23 Tg in 1995. Its not that Delhi became any cleaner in the interim period but other districts became much worse. The capital districts of various states have shown an increasing trend in their CO_2 emissions with their cumulative emissions showing an upward shift by 14% in these five years. Oil product consumption is the main contributor for almost all of these. Coal is only a marginal component except in Delhi, Chennai, Gandhinagar, Calcutta, Cuttak, Lucknow and Patna.

All India per capita CO_2 emission were 0.7 tons in 1990 and increased to 0.84 tons in 1995. Table 6 gives the five largest CO_2 emitters for important sectors in 1995. It is apparent that emissions from electric power generation dominate the overall hotspot CO_2 emitters of the country. In electric power generation, the ranking of the top five emitter districts have changed over the period 1990–1995. Bilaspur, Sonbhadra, Mirzapur, Karimnagar and Nagpur occupied the top five positions in 1990. These changed to Bilaspur, Sonbhadra, South Arcot, Karimnagar and Chandrapur in 1995 due to higher growth rates of coal-based thermal power CO_2 emissions from the new entrants.

3.2. Methane emissions

The total amount of methane emitted from the country increased from 17 Tg in 1990 to 18 Tg in 1995. Fig. 4 gives the spatial distribution of CH_4 emissions in the country at a district level. Dark spots in this figure indicate the most intense emitters in India. The national methane emission profile is agriculture dominant and is evenly spread across the country with the Gangetic plains and delta areas, coastal Maharashtra, Tamil Nadu and Andhra Pradesh states contributing most.

Fig. 5 gives the sectoral shares of methane emissions in 1995. Livestock emissions are the major source of methane in India (45%) followed by emissions from rice

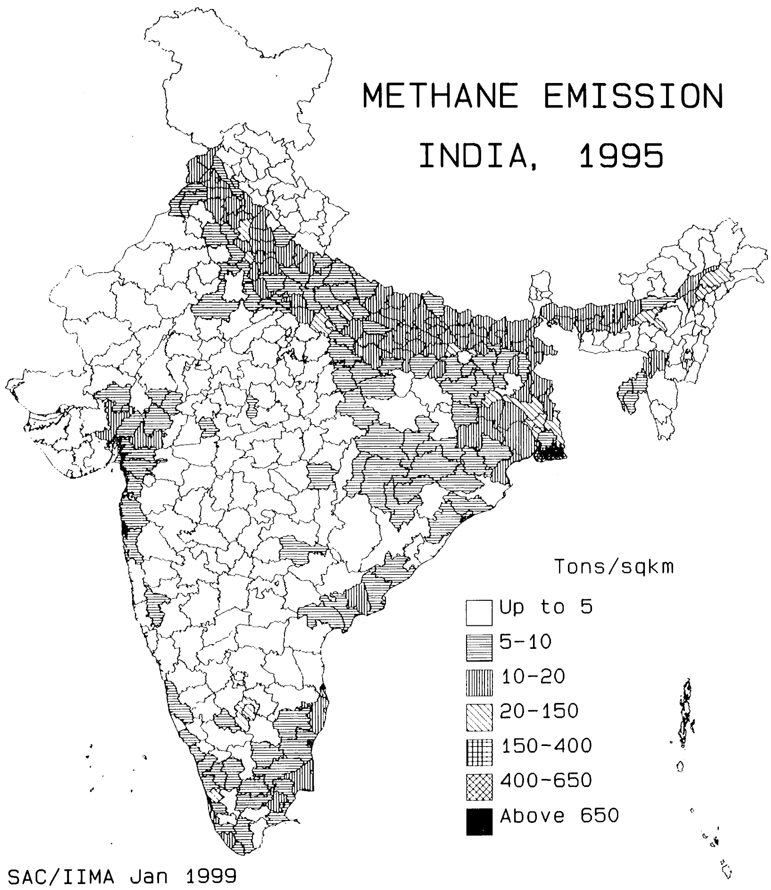

Fig. 4. CH_4 emission from Indian districts in 1995.

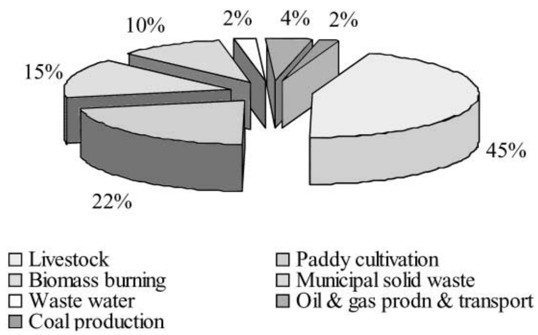

Fig. 5. Sector distribution of methane emissions (1995).

cultivation (22%), biomass burning (15%), municipal waste disposal (10%), coal mining (2%), fugitive emissions from oil and natural gas production and handling (4%) and waste water disposal (2%).

The five largest methane-emitting districts are indicated in Table 7. The largest emitter Greater Mumbai contributes almost 2.7% of the total CH_4 emitted in the country. Its main methane-emitting sources are wastes and natural gas production. This is different from other hotspot methane-emitting districts in Table 7, which have a dominance in CH_4 emission from livestock population and paddy cultivation. Per capita methane emission analysis indicates Greater Mumbai as the highest emitter and two times more than the national average. The average CH_4 emissions from majority of Indian districts are low (Table 8). The average methane emissions per district were 0.04 Tg as compared to 1.67 Tg for CO_2 in 1995. Even after weighing the methane emissions by a factor of 21 (methane's CO_2 equivalent global warming potential), the average CH_4 emissions are half of average CO_2 emissions for Indian districts. This indicates a dominance of GHG emissions from energy use over those from agriculture sector in India. The all India annual growth rate of methane emissions between 1990 and 1995 was 1.1%, much lower than that for CO_2 (5.6%). The slower growth rates of CH_4 emissions are due to predominance of agriculture- and livestock-related emissions in methane, which are growing below 2%

Table 7
Methane emission hotspot districts in India (1995)

District	Total emissions (Tg)	Emissions (kg capita^{-1})	Main contributors
Greater Mumbai (Mah)	0.51	47.6	Oil and gas production, MSW
Medinipur (WB)	0.24	26.3	Paddy cultivation, livestock
Bilaspur (MP)	0.17	40.3	Paddy, livestock, coal production
Barddhaman (WB)	0.16	24.6	Paddy, livestock, coal production
Raipur (MP)	0.15	35.8	Paddy, livestock, biomass burning
All India	18	20.04	Livestock, paddy cultivation, biomass

Table 8
Distribution of CH_4 emissions from Indian districts

No. of largest emitter districts	% of total emissions		(%) CAGR (1990–1995)
	1990	1995	
1–5	6.71	6.63	0.95
1–15	13.3	12.98	1.04
1–25	18.5	18.04	1.17
1–47	27.88	27.74	1.01
1–233	77.38	77.59	1.27
All India (1–466)	100	100	1.1

per annum. This is also reflected in slower upward shift of districts towards higher emission ranges between 1990 and 1995 (Table 8). This also implies that the highest methane emitter districts in these sectors appear in the overall hotspot districts in India (Table 9).

3.3. Nitrous oxide emissions

Total N_2O emissions from India were 230 Gg in 1990 and 260 Gg in 1995, respectively, indicating a marginal growth. The spatial distribution of N_2O emission at district level is shown in Fig. 6. Dark spots indicate the most intense emitters in India. Unlike CO_2 emissions, these dark spots are not centered around the coal-consuming districts. The driving factor here is the use of synthetic fertilizer, which depends upon the area cultivated and local harvesting practices. India consumed about 8 Tg N fertilizer in 1990 and 9.8 Tg in 1995 with no significant change in the total cultivated area, thus indicating a more intense use of synthetic fertilizers which is a continuing trend (FAI, 1998).

Nitrous oxide sectoral shares indicate that of the total N_2O emissions, 60% is due to use of nitogen fertilizer and about 10% of each from crop residue burning and indirect soil emissions due to NH_3 and NO_x (Fig. 7). In fact, agriculture-related activities account for around 90% of total N_2O emissions. These include use of nitrogen fertilizer, biomass burning, indirect soil emissions and livestock-related emissions. Emissions from agriculture sector are very dispersed and mitigation efforts required will be quite substantial as compared to those for CO_2 and CH_4.

The district level emissions analysis indicates that Moradabad district (UP) was the largest N_2O-emitting district in India in 1995 (Table 10). The N_2O emissions from Indian districts have a more even spread than those for CO_2 and CH_4 due to agriculture dominance which is very well spread over across the country (Table 11). There is a reduction in total number of districts in lower emission ranges (up to 1 Gg/yr) over the period 1990–1995. However there is almost a two-fold increase in districts with emissions above 2 Gg/yr. In fact the district level N_2O emissions have witnessed an upward shift throughout India with emissions from only about 100 districts remaining stagnant during these five years due to increased intensity of synthetic fertilizer use.

Table 12 lists the five largest hotspot districts in India for different sectors. Each category has witnessed a change in top five hotspots between 1990 and 1995. The most significant changes have been observed in N_2O emission due to synthetic fertilizer use (the top two districts in 1995 were not in the top five list in 1990) and livestock excretion (only Medinipur retained its place in top five districts while all other four districts are new in the 1995 list). Seventy to ninety percent of the total N_2O emissions from the hotspots were from the use of synthetic fertilizer, Greater Mumbai being an exception. Its 82% emissions were contributed by production of nitric acid. Indirect emissions due to NH_3 and NO_x contributed around 6% for all these top emitters.

3.4. Aggregate emission analysis

In 1990 the contribution of CO_2 to the total GHG emission from the country is the highest (58%), followed by CH_4 (36%) and N_2O (6%) – see Table 13. A similar pattern is followed in 1995 with CO_2 share increasing to 61% at methane's expense. Indian GHG emissions in terms of CO_2 equivalent were 1016 Tg in 1990 that is

Table 9
Sector hotspot districts for methane emissions in India (1995)

Sectors	Largest	Second	Third	Fourth	Fifth
Agriculture residue burning	Muzaffarnagar	Bijnor	Meerut	Moradabad	Belgaum
Biomass consumption	Cuttak	Medinipur	Puri	Ganjam	South Arcot
Coal production	Dhanbad	Bilaspur	Shahdol	Hazaribag	Dhenkanal
Oil & natural gas related	Greater Mumbai	Bharuch	Vadodara	Dibrugarh	Sibsagar
Livestock	Medinipur	Jaipur	Udaipur	Cuttak	Raipur
Manure management	Medinipur	Cuttak	Raipur	Jaipur	Bilaspur
Paddy cultivation	Medinipur	Raipur	Bilaspur	Barddhaman	Bastar
Municipal solid waste	Delhi	Greater Mumbai	Chennai	Ahmedabad	Bangalore
Waste water	Greater Mumbai	Delhi	Calcutta	Bangalore	Chennai
Overall	Greater Mumbai	Medinipur	Bilaspur	Barddhaman	Raipur

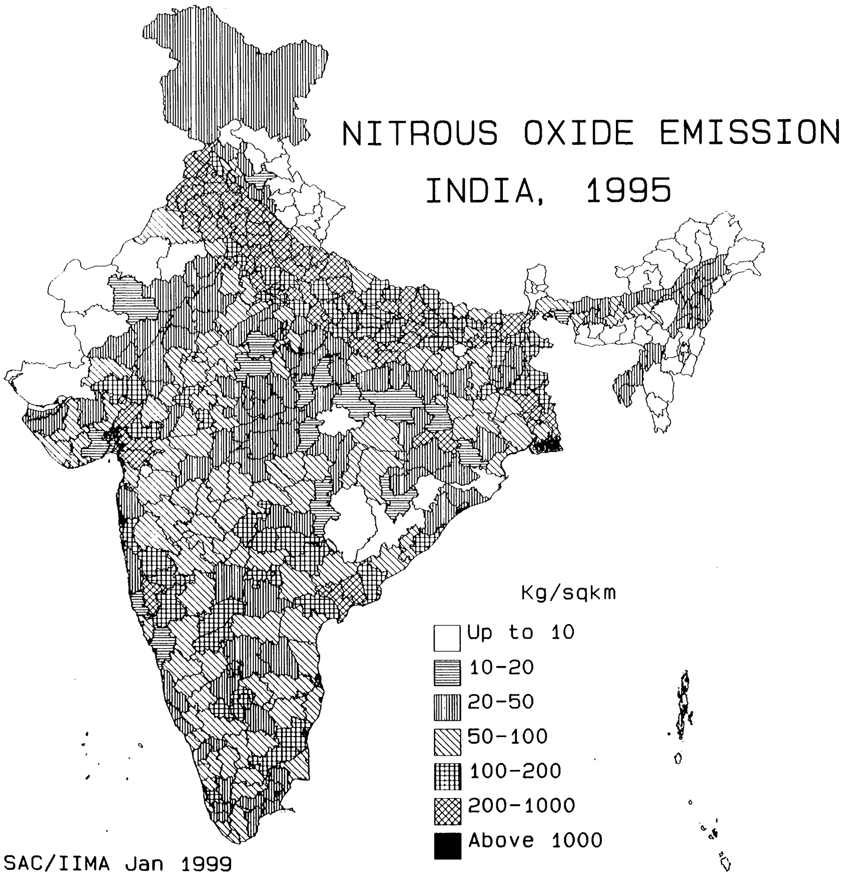

Fig. 6. N_2O emissions from Indian districts in 1995.

only 2.7% of the global GHG emissions due to anthropogenic activities (26400 Tg-CO_2, 375 Tg-CH_4 and 9 Tg-N_2O; Global CO_2 equivalent emissions were 37052 Tg, IPCC, 1996). These ratios have remained almost the same in 1995 (WRI, 1996, 1998). Indian per capita CO_2 equivalent emissions were 1.2 tons as compared to the global average of 6.5 tons/capita in 1990 and the value marginally increased to 1.3 in 1995. At a sub-regional level, 80% of the Indian districts covering almost 3/4th of the total Indian population (Census of

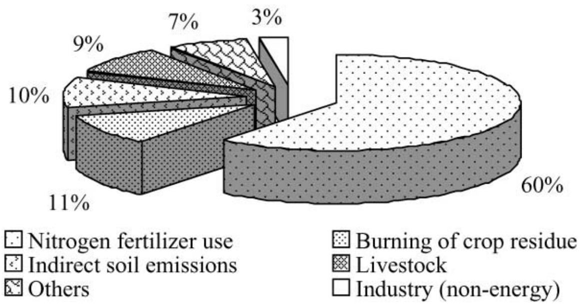

Fig. 7. Sector distribution of nitrous oxide emissions in 1995.

Table 10
N_2O emission hotspot districts in India (1995)

District	Total N_2O (Gg)		(%) CAGR (1990–1995)
	1990	1995	
Moradabad (UP)	2.0	3.1	9.2
Firozpur (Pun)	1.9	2.8	8.1
Muzaffarnagar (UP)	2.1	2.6	4.4
Greater Mumbai (Mah)	2.0	2.4	3.7
West Godavari (AP)	2.3	2.4	1.8
All India N_2O (Gg)	213	251	3.3

Table 11
Distribution of N_2O emissions from Indian districts

No. of largest emitter districts	% of total emissions		(%) CAGR (1990–1995)
	1990	1995	
1–5	5.01	5.29	5.42
1–15	13.75	13.81	4.2
1–25	21.27	20.82	3.88
1–47	34.24	33.6	3.97
1–233	86.11	85.11	3.32
All India (1–466)	100	100	3.33

India, 1992) emit less than 2.5 Tg annual CO_2 equivalent GHG. These districts have low absolute emission levels and also low emission growth trajectories. In contrast the hotspot districts, separately for each gas, are showing high growth rates and the largest 25 hotspots account for more than 37% of all India CO_2 equivalent GHG emissions (Table 14). Therefore there exists a strong regional variability in the Indian GHG emissions.

The total emissions and per area (ton/km^2) emissions present different pictures for the regional distributions. While the former are important for global greenhouse effect, the latter provide a better picture for regional mitigation and impact assessments. One of the most important features that have emerged from this study is the relatively high emission intensity from the Gangetic plains and delta areas. In addition Kerala, coastal Maharashtra, Tamil Nadu and Andhra Pradesh also show higher intensities. These high emission areas overlap with highest coal production and consumption centers also fall in these areas, high paddy cultivation and synthetic fertilizer use. Our analysis also indicates that out of the four metro districts (Delhi, Calcutta, Mumbai and Chennai), Delhi and Mumbai emit much more GHG than the other two. However Chennai district tops the list for per area emission levels for all gases among all the Indian districts in 1995 mainly due to its smaller size (Fig. 8).

4. Mitigation flexibility

The main contributions to Indian GHG emissions are concentrated at about 60 large point sources (40 coal-based power plants, five large steel plants, and 15 cement industries) thus offering a very good opportunity for focusing mitigation efforts (Table 15). A 5% reduction in India's CO_2 equivalent GHG emissions (or 8% reduction in CO_2 emissions) would require a 20% emission reduction from these 60 sources put together. Operational improvements (like heat rate reduction, better excess air control, etc.), better maintenance, reducing transmission and distribution losses in the power sector, etc. would go a long way in mitigating GHG emissions (Guha, 1999). Efficiency improvement measures in other energy-intensive industries like steel, cement, soda ash, caustic soda, fertilizer, etc. would improve productivity while reducing overall GHG emissions. Transport sector GHG emissions are widely dispersed across the country and contribute around 9.5% to India's CO_2 equivalent GHG emissions. Thus GHG mitigation efforts may not be cost effective for transport sector. However measures like improving diesel and gasoline quality and stricter vehicle emission norms will reduce local pollution levels and to a certain extent GHG emissions as well. Agriculture sector emissions, although contributing almost 29% to CO_2 equivalent GHG emissions, are much more widely and evenly dispersed. This sector is mostly unorganized in India and mitigation efforts would be much more difficult. However efforts like adoption of better farming practices for paddy cultivation such as utilization of less water, more productive cultivars, more efficient utilization of synthetic fertilizers, developing better cattle feed, etc. should continue as independent activities to improve agriculture sector productivity.

It may be prudent therefore, to target the 40 largest coal-based thermal plants, five largest steel plants and 15 largest cement plants in India for GHG emissions mitigation as the first step. Efficiency improvement measures

Table 12
Sector hotspot districts for N_2O emissions in India (1995)

Categories	Largest	Second	Third	Fourth	Fifth
Coal consumption	Sonbhadra	Bilaspur	South Arcot	Karim Nagar	Chandrapur
Oil consumption	Greater Mumbai	Delhi	Kheda	Thane	Raigarh
Crop residue	Muzaffarnagar	Bijnor	Meerut	Moradabad	Belgaum
Biological N_2 fixation	Muzaffarnagar	Bijnor	Meerut	Moradabad	Belgaum
Natural gas	Bulandshahr	Etawah	Surat	Kota	Bharuch
Synthetic fertilizer	Firozpur	Moradabad	Faridkot	West Godavari	Guntur
Livestock excretions	Cuttak	Dakshin Kannad	Medinipur	Greater Mumbai	Bastar
Industrial processes	Greater Mumbai	Sundargarh	Bharuch	Raigarh	Rupnagar
Indirect emissions	Cuttak	Medinipur	Moradabad	Firozpur	Raipur
Overall	Moradabad	Firozpur	Muzaffarnagar	Greater Mumbai	West Godavari

Table 13
Greenhouse gas emissions in India at a national level

	1990	CO_2 equivalent	1995	CO_2 equivalent
Population	846307720		926695378	
Area (km^2)	3301581			
All India CH_4 emissions (Tg)				
Agriculture residue	0.09	1.9	0.10	2.1
Biomass	2.82	59.2	2.88	60.5
Coal production	0.33	6.9	0.38	7.9
Oil & natural gas	0.72	15.1	0.79	16.6
Livestock	6.91	145.1	7.26	152.5
Manure management	0.35	7.4	0.40	8.4
Paddy cultivation	4.02	84.4	4.01	84.2
MSW	1.42	29.8	1.82	38.2
MWW	0.39	8.2	0.42	8.8
Total CH_4	17.05	358	18.05	379
All India CO_2 emissions (Tg)				
Coal	432.7	432.7	566.5	566.5
Oil products	141.1	141	188.4	188.4
Natural gas	18.8	18.8	23.1	23.1
Total CO_2	592.6	592.6	777.9	777.9
All India N_2O emissions (MT)				
Coal	0.01	1.9	0.01	2.5
Oil	0.001	0.3	0.001	0.3
Crop residue	0.02	7.4	0.03	8.1
Biological N_2 fixation	0.01	1.6	0.01	1.6
Nitrogen fertilizer	0.14	42.8	0.16	50.8
Livestock	0.01	3.4	0.01	3.7
Industrial processes	0.01	1.6	0.01	2.5
Indirect emissions	0.02	6.8	0.02	7.4
Total N_2O	0.23	65.7	0.26	76.6
Total CO_2 equivalent emissions (Tg)	—	1016.3	—	1234.1
Per capita CO_2 equivalent emission (ton)	—	1.2	—	1.3
Per area intensity (tons/sq km)	—	308		374

should be initiated for this purpose. All new capacity additions in these sectors should use cleaner technology options. Otherwise capacity additions to existing large coal-based power plants should be avoided since it would further increase emissions from hotspot districts. Most of these districts are in the hinterland (Fig. 1) and hence

Table 14
Analysis of 25 hotspot districts for each emission type in India

Emission type	Emissions in 1995		% CAGR[a] (1990–1995)	
	Cumulative (Tg)	% of all India	Hotspots	All India
CO_2	401	51.5	10.95	5.6
CH_4	3.35	18.4	1.44	1.12
N_2O	0.052	20.8	4.01	3.34
CO_2 equivalent	465	37.5	8.83	3.94

[a]Compounded annual growth rate.

Table 15
Main contributors to India's CO_2 equivalent GHG emissions, 1995

Source categories/sectors	Percentage share	Main emission sources
Coal-based power generation	29.6	40 large plants
Steel industry	8.8	5 large plants
Cement industry	5	15 large plants
Livestock	12.6	Highly dispersed
Paddy cultivation	6.8	Highly dispersed
Biomass consumption	5.4	Highly dispersed
Synthetic fertilizer use	4.1	Highly dispersed
Transport sector	9.5	Highly dispersed and mobile
Waste disposal	3.7	15 large districts
Other sources	14.5	Varied and dispersed
All India	100	As above

there would be a reasonable possibility of acid rains in the surrounding areas if their capacities were increased without proper pollution control measures being taken. A similar situation would arise if future large coal-based thermal power plants were situated near the mine mouths alone, which already have many large plants in place. A more dispersed generation base would be preferable for India. Coastal districts offer a good alternative due to their higher pollutant-carrying capacities and easy access to coal transport through sea routes.

5. Conclusion

The study indicates that between 1990 and 1995, the composition of sectoral emissions has not changed much. Electric power generation the largest source, contributes to almost half of India's total CO_2 equivalent emission (40%) and is growing at the rate of 10% per annum. Emissions from the steel and cement sectors are next. These sectors are having high growth rates as well. Emissions from these three sectors have concentrated regional emission distribution patterns. Transport sector emissions do not contribute much to GHG emissions but are a major source of local pollution concerns in many districts. The study also brings out distinct emission profiles for predominantly urban and rural districts where industry and transport sector emissions dominate the former while agriculture sector dominates the latter. The mitigation efforts for urban districts would therefore be relatively easier as the industry sector has large point sources. Moreover industry and transport activities are also more organized than the agriculture sector in India.

Despite the uncertainties, we believe that district level inventories are useful tools for bridging the uncertainties in the national emissions. The relative importance of the different GHG sources depends on an array of demographic, economic and ecosystem variables. Identifying these variables and calculating source magnitudes at district level provides quantitative data necessary to develop sectoral and regional impact assessment, offers enhanced GHG mitigation flexibility to the policy makers and an array of adaptation strategies to combat the related climate change. The basket approach for all the GHGs offers policy makers flexibility such that the marginal costs of mitigation are balanced across GHGs and sectors.

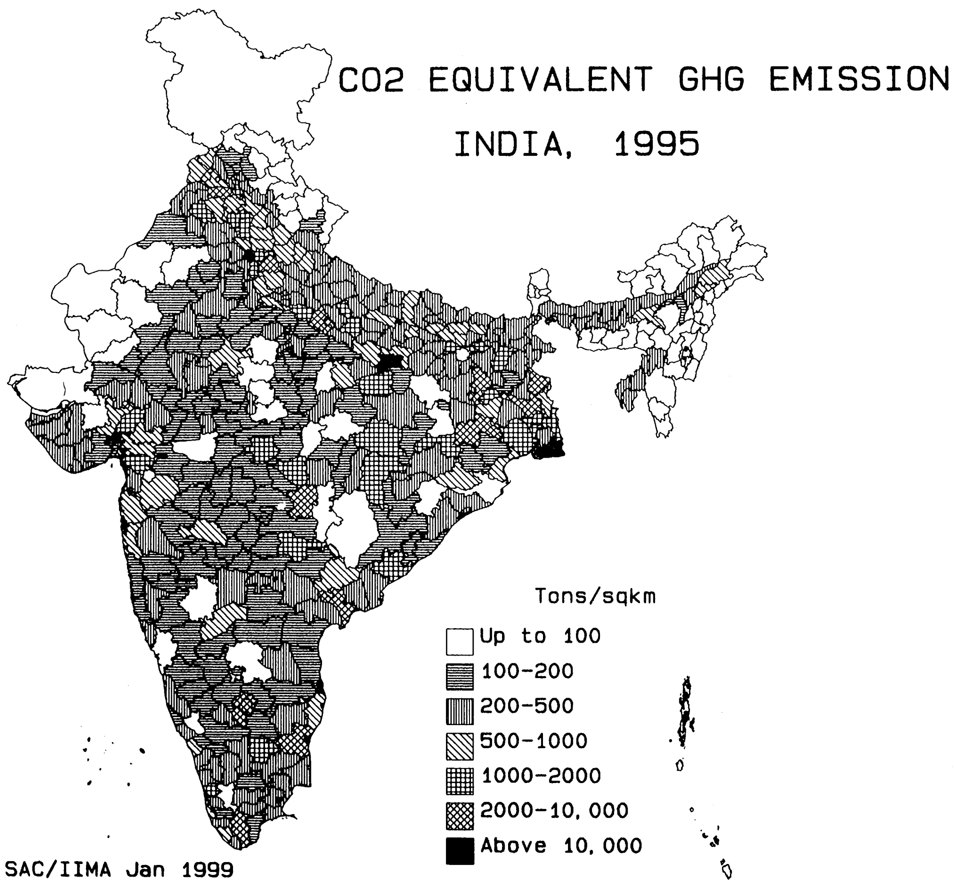

Fig. 8. CO_2 equivalent GHG emissions from Indian districts in 1995.

The challenge therefore is to select a prudent strategy and to adjust it over time in the light of new information. In the long run, however, the choice of developmental path is the most vital determinant of emissions profile. For a country like India, the importance of climate change mitigation policies is secondary in the national policy agenda as its policies are necessarily focused on fundamental issues such as alleviation of poverty and creating basic conditions for human development. Therefore, in order to gain even primary attention of policy makers, the greenhouse gas mitigation strategies have to be integrated with national development plans rather than compete with them for resources. The present work has highlighted mitigation flexibility in India across gases, sectors and regions, and therefore provides a policy linkage with national priorities such as for control of local pollution, energy and infrastructure plans, urban development and industrial location policies.

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