Greenhouse gas inventory estimates for India

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This article reports the greenhouse gas emissions of anthropogenic origin by sources and removals by sinks of India for 2007 prepared under the aegis of the Indian Network for Climate Change Assessment (INCCA) (note 1). The emission profile includes carbon dioxide (CO_2), methane and nitrous oxide. It also includes the estimates of hydrofluorocarbons, perfluorocarbons and sulphur hexafluoride at the national level from various sectors, viz. energy, industrial process and product use, agriculture, land-use, land-use change and forestry (LULUCF), and waste. In 2007, emissions were of the order of 2008.67 Tg (note 2) of CO_2 equivalents without emissions from the LULUCF sector. Whereas with LULUCF the emissions were about 1831.65 Tg CO_2 equivalents. The energy sector accounted for 69% of the total emissions, the agriculture sector contributed 19% of the emissions, 9% of the emissions was from the industrial processes and product use, and only 3% of the emissions was attributable to the waste sector. The LULUCF sector on the whole was net sink category for CO_2. The study tracks the improvements made in inventory estimates at the national level through the years, in terms of the expanding coverage of sources, reducing uncertainties and inclusion of new methodologies, including some elements of future areas of work.

Keywords: Anthropogenic origin, emissions, greenhouse gas inventory, IPCC, source and sink.

Introduction

Estimation and reporting of greenhouse gas (GHG) emissions from anthropogenic sources and removals by sinks have become an important activity of Parties to the United Nations Framework Convention on Climate Change (UNFCCC) towards implementation of their commitment under the Convention. This information from the Parties to the Convention helps to ascertain their levels and trends of GHG emissions nationally and determine their respective contribution to the total GHG pool at a global level. The emission inventories are estimated from the sectors such as energy, industrial process and product use, agriculture, land-use, land-use change and forestry (LULUCF), and waste using the Intergovernmental Panel on Climate Change (IPCC) guidelines to develop comprehensive, comparable, transparent and accurate GHG inventories. The comprehensive methodological guidelines were published in 1996 (ref. 1), which was subsequently upgraded in 2006 (ref. 2). In the interim period, Good Practice Guidance (GPG) was published in 2000, covering energy, industrial process, agriculture and waste sectors[3]; the LULUCF sector was covered in the 2003 GPG–LULUCF (ref. 4). The GPG essentially focused on reducing uncertainties in the estimates by incorporating the concepts of key source category analysis, uncertainty analysis, and measures for quality assurance (QA) and quality control (QC).

An inventory of GHG emissions of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) by sources and removal by sinks at the national level using the IPCC 1996 guidelines was first published in 1998 (ref. 5). These estimates indicated that the total CO_2 equivalent

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emissions from India in 1990 were around 1001.35 Tg. In 2004, India's Initial National Communication (INC) to UNFCCC[6], included more number of source categories for the above-mentioned three gases. The total emission for the reporting year 1994 was 1228.82 Tg CO_2 equivalents. The inventory information provided in the INC was a concerted effort of 19 institutions across India, covering research institutions, technical institutions, universities and industry associations. The efforts were focused not only to estimate the emissions by sectors, but also to reduce uncertainties through development of country-specific emission factors[7]. Under the aegis of INCCA[8], a national-level GHG inventory for CO_2, CH_4 and N_2O inventory was published in 2010 for 2007. In this assessment, the IPCC 1996 methodologies with GPG and IPCC 2006 guidelines have been used, but the industry emissions resulting from fossil-fuel combustion and from processes were clubbed together for ease of reference by various target groups.

Over the years, several researchers have also reported GHG emissions at various spatial scales such as at the district level covering the entire country[9], at point-source level[10] and also at aggregated level for years beyond 1990 up to 2005 (ref. 11). The GHG emissions from sectors and subsectors are also well documented such as those of road transport[12], fugitive emissions[13], livestock[14], crops and soils[15], forestry[16] and solid waste-management practices[17].

Reduction of uncertainties in GHG inventory preparation has continued to engage the attention of researchers since 1990s. This was triggered by the reports of over estimates of CH_4 (~ 38 Tg) from rice paddy fields in India[18]. A country-wide campaign launched by the Ministry of Environment and Forests, Government of India in association with the National Physical Laboratory, New Delhi and other agencies across India conducted measurements covering all rice ecosystems under different water-management practices[19–22], which resulted in the development of country-specific CH_4 emission factors (EFs) for each water management practised in the country, such as irrigated continuously flooded, single aeration, multiple aeration, rainfed flood-prone, rainfed drought-prone, and deep water. These initiatives also have ascertained that the CH_4 emission from this source is around 3–6 Tg/yr in comparison to earlier estimates[18]. Additional efforts have also been made to develop country-specific CO_2-EFs for Indian coking coal, non-coking coal and lignite; CH_4-EF for Indian underground coal mines with different levels of gassiness; N_2O-EF from nitric acid production; CH_4-EF from enteric fermentation in livestock; N_2O-EF from soils and CH_4-EF from solid waste management. The estimates from country-specific emission factors have added to the robustness of the GHG inventory.

This study briefly describes the GHG emission inventory of emissions of GHGs of anthropogenic origin and removals by sinks for 2007. It includes the emissions of CO_2, CH_4, N_2O, hydrofluorocarbons (HFCs; HFC-23, HFC-134a), perfluorocarbons (PFCs) (tetrafluoromethane (CF_4) and hexafluoroethane (C_2F_6)) and SF_6 from source categories. It differs from the assessment one brought out in May 2010 (ref. 8), in its treatment of emissions from industries and reports separately the GHG emissions from fossil-fuel combustion in industries and emissions from their processes. The study tracks the improvements made in inventory estimates at the national level through the years, in terms of the expanding coverage, reducing uncertainties, inclusion of new methodologies and the changing key sources as the coverage of sources has expanded. It also focuses on the QA/QC measures applied in this effort to make the estimates more robust.

Activity data, emission factors and methodology

There is no comprehensive database available in India covering all types of sources in different sectors; therefore, many diverse sources covering various sectors have been utilized. Most of the activity data are derived from published reports/documents of Government sources, such as that of fossil-fuel use by source category[23–28]. The agriculture-related data such as livestock statistics, area under rice cultivation and quantity of production of different crops were obtained from the Ministry of Agriculture reports[29–31]. For the LULUCF sector, information from land-use statistics developed by the Forest Survey of India and National Remote Sensing Centre has been used[8]. The urban population statistics from Census of India[32] has been utilized for the generation of municipal solid waste and domestic wastewater, whereas the data for industrial wastewater have been obtained from various publications of the Central Pollution Control Board[33–37]. The activity data for various industrial products have been compiled from relevant publications such as that of Ministry of Steel, Ministry of Fertilizer, *Indian Mineral Year Book* published by the Ministry of Mines, reports of the ozone cell, Ministry of Environment and Forests, etc. When some of the industrial production data were not available, the relevant industry associations were directly consulted such as cement production data have been sourced from the Cement Manufacturers' Association[38].

The emission factors used for the estimation of emissions are a mix of default emission factors available in IPCC publications[1–4] and country-specific emission factors. Default emission factors have been used for gases and/or categories where country-specific factors are not available. The country-specific EFs that have been used in this assessment include CO_2-EFs for Indian coking coal, non-coking coal and lignite[39]; CH_4-EF for Indian underground coal mines with different levels of gassiness[14]; CH_4-EF from enteric fermentation in livestock[40]; N_2O-EF from soils[41]; updated CH_4-EFs from rice cultivation[42,43] (Table 1); N_2O-EF from nitric acid production[44]; CO_2 from cement[44]; CO_2 from ammonia production[45] and CH_4–EF from solid waste management[46].

The methodologies used for this assessment follow the revised IPCC guidelines 1996, supported by the IPCC GPG 2000 and 2003 and IPCC 2006 guidelines[1–4]. The LULUCF sector estimations are made using the IPCC GPG, 2003. GPG methodologies[4] support the development of inventories that are transparent, documented, consistent over time, complete, comparable, assessed for uncertainties, subject to quality control and quality assurance, and efficient in the use of resources. The tiers of estimate range between tiers 1 and 3 (note 3). Table 2 describes the methodological tiers and type of emission factors used for the different source categories. Higher tier (T3) implies more data-intensive, and methodologies that take into account several steps of emission which might be grossed over in tier 1. For example, CH_4 from rice cultivation is estimated using tier-3 approach, whereby the total rice area is divided into areas characterizing different water-management practices in the country. The GHG emission factors used for estimating CH_4 from these areas are actual measurements carried out that represent CH_4 emission/unit area covering each water-management practice. Efforts are generally made to use a tier 2 or 3 which is a data-intensive approach for categories that are identified as key source emissions categories.

Key source analysis leads to the identification of sources of emission category, which have significant impact on total emissions or trends accounting for up to 95% of the total emissions. The key source analysis is carried out to prioritize sectors where higher tier methodologies need to be used for greater accuracy, to design additional requirements of QA/QC for key sources, and for allocation and to make the best use of available resources for sources with significant impact on total emission estimate, that would lead to reduction in uncertainties in the estimates to the maximum extent possible. In order to identify the key sources, tier-1 level analysis has been carried out according to the IPCC GPG[3]. The level analysis is calculated without the LULUCF sector and includes all gases for which estimates have been presented for total emissions.

Table 1. Emission factor used for estimation of emissions from rice cultivation

Type	Emission factor (kg CH_4/ha)
Irrigated	
Continuously flooded	162
Single aeration	66
Multiple aeration	18
Rainfed	
Drought-prone	66
Flood-prone	190
Deep-water	190

GHG emissions

The estimates of CO_2, CH_4, N_2O, HFCs (HFC-134a, HFC-23), PFCs (CF_4, C_2F_6) and SF_6 emitted by sources and their removals by sinks covering the sectors of energy, industrial process and product use, agriculture, LULUCF, and waste for 2007 are provided in Table 3. The total CO_2 equivalent emission estimates were about 2008.67 Tg without inclusion of the LULUCF sector. However, with LULUCF, the emissions were of the order of 1831.65 Tg CO_2 equivalent. This indicates that LULUCF as a whole acts as a sink for CO_2. The percentage contribution of all sectors (except LULUCF) to the total GHG emissions from India is provided in Figure 1, and the global warming potential used for calculation of CO_2 equivalent is given in Table 4 (ref. 47).

The energy sector comprises emission estimates due to combustion of fossil fuel in stationary sources, mobile sources, and fugitive emissions from mining and handling of coal, oil and natural gas. Stationary sources include fossil-fuel combustion in electricity generation, manufacturing of solid fuels, refineries for refining crude oil, manufacturing industries and fossil-fuel use in residential, commercial/institutional, and agriculture/fisheries activities. CO_2 emissions result from the release of carbon in the fuel during combustion and the quantity of emission depends not only on the quantity of the fuel combusted, but also on the carbon content of the fuel and the technology of combustion. Most of the carbon (C) is emitted as CO_2 immediately during the combustion process. However, some carbon is released as CH_4, carbon monoxide (CO) or non-CH_4 volatile organic carbon (NMVOC), which oxidizes to CO_2 in the atmosphere within a period of a few days to about 12 years. The quantity of CH_4 and N_2O released depends on the technology used in mobile combusting source. Mobile sources include road transport, civil aviation, railways and navigation. Fugitive emissions of CH_4 occur from coal seams trapped during the geological process of coal formation. Generally, deeper underground coal seams contain more

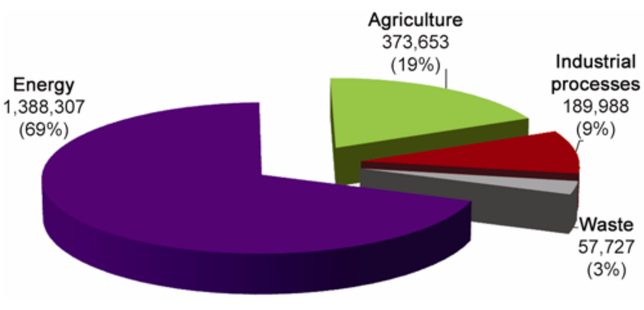

Figure 1. Greenhouse gas emissions by sectors (Gg) in 2007 without land-use, land-use change and forestry sector (CO_2 equivalent). The number indicated under each sector represents the total CO_2 equivalent emissions and the percentage of emission with respect to the total CO_2 equivalent emissions.

Table 2. Emission factor and tier used for greenhouse gas estimation

	CO_2		CH_4		N_2O	
	Method applied	Emission factor	Method applied	Emission factor	Method applied	Emission factor
Energy						
Fuel combustion activities*	T1, T2	Cs, D	T1	D	T1	D
Other (residential, commercial/institutional, agricultural/fisheries)	T1	Cs, D	T1	D	T1	D
Fugitive emission from fuels						
Solid fuels			T2	Cs		
Oil and natural gas			T1	D		
Industrial process and product use						
Mineral products						
Cement production	T2	Cs, D	T2	D	T2	D
Lime production**	T1	Cs, D	T1	D	T1	D
Soda ash production and use	T1	Cs, D				
Glass		Cs, D				
Chemicals†	T1	Cs, D	T1	D	T1	D
Metal production††	T1	Cs, D	T1	D	T1	D
Others	T1	Cs, D	T1	D	T1	D
Non-energy product use¶	T1	Cs, D	T1	D	T1	D
Agriculture						
Enteric fermentation			T3	Cs	T2	D
Manure management			T1	Cs, D	T1	Cs, D
Rice cultivation			T3	Cs		
Agricultural soils					T2	Cs, D
Field burning of agricultural residues			T1	Cs< D	T1	Cs, D
Land-use, land-use change and forestry						
Forest land	T2	Cs, D				
Cropland	T2	Cs, D				
Grassland	T2	D				
Wetland	T2	D				
Others	T2	D				
Settlement	T2	D				
Waste						
Solid waste disposal on land						
Managed waste disposal on land			T2	Cs, D		
Waste-water handling						
Industrial wastewater			T1, T2	Cs, D		
Domestic and commercial wastewater			T1	D		
Memo items						
International bunkers						
Civil aviation	T1	D	T1	D	T1	D
Navigation	T1	D	T1	D	T1	D
Biomass combustion	T1	Cs, D				

T1, Tier 1; T2, Tier 2; T3, Tier 3; Cs, Country specific; D, Default. *Energy industries, manufacturing industries, and construction and transport. **Limestone and dolomite use. †Ammonia production, nitric acid production, carbide production, titanium dioxide production, methanol production, ethylene production, ethylene dichloride (EDC) and vinyl chloride monomer (VCM) production, ethylene oxide production, acrylonitrile production, carbon black production, caprolactam and fluorochemical production. ††Iron and steel production, ferroalloys production, aluminium production, lead production, zinc production, magnesium production. ¶Lubricant, paraffin wax.

in situ methane than shallower surface seams. Fugitive emissions from oil and natural gas activities include all emissions from the exploration, production, processing, transport and use of oil and natural gas, and from non-productive combustion (e.g. flaring). The total emissions from the energy sector in 2007 were 1388.31 Tg of CO_2 equivalent. Of this, 1285.81 Tg was emitted as CO_2, 4.06 Tg as CH_4 and 0.06 Tg as N_2O. The energy sector contributed 69% of the total emissions in 2007 without LULUCF. For details of emissions by sectors see Table 3.

Industrial production processes also produce GHGs from a variety of industrial activities which chemically or physically transform materials. During these processes, many different GHGs, including CO_2, CH_4, N_2O, HFCs,

Table 3. Inventory of GHG emissions of anthropogenic origin by sources and removals by sinks for the year 2007 (in Gg; 1 Gg = 1000 tonnes)

					HFCs		PFCs			
Sector	CO_2 emission	CO_2 removal	CH_4	N_2O	HFC-134a	HFC-23	CF_4	C_2F_6	SF_6	CO_2 equivalent
Energy										
Fuel combustion activities	1,285,814.30		2,457.22	55.53						1,354,629.04
Energy industries	784,367.53		11.22	11.01						788,016.99
Electricity production	715,829.84		8.08	10.66						719,302.73
Refinery	67,643.22		3.14	0.34						67,814.93
Manufacturing of solid fuel	894.47		0.01	0.02						899.33
Manufacturing industries and construction	258,101.76		3.80	2.97						259,102.38
Transport	138,984.01		17.89	8.25						141,918.47
Commercials/institutional	1,657.00		0.30	0.02						1669.50
Residential	69,427.00		2,420.00	33.00						130,477.00
Agricultural/fisheries	33,277.00		4.00	0.27						33,444.70
Fugitive emission from fuels			1,603.71							33,677.99
Sub-total	1,285,814.30		4,060.93	55.53						1,388,307.03
Industrial process and product use										
Mineral products	82,141.98									82,141.98
Chemicals	19,088.65		10.58	17.13						24,622.46
Metal production	52,004.91		0.08				1.47	0.15	0.004	62,991.45
Others*					1.67	1.24			0.12	19,382.48
Non-energy product use	849.49									849.49
Sub-total	154,085.03		10.65	17.13	1.67	1.24	1.47	0.15	0.12	189,987.86
Agriculture										
Enteric fermentation			10,609.73							222,804.36
Manure management			120.44	0.08						2,553.55
Rice cultivation			3,323.30							69,789.30
Agricultural soils				225.93						70,036.75
Field burning of agricultural residues			257.21	6.67						7,469.11
Sub-total			14,310.68	232.67						372,653.07
Land use, land-use change and forestry										
Forestland		67,800.00								–67,800.00
Cropland		207,520.00								–207,520.00
Grassland	10,490.00									10,490.00
Settlement		38.00								–38.00
Wetland	NE									NE
Others	NO									NO
Fuel wood use from forests	87,840.00									87,840.00
Sub-total	98,330.00	275,358.00								–177,028.00
Waste										
Solid waste disposal on land			604.51							12,694.71
Managed waste disposal on land			604.51							12,694.71
Waste-water handling			1,911.00	15.81						45,032.10
Industrial wastewater			1,050.00							22,050.00
Domestic and commercial wastewater			861.00	15.81						22,982.10
Sub-total			2,515.51	15.81						57,726.81
Grand total (Gg)	1,538,229.33	275,358.00	20,897.77	321.14	1.67	1.24	1.47	0.15	0.12	1,831,646.77
Memo item										
International bunkers	3,454.00		0.03	0.10						3,484.45
Aviation	3,326.00		0.02	0.09						3,355.31
Marine	128.00		0.01	0.003						129.14
CO_2 from biomass	566,788.00									566,788.00

*Includes production of halocarbons and consumption of SF_6.

PFCs and SF_6 are released. Cement and iron–steel production are notable examples of an industrial process that releases a significant amount of CO_2. Different halocarbons and SF_6 are also produced or used as alternatives to ozone-depleting substances in various applications. In some instances industrial process emissions are produced in combination with fuel combustion emissions, where the main purpose of the fuel combustion is to use the heat released; the resulting emissions are included as energy emissions, not industrial process emissions. There are, however, some chemical processes or stages of processes, which oxidize carbon as a feedstock and are exothermic. The reduction of iron in a blast furnace through the combustion of coke is an example. In some cases not all fuel feedstock delivered to petrochemical plants is used for manufacture of other products. These constitute important factors for estimating the GHG emissions from the industrial process sector. In 2007, the industrial processes, comprising metal industries (note 4), mineral industries (note 5), chemical industries (note 6), use of non-energy products such as paraffin wax and lubricants, and consumption and production of HFCs (note 7) and SF_6, have resulted in an emission of 154,085.03 Gg (note 8) of CO_2, 10.65 Gg of CH_4, 17.13 Gg of N_2O, 1.67 Gg of HFC-134a, 1.24 Gg of HFC-23, 1.47 Gg of CF_4, 0.15 Gg of C_2F6 and 0.12 Gg of SF_6 (Also see Table 3 for emissions by source category). Together this resulted in an emission of 189.99 Tg of CO_2 equivalent, which was 19% of the total GHG emissions without LULUCF.

The agriculture sector includes non-CO_2 emissions from enteric fermentation from livestock, manure management, rice cultivation, agricultural soils and burning of crop residue in the fields. Enteric fermentation in livestock is a digestive process by which carbohydrates are broken down by microorganisms, leading to emission of CH_4. The amount of CH_4 that is released depends on the type, age and weight of the animal, the quality and quantity of the feed, and the energy expenditure of the animal. The decomposition process of manure under anaerobic conditions also leads to release of CH_4, while some nitrogen in the manure is converted to N_2O resulting into emission. As mentioned earlier, anaerobic decomposition of organic material in flooded rice fields produces methane. The amount of CH_4 emission depends on irrigation practices, rice species, number and duration of harvests, soil type and temperature, and usage of fertilizer. Burning of crop residues is considered C neutral, as it is reabsorbed during the next growing season. However, burning is a significant source of CH_4 and N_2O amongst other non-CO_2 emissions. The N_2O from agricultural soils is released due to the microbial processes of nitrification and denitrification in the soil resulting in direct or indirect emissions. Direct soil emissions may result from nitrogen input to soils such as synthetic fertilizers, animal waste, through biological nitrogen fixation, from reutilized nitrogen from crop residues, and from sewage sludge application, and from organic soil due to enhanced mineralization. Indirect N_2O emissions take place after nitrogen is lost from the field as NO_x, NH_3 or after leaching or run-off. In 2007, the total emissions of CH_4 and N_2O from these activities in India were 14.3 Tg and 0.23 Tg respectively, resulting in 372.65 Tg of CO_2 equivalent emissions, which was 19% of the total GHG emissions from the country without inclusion of LULUCF.

Table 4. Global warming potential (GWP) of GHGs used for CO_2 equivalent

Gas	GWP*
CO_2	1
CH_4	21
N_2O	310
HFC-134a	1,300
HFC-23	11,700
CF_4	6,500
C_2F_6	9,200
SF_6	23,900

*Hundred year time horizon[47].

The estimates from the LULUCF sector include emission by sources and/or removal by sinks from changes in forest land, crop land, grassland and settlements. The sources of the C pool are the above and below ground biomass, dead organic matter such as dead wood and litter, and organic matter in forest soils. Changes in forest land remaining forestland, land getting converted to forest land or other types of land affect the C pool in the forest. Similarly changes in C pool occur due to land remaining crop land or getting converted to other types of land, or acquiring land under cropping system from other land uses. Similarly, C pool is disturbed when conversion to and from grassland, settlements and waste land takes place. In this estimate, waste land has not been considered due to lack of data on its conversion to various land use types and vice versa. The methodology for estimating the changes in C pool are detailed in the INCCA report[8]. The estimates indicate that the LULUCF sector was a net sink in 2007. It sequestered 177.03 Tg of CO_2.

GHG emissions from the waste sector have been estimated from activities related to management of municipal solid waste (MSW), industrial wastewater, domestic wastewater and commercial wastewater practices in India. Systematic disposal over the years in solid waste sites led to degradation of organic C present in the waste in anaerobic conditions, resulting in CH_4 emissions. MSW management is carried out systematically only in the cities of India. It is estimated that MSW generation and disposal resulted in 0.60 Tg of CH_4 emissions or 12.69 Tg of CO_2 equivalents in 2007. Similarly, domestic wastewater from urban centres (class I and II cities) and also the industrial wastewater are handled systematically. Domestic wastewater emitted 0.86 Tg of CH_4 and 0.016 Tg of N_2O, resulting in 22.98 Tg of CO_2 equivalent. The industrial

Table 5. Key source categories of emissions

Source category	CO_2 equivalent (Gg)	Cumulative CO_2 equivalent (Gg)	Percentage of total CO_2 equivalent
1A1.a. Electricity production	719,303	719,303	35.81
3a Enteric fermentation	222,804	942,107	46.90
1A4b. Residential	130,477	1,072,584	53.40
1A3a. Road transport	123,434	1,196,018	59.54
1A2j. Nonspecific industries	88,231	1,284,249	63.94
3d. Agricultural soils	70,037	1,354,286	67.42
3c. Rice cultivation	69,789	1,424,075	70.90
1A2b. Iron and steel	69,534	1,493,609	74.36
1A1.b. Refinery	67,815	1,561,424	77.73
2Aa. Cement production	67,219	1,628,643	81.08
2ca. Iron and steel production	47,782	1,676,425	83.46
1A2a. Cement	44,778	1,721,203	85.69
1A4c. Agricultural/fisheries	33,445	1,754,648	87.35
1A1.b. Refinery	32,947	1,787,594	88.99
1A2f. Food and beverages	27,718	1,815,313	90.37
5c. Domestic wastewater	22,982	1,838,295	91.52
5b. Industrial wastewater	22,050	1,860,345	92.62
1A2d. Chemicals	18,930	1,879,275	93.56
1B2. Oil and natural gas	18,259	1,897,534	94.47
2D1. Production of halocarbons	16,632	1,914,166	95.29

wastewater management practices for industries such as pulp paper, food and beverage and tanneries, lead to emissions of 1.05 Tg of CH_4, resulting in 22.05 Tg of CO_2 equivalent. The total amount of GHG emitted from the waste sector in 2007 was 57.73 Tg of CO_2 equivalent.

Key source analysis

Table 5 identifies 20 amongst the total 55 source categories as key source categories, as they constituted 95.29% of the total emissions from India in 2007. Of these, 60%, i.e. 12 categories are from the energy sector alone, including fugitive emissions from coal, while the rest 40% is from industrial processes and product use, agriculture, and waste sectors. The 12 sources within the energy sector are likely to remain key sources, unless a large chunk of the energy mix shifts towards the renewable energy. An interesting fact that has emerged is that apart from the iron and steel and the cement processes appearing as key sources in the analysis from the industrial process and product use sector, production of halocarbons is appearing as a key source as well. The two sources in the waste sector, namely domestic wastewater and industrial wastewater are key sources. The key source in the agriculture sector is CH_4 emission from enteric fermentation from livestock population. Emission from rice is now though appearing as a key source, may diminish in the future as new water conservation technologies are introduced in the country, such as system of rice intensification (SRI), direct bed plantation of rice sapling, no tillage policies, etc.

Elements of improvement in inventory assessments

Since the first inventory was published in 1998, continuous improvements have been made in the inventory development. The element of improvements made in each assessment is shown in Table 6. Improvements have been made in terms of the methodologies, updated EFs and coverage of the source categories under various sectors. The total number of sources covered increased from 18 in the 1990 assessment to 29 in the 1994 assessment, and to 55 in the present assessment, i.e. for 2007.

The 2007 inventory had used the 2006 IPCC Guidelines in part for the first time for estimating the GHG emissions from the LULUCF sector. The estimates indicate that this sector is a net sink. In previous efforts, forest estimations were only the forest and grassland conversions according to the revised 1996 methodology. Whereas in the present estimate, both forests and crop land have been estimated and emerged as net sequesters of CO_2, which is principally due to enhancement of the activities towards increasing the tree cover in and outside forests through various afforestation programmes.

Key source analysis has now become the integral part of the assessments. In this article, only level assessment has been presented, though trend assessments could have narrowed down the list of key sources further. But it can only be done, if recalculations are carried out for at least the 1994 assessments, to cover the additional source categories added in the 2007 assessment as well as the additional gases such as HFCs, PFCs and SF_6 included only in 2007. Further, the usage of country-specific EFs

Table 6. Improvements in national GHG estimation

Parameters	1990*	1994**	2007***
Gases covered	Emission estimates of CO_2, CH_4 and N_2O	Emission estimates of CO_2, CH_4 and N_2O	Emission estimates of CO_2, CH_4, N_2O, HFC-134a, HFC-23, CF_4, C_2F_6 and SF_6
Guidelines used for estimation	Estimates made using 1996 revised guidelines	Estimates made using only revised 1996 IPCC guidelines	Estimates made using revised IPCC 1996 guidelines (1997), IPCC Good Practice Guidance (2000), the LULUCF Good Practice Guidance (2003) and 2006 IPCC guidelines
Source category	Only 18 source categories were covered	Total 29 source categories were covered	Total 55 source categories covered
Treatment of LULUCF estimation	LULUCF included C pools of forest, grassland and abandonment of managed land	LULUCF included C pools of forest, grassland and abandonment of managed land	Carbon pools in addition to forests have been considered in the LULUCF sector (crop land, grassland, settlements). Wasteland conversions have not been estimated as reliable statistics was not available
Emission factors (EFs)	EFs were a mix of both country-specific and default factors. Country-specific EFs of CH_4 were used for rice cultivation and enteric fermentation only	EFs were a mix of default factors taken from IPCC and Cs EFs. Twenty-six per cent of the source categories used Cs factors. New EFs developed were that of CO_2 from Indian coal, N_2O from nitric acid production, CH_4 from fugitive emissions from coal, CH_4 emission factors for crop residue and N_2O EF for soils	EFs were also a mix of default and Cs, but leading to improved accuracy as more number of Cs EFs have been used in this assessment. These include EFs from the literature. About 35% of the source categories used Cs EFs
QA/QC	QA/QC efforts could not be made	Large-scale QA/QC efforts could not be made. QA/QC performed only at individual level	All source categories were subjected to QA/QC checks. Also a third-party review was undertaken
Key source analysis	No key source analysis made	Key source analysis carried out; only 14 sources identified as key sources	Key source analysis carried out; 21 sources identified as key sources

*ALGAS[5]; **INC[6]; ***Present estimates.

is increasing, which indicates comprehensiveness in inventory development. This aspect can be further improved if efforts are made to develop country-specific EFs for the key sources identified, at least for the top 16 sources that contribute about 90% of the total emissions from the country.

Reduction in uncertainties in the estimation of GHG inventories for 2007 has been through multi-pronged approach. Initially, QA of the activity data being used for the inventory estimation are ensured and then the uncertainties are reduced through utilization of country-specific EFs as mentioned in the previous section, and also through overall QC checks.

For undertaking the QA/QC operations, first a QA/QC plan was developed compatible with the respective methodologies such as tiers 1–3. The QA/QC checks were performed for accuracy of data collected through secondary sources[3]. Cross-check on reliability of activity data collected from secondary sources for proper documentation and record was also performed. The QA/QC checks include cross-checking for transcription errors in activity data; check on consistency, completeness and integrity of the database; documentation and reporting of the rationale of assumptions used for the activity data; documentation and reporting of gaps in the database; consistency in labelling of units in ensuing calculations, and complete checks on reported datasets.

It has been assumed that the activity data taken from various reports, of ministries/government departments/industry associations/the remote sensing agency have already gone through their own QC checks before being published. QC activities include general methods such as accuracy checks on data acquisition and calculations, and the use of approved, standardized procedures for emission calculations, measurements, estimating uncertainties, archiving information and reporting. Higher-tier QC activities include technical reviews of source categories, activity and emission factor data, and methods. The entire process of QC was further strengthened by undertaking checks to ensure that data provided cover all the sources that were set out to be collected. A third-party review was conducted on the finalized inventory following the implementation of QC procedures thorough checking the consistency in reporting, the appropriateness of methodologies used and verifying the accuracy of the estimates.

Table 7. Compounded annual growth rate (CAGR) of CO_2 equivalent* emission between 1990–1994 and 1994–2007

	1990 (Gg CO_2 equivalent)	1994 (Gg CO_2 equivalent)	CAGR (1990–1994)	2007 (Gg CO_2 equivalent)	CAGR (1994–2007)
Energy	622,587	743,820	4.5	1,388,307	4.9
Industrial processes	24,510	102,710	43.1	159,620	3.4
Agriculture	325,188	344,485	1.5	372,653	0.6
LULUCF	1,467	14,291	76.7	–177,028	–221.4
Waste	14,133	23,233	13.2	57,727	7.3
Total emissions with LULUCF	987,885	1,228,539	5.6	1,978,307	3.7
Total emissions without LULUCF	986,418	1,214,248	5.3	1,801,279	3.1

*Does not include HFC, PFC and SF_6.

Trends of GHG emissions

The compounded annual growth rate of the total emissions between 1990 and 1994 was 5.3%, and it has reduced to 3.1% for the 1994–2007 period in the absence of the LULUCF sector (Table 7). However, with LULUCF also, the total emissions showed a decline in growth rate from 5.6% to 3.7% between the two periods.

The energy sector grew at a rate of 4.5% from 1990 to 1994 and from 1994 to 2007 the growth rate increased to 4.9%. The growth rate of 43.1% for the industrial process sector between 1990 and 1994 is spurious as most of the industrial processes were not covered during the assessment. However, between 1994 and 2007, a growth rate of 3.4% was registered for the industrial processes and product use sector as a whole. The growth rates in the emissions from the agriculture sector are reducing due to continuous improvement in EFs in rice cultivation, with reduced values for continuously flooded fields, which indicates the slow penetration of water-conservation technologies. The LULUCF sector shows a diametrically opposite trend, which is essentially due to increase in forest tree cover across the country during the last decade and also because of change in methodology that includes C pools in addition to forest. These efforts have contributed to the LULUCF sector emerging as a net sink for CO_2 in 2007. The main reason for the change in the GHG inventory estimates for the LULUCF sector is due to change in the methods adopted for the 1994 and 2007 estimates. The 1994 estimate is based on IPCC-1996 revised guideline method and the 2007 estimate is based on IPCC GPG for LULUCF, 2003. The main difference being that the latter covers all land categories; forestland, cropland, grassland, wetland, settlement, etc. CO_2 and non-CO_2 gas emissions and removals from all land categories are estimated for the total land area of India.

The waste sector emissions also show a decreasing trend between 1990–1994 and 1994–2007 from 13.2% compounded annually to 7.3% compounded annually. Such significant decline can be attributed to effective implementation of water and sanitation programmes over a larger scale across the country.

Future directions

Improvement in quality of estimation should continue to be an important issue. Some of the steps that need to be taken may include recalculation of GHG emission inventory for the year 1994 so that a fair comparison can be made with the 2007 assessment and the subsequent assessments thereafter in the future. These recalculations could be in terms of usage of updated EFs, reducing uncertainties, and comprehensive coverage of source categories as well as GHGs. All the eight gases, namely CO_2, CH_4, N_2O, HFC-23, HFC-134a, CF_4, C_2F_6 and SF_6 can continue to be estimated for future assessments.

Furthermore, additional efforts can be made to develop the EFs of CO_2, CH_4 and N_2O for the 20 key sources identified. Extensive measurements of CH_4 emissions from waste disposal need to be carried out for class I, II and III cities. It has been reported that the composition of waste is changing, with organic component of waste having a smaller ratio than the non-organic component.

Iron and steel has been identified as a key source; therefore, it would be worthwhile to undertake representative measurements for different steel-making processes in the country that take into account the production process and fossil-fuel combustion. Sample surveys may be carried out to ascertain the amount of diesel and other liquid fuels being used in the country due to electricity outages, in commercial, domestic as well as agricultural operations, as the residential sector is already a key source for reducing the uncertainty in activity data. Further within this sector, there seems to be uncertainty associated with biomass consumption. In the industrial process sector, sources such as the manufacturing of electrical and electronic items need to be included, which are increasing every year. Further, sources such as the non-specific industries included in the energy sector, need to be identified, as, only a few of them have been so far considered in GHG assessments.

Notes

1. The Indian Network for Climate Change Assessment (INCCA) is an initiative of the Ministry of Environment and Forests, Govern-

ment of India. Details are provided elsewhere in this special section.
2. Teragram (Tg); 1 Tg = 1 million tonnes.
3. Tier 1 approach employs activity data that are relatively coarse, such as nationally or globally available estimates of deforestation rates, agricultural production statistics, and global land-cover maps. Tier 2 use the same methodological approach as tier 1, but applies emission factors and activity data which are defined by the country. Tier 3 approach uses higher-order methods, including models and inventory measurement systems tailored to address national circumstances, repeated over time, and driven by disaggregated levels.
4. Iron and steel, ferro-alloys, aluminium, lead, zinc and magnesium.
5. Cement, lime production, dolomite use, glass and ceramics.
6. Ammonia, nitric acid, carbon black, carbide, titanium dioxide, methanol, EDC and VCM, ethylene oxide, acrylonitrile and caprolactam.
7. Here estimates of HFC-23, HFC-134a, CF_4, C_2F_6 and SF_6 have been included. HFC-23 is generated as a by-product during the manufacture of HCFC-22. HCFC-22 is used as a refrigerant, as a blend component in foam-blowing and as a chemical feedstock for manufacturing synthetic polymers. All uses of CFC-12, an ozone-depleting substance in RAC sector have to be phased out. This is being replaced by HFC-134a, in domestic and commercial refrigeration, including air-conditioning, especially in the car segment. PFCs such as CF_4 and C_2F_6 are produced during aluminium production and SF_6 is also produced during magnesium production.
8. 1 Gg = 1000 tonnes = 10^{-3} Tg.

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