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N_2O emissions of India: an assessment of temporal, regional and sector trends

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Abstract This paper estimates the national level trend of India's N_2O emissions from 1985–2005 and detailed sub-regional (594 districts) level and sector emissions for the year 2005. N_2O emissions are estimated using the latest methodologies (IPCC 2006), disaggregated activity data and indigenized emission factors. The estimates show that India's N_2O emissions have grown from 144 Gg in 1985 to 267 Gg in 2005 exhibiting a compounded annual growth rate of 3.1%, which has been gradually declining from 4.7% over 1985–1990 to 2.4% over 2000–2005. N-fertilizer application contributed most to N_2O emissions, a 49% share in 2005 compared to 40% in 1985. Sub-regional (district-level) distribution of N_2O emissions showed rising mean and spread over the years, with average emissions per districts increasing from 305 ton N_2O per year in 1990 to 450 tons in 2005. The main reason being increased use of N-fertilizer. However crop selection plays an important role in N_2O emissions and there are crops providing high economic returns but low N-fertilizer requirements. Agriculture sector could contribute considerably to GDP even with very low N_2O emissions. Indian agriculture practices vary widely in input applications and crop yields across states. The gradual transition from traditional to modern agriculture over past two decades has enhanced the intensity of inputs like N-fertilizer. A simple correlation

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based on 1985–2005 trends shows that, *ceteris paribus*, a 10% increase in total crop production is accompanied with a 12.4% increase in N-fertilizer application and a 9.7% increase in total N_2O emissions from India.

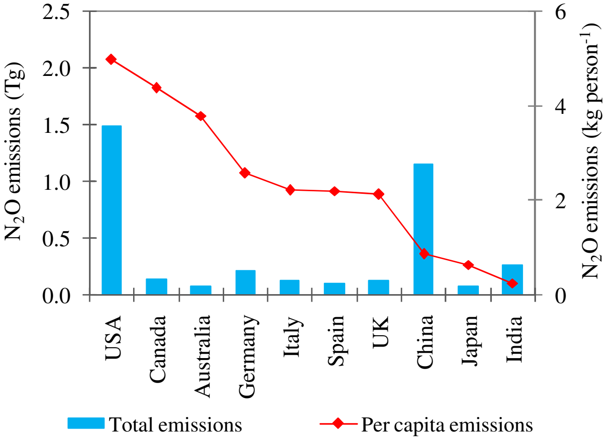
1 Introduction

Nitrous oxide (N_2O) is one of the six Kyoto greenhouse gases (GHG) contributing around 5% of the global GHG emissions (IPCC 2007a). Much concern is shown about it due to several reasons: (1) longer atmospheric lifetime and high global warming potential—310 times greater than carbon dioxide over a 100 year period (IPCC 2001), (2) important role in the photochemical formation of NOx, a component of acid rain (Sharma et al. 2008), (3) high influence on stratospheric ozone destruction. N_2O emissions from emerging economies are attracting global attention due to the high growth trend and high cost of mitigation (Garg et al. 2004; IPCC 2007a).

USA, China and India are the three largest contributors of N_2O emissions globally (Fig. 1). Agriculture sector activities (mainly nitrogen (N) fertilizer use) are the main contributor of global anthropogenic N_2O emissions (58%), with a much higher share in emerging economies like India (75%) and China (89%) (IPCC 2007b; ICTSD 2010). During 2005, 93 Tg of N-fertilizer was consumed globally, which has increased at a rate of 1.77% per year since 1995, out of which China (30 Tg) consumed the highest amount followed by India (13 Tg) and USA (11 Tg) (IFA 2008). The demand for N-fertilizer is expected to rise in the wake of rising global food demand (Ladha et al. 2005) and therefore understanding N_2O emission dynamics from India assumes contextual relevance.

Though Indian agriculture is second largest consumer of N-fertilizer in the world, its contribution to the global N_2O emissions is only 2.7% (Sharma et al. 2008). India is a predominantly agrarian country with over 650 million persons depending on agriculture related activities for their livelihoods. These represent over 60% of total Indian population and 70% of lowest income groups in Indian economic order (NSSO 2008). Therefore democratic governments (federal and state) are obliged to make facilitative policies for their welfare through appropriate interventions in the

Fig. 1 N_2O emissions from large emitter countries during 2005. UNFCCC (2008), Ecofys (2007), HDR (2007) and our estimates



agriculture sector, such as through targeted subsidy on N-fertilizer and electricity to farmers. These could however have adverse implications for N_2O emissions, as this paper would analyze. Integrated strategies are therefore needed so as to ensure climate friendly food security.

This paper estimates the national level trend of India's N_2O emissions from 1985–2005. Detailed sub-regional (594 districts) and sector emission estimates are also presented for the year 2005. The 594 districts reasonably capture the diversity of Indian emission patterns due to diverse resource endowments and agriculture practices. Above 80% of districts are smaller than 1 × 1 degree resolution and 60% are even smaller than 1/2 × 1/2 degree. District level emissions thus represent very finely gridded inventory information by international standards. Moreover, districts in India have well established governance structures which are well suited for implementing and monitoring mitigation measures. Our estimates also incorporate the most recent scientific estimation methodologies (IPCC 2006), indigenized emission factor estimates (Mitra et al. 2004) and best available district and sector level data sources for India. Our emission estimates are different from other inventory estimates such as INCCA (2010) mainly due to different years of estimation, bottom-up activity data coverage and application of the latest IPCC (2006) methodology.

2 Emission sources

N_2O emissions have been estimated from energy sector (fossil fuel and biomass burning), industrial processes (nitric acid production), agricultural activities (direct, indirect emissions, agriculture residue burning), and waste (municipal waste management). Direct N_2O emissions from soil mainly occur during microbial nitrification and denitrification processes, during which N_2O leaks into the soil as a gaseous intermediate and a by product, and ultimately adds to the atmosphere. Indirect N_2O emissions from managed soil occur through two pathways. The first involves volatilization with subsequent deposition of N onto soils and waters, while the second includes leaching and runoff of N from anthropogenic input into groundwater, riparian areas, wetlands, rivers, and eventually the coastal ocean. Such excess of inorganic N present in soil and water gets transformed into N_2O through combined nitrification and denitrification processes.

Over a fourth of the total primary energy requirement for India and two third of rural Indian energy requirement are met by biomass energy (Ravindranath et al. 2007). It is interesting to note that, biomass burning is considered as carbon-neutral in case of CO_2 emissions (IPCC 2006), where as the same source contributes a major portion of N_2O emissions, even higher than fossil based emissions (Garg et al. 2006).

3 Methodology, activity data and emission factors

3.1 Activity data

Emission inventory estimation has three building blocks—methodology, activity data and emission factor. The activity data is captured at quite sufficient disaggregated level (sub-regional and sector) for India. These are mostly based on published

Table 1 Allocation index for disaggregated data

Activity data	Year of available data	Level (and source)	Allocation/estimation index	
			Need	Methodology
Human population	2001	District (CoI 2001)	2005 data	1991–2001 CAGR[a]
District GDP	2006	District (Indicus Analytics 2006–2007)	2005 data	2001–2006 district level GDP growth rate database (Indicus Analytics)
Livestock population	2003	District (DAHDF 2008)	2005 data	1997–2003 CAGR
Charcoal consumption	2005	State (NSSO 2007)	District level data	Allocated to rural population using 2005 urban–rural population ratio
Fuel wood consumption	2005	State (India Stat 2008)	District level data	Sector allocation to brick industry (Pachauri 2006) and residential sector (Ravindranath et al. 2007). District level allocation to rural population using urban–rural population ratio
Dung cake production			District level data for 2005	Dung generation rate (Mitra et al. 2004), district level livestock population and Ravindranath et al. (2007)
Biogas generation			District level data for 2005	% of dung used for biogas plant (Ravindranath et al. 2007), biogas generation factor (MNRE 2008)
Fossil fuel combustion				
Gasoline, diesel and fuel oil	2005	National (CMIE 2007)	District level data	State level allocation using 1995 fuel consumption (Garg and Shukla 2002). District level using total population

Coal (rail transport)	2005	Zonal level data (IR 2006; CMIE 2007)	District level data	Allocated using district level track km for coal-using traction routes only
Coal use (residential)	2005	National (CMIE 2007)	District level data	Number of household
Diesel (rail transport); aviation turbine fuel; diesel and fuel oil (navigation and other transport)	2005	National (CMIE 2007)	District level data	Total population
Natural gas & liquefied petroleum gas (residential); coal (commercial)	2005	National (CMIE 2007)	District level data	Urban population
Nitric acid production	2005	National (Mitra et al. 2004)	District level data	Plant location and capacity (CMIE 2008a)
Municipal solid waste generation	2005	National	District level data	Per capita MSW generation (CPCB 2007), urban population and UMP (1999)

Data sources for categories where no allocation was needed since 2005 district level data was available—crop production and area sown (CMIE 2008b), synthetic fertilizer used (FAI 2006), energy industries (CEA 2006; Indiastat 2007; MoPNG 2008), large point source data from sectoral reports (SAIL 2004; Essar 2005, 2006; JSW 2005; CMA 2006; FAI 2006; CRIS INFAC 2007a, b; Pachauri 2006; Das and Kandpal 1998; CMIE 2007, 2008a, b; Indiastat 2007, 2008)

[a] India conducts decadal population census. The last one was conducted in 2001

Table 2 Methodology used for estimation of N_2O emissions (IPCC 2006)

Emission source	IPCC (2006) methodology	Tier[a]	Equation no.	Emission factors used for this study
Direct N_2O emissions	Vol. 4 (AFOLU) Ch. 11	2	11.1	
Synthetic fertilizer used	Vol. 4 (AFOLU) Ch. 11	2	11.2	Table 3
Organic nitrogen applied to the soil	Vol. 4 (AFOLU) Ch. 10, 11	2	11.2 to 11.4, 10.34	Table 4
Nitrogen from crop residue left	Vol. 4 (AFOLU) Ch. 11	2	11.6	Table 5
Indirect N_2O emission	Vol. 4 (AFOLU) Ch. 11	2	11.9, 11.10	Table 6
Agriculture residue burning (onsite)	Vol. 4 (AFOLU) Ch. 2, 11	2	2.27	Table 7
Biomass burning (offsite) (fuel-wood, charcoal, dung-cake and biogas)	Vol. 2 (ENERGY) Ch. 2	1	2.1	Table 8
Fossil fuel combustion	Vol. 2 (ENERGY) Ch. 2	1, 2/3[b]	2.1	Table 8
Industrial processes	Vol. 3 (IPPU) Ch. 3	2, 3	3.5	Table 8
Waste management	Vol. 5 (WASTE) Ch. 4, 6	1, 2	4.2, 6.7, 6.8	Tables 8 and 9

[a] Tier represents the level of methodological complexity. Tier 1 is the basic method, tier 2 intermediate and tier 3 most detailed in terms of complexity, accuracy and data requirements

[b] Transport and residential at tier 1 level, while industry and power estimations at tier 2/3 levels

Table 3 Direct N_2O emission

Emission factor	kg N_2O_N/kg N input
EF_1	0.0065

INCCA (2010), Bhatia et al. (2010), Mitra et al. (2004), Pathak (1999)

sources of the Government of India, industry associations and international organizations. The activity data used is at sub-regional (district) level, generally termed bottom-up data. In a few instances, where district level data was not available, a higher aggregated data was allocated to districts based on a suitable allocation index like district population, area, road density etc for 2005 (Table 1). All activity data are collected for the years 2004–2005 and 2005–2006.[1] Most activity data for stationary emission sources are collected at large point source (LPS) level, based on published central and state government sources, plant level reports, latest statistical and annual reports of various ministries, industries, and paid statistical databases. We have tried to cross-verify activity data from two independent sources for most LPS, to the extent available.

Activity data sources used for preparation of national N_2O emission inventories for 1985–2005 are those sources which had all these year's activity data at one place so as to minimize source based data errors. These data are at national level and are generally termed as top–down data. Top–down data may not exactly match with bottom-up district level data due to aggregation errors. Some minor error is also introduced due to different data sources, especially for biomass production.

3.2 Methodology and emission factors

Main source categories and the respective detailed IPCC (2006) methodology used for emissions estimation have been summarized in Table 2, however detailed equations and explanation of methodology is not given in this paper to avoid repetition of already published IPCC methodological guidelines (2006). For the emission factors, we have used published emission factors for India that are based on actual measurements conducted in field trials to estimate India specific actual emissions. These measurements have been conducted by Indian scientists at many national laboratories involving N_2O emissions measurements from diverse source categories such as synthetic fertilizer application to rice and wheat cropping systems, biomass combustion, livestock activities, and nitric acid production. These are documented in Mitra et al. (2004), the seminal work on Indian emission measurements till date, which we have used extensively for emission estimation. We have used the IPCC default emission factors only where India specific measured emission factors were not available.[2] Emission factors used for each source category have been presented separately in Tables 3, 4, 5, 6, 7, 8 and 9.

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[1] Indian financial year 2005–2006 is 1st April 2005 until 31st March 2006. The calendar year 2005 data is estimated as sum of 75% of 2005–2006 year data and 25% of 2004–2005 year data.

[2] The lead author has also been fortunate enough to be a Coordinating Lead Author of IPCC (2006) GHG inventory guidelines (Energy volume) and a member of the Editorial Board of IPCC Emission Factor Database (EFDB), the premier UN body on GHG emission measurement repository.

Table 4 Organic nitrogen (F_{ON}) applied to the soil

Livestock species	N excretion rate $Nex_{(T)}$ (kg N animal^{-1} year^{-1})[a]	Live-weight (kg)[b]	% N lost during manure management FracLossMS[c]	% N managed in manure management system MS[d]
Dairy cattle	41.17	240	28	0.5
Other cattle	29.78	240	50	0.5
Buffalo	33.29	285	15	0.5
Sheep	11.53	27	15	0.5
Goats	12.50	25	15	0.5
Swine	7.30	40	25	0.5
Poultry	1.50	5	50	0.5
All others	3.36	20	15	0.5

[a] Estimated using IPCC (2006) default N excretion rate and live-weights
[b] Mitra et al. (2004)
[c] IPCC (2006)
[d] Discussion with sectoral experts
$Nex_{(T)}$ annual average N excretion per animal of species/category T, *FracLossMS* amount of managed manure nitrogen for livestock category that is lost in the manure management system, *MS* fraction of total annual nitrogen excretion for each livestock species/category T that is managed in manure management system

To give an example of the rigor in our estimates, direct N_2O emission estimates from managed soil uses tier 2 methodology for human induced N input to the soil including application of synthetic fertilizer (nitrogenous), organic N (livestock manure) applied as fertilizer, and N from crop residues left on ground rather than burnt of all species (including N-fixing crops). The equation used for estimation of direct N_2O from managed soils is as under:

$$N_2O_{Direct} = (F_{SN} + F_{ON} + F_{CR}) \cdot EF_1 \cdot (44/28)$$

where

F_{SN}	Annual amount of synthetic fertilizer N applied to soils, kg N year^{-1}
F_{ON}	Annual amount of animal manure applied to soils, kg N year^{-1}
F_{CR}	Annual amount of N in crop residues (above-ground and below-ground), including N-fixing crops, and from forage/pasture renewal, returned to soils, kg N year^{-1}
EF_1	Emission factor for N_2O emissions from N inputs, kg N_2O–N (kg N input)$^{-1}$

India specific value of EF_1 (0.0065) is taken for the estimation including rice and wheat cropping systems (Mitra et al. 2004). District level consumption of synthetic nitrogenous fertilizer (F_{SN}) for the year 2005–2006 is taken (FAI 2006).

Other components of direct emissions are calculated as per IPCC (2006) methodology by using IPCC default as well as India specific factors (Tables 3 and 4) for the different species of livestock (F_{ON}) including dairy cattle, other cattle, buffalo, sheep, goats, swine, poultry, and others (DAHDF 2008); and crops (F_{CR}) including rice, wheat, maize, other cereals, pulses, groundnut, sugarcane, rapeseed and mustard, cotton, other seeds, coconut and other crops (CMIE 2008b).

Topography and geology have been taken into consideration while estimating the indirect N_2O emissions by potential leaching and runoff in respective regions of India. N_2O emissions from leaching and runoff are taken as 25% in Himachal

Table 5 Nitrogen from crop residue left (F_{CR})

Crop name	Slope	Intercept	Ratio of below ground and above ground biomass R_{BG_BIO}	N content of above-ground residues for crop T (kg N kg d.m.$^{-1}$) $N_{(AG)}$	N content of below-ground residues for crop T (kg N kg d.m.$^{-1}$) $N_{(BG)}$
Rice	0.95	2.46	0.16	0.007	0.009
Wheat	1.51	0.52	0.24	0.006	0.009
Maize	1.03	0.61	0.22	0.006	0.007
All other grains	1.09	0.88	0.22	0.006	0.009
Soyabeans	0.93	1.35	0.19	0.008	0.008
Pulses	1.13	0.85	0.19	0.008	0.008
Groundnuts	1.07	1.54	0.20	0.016	0.014
Sugar cane	0.18	0.00	0.54	0.150	0.012
Rapeseed & Mustard	1.13	0.85	0.19	0.008	0.008
All others	0.30	0.00	0.22	0.015	0.012

IPCC (2006)
kg d.m. kilogram of dry matter

Table 6 Indirect N_2O emission factors

Factor	Value
EF_4[a] (Kg N N_2O (kg $NH_3\_N + NOx\_N$ volatized)$^{-1}$)	0.005
EF_5[b] (kg N_2O-N (kg N leached and runoff)$^{-1}$)	0.0075
$Frac_{GASF}$[a] (Kg N volatized (kg N applied)$^{-1}$)	0.15
$Frac_{GASM}$[b] (Kg N volatized (kg N applied or deposited)$^{-1}$)	0.2
$Frac_{LEACH\text{-}(H)}$[b] (Kg N (kg of N additions)$^{-1}$)	0.3

[a] Bhatia et al. (2004)
[b] IPCC (2006), Mitra et al. (2004)

Table 7 Field burning of agriculture residue

Factor	Value
$Frac_{Remove(T)}$[a]	0.8
Combustion factor (C_f)[b]	0.9 (wheat), 0.8 (all others)
Emission factor (G_{ef})[b]	0.07

[a] Discussion with sectoral experts
[b] IPCC (2006)

Table 8 N_2O emission factor for fossil fuel consumption, biomass burning, industrial process and municipal solid waste management

Source category	N_2O emission coefficient
Crude oil and oil products[a]	0.6
Natural gas and liquefied petroleum gas[a]	0.1
Jet fuel (aviation turbine fuel)[a]	2
Coal products[a]	1.5
Charcoal consumption[b]	4
Wood or wood waste and dung-cake[a]	4
Biogas burning[a]	0.1
Nitric acid production (kg N_2O Ton^{-1})[c]	8.43
Biological treatment of municipal solid waste (composting) (g N_2O (kg waste treated)$^{-1}$)[a]	0.3

[a] IPCC (2006)
[b] IPCC (1996)
[c] Mitra et al. (2004)

Table 9 Domestic waste water treatment

Factor	Value
$EF_{EFFLUENT}$ (emission factor, kg N_2O-N (kg N)$^{-1}$)[a]	0.005
Annual per capita protein consumption (kg person^{-1})[b]	18.25
F_{NPR} (fraction of nitrogen in protein, kg N (kg protein)$^{-1}$)[a]	0.16
$F_{NON\text{-}CON}$ (non-consumed protein added to the waste water)[a]	1.2
$F_{IND\text{-}COM}$ (industrial and commercial co-discharged protein into sewer system)[a]	1.25

[a] IPCC (2006)
[b] Grigg (1995)

Pradesh, Maharashtra, Orissa, Andhra Pradesh, Karnataka, Kerala, Tamil Nadu, Dadra and Nagar Haveli, Daman and Diu, Pondicherry and states of NE region; where as 50% for the remaining states and union territories (Sharma et al. 2008).

Dung-cake production was taken differently in HP, J&K, Kerala, Goa, Sikkim, Arunachal Pradesh, Nagaland, Manipur, Mizoram, Tripura, Meghalaya, Assam as 10% of the total dung generation where dung-cake is not used as a chief source of cooking fuel, 30% in Delhi, and 90% for all other areas (Mitra et al. 2004).

4 Emission trends

4.1 National emission trends over 1985–2005

The absolute N_2O emissions from India during the years 1985, 1990, 1995, 2000 and 2005 are estimated as 144, 181, 215, 238 and 267 Gg respectively (Table 10). These emission estimates are an improvement over our own previous estimates (Garg et al. 2006). The major changes in present emission estimates are mainly due to inclusion of some new source categories that were missed in our previous estimates for the same year 2005 (such as 16.8 Gg added due to N from crop residue left, 11.5 Gg added due to Organic N applied to the soil); new emission factors (0.0065 kg N_2O–N per kg synthetic fertilizer applied instead of earlier 0.01), coal combustion, agriculture crop residue burning, indirect emissions volatilization, Nitric acid production); new methodology (full sectoral coverage of indirect N_2O emissions added 34.4 Gg); and changed activity data for 2005 (actual numbers available now against estimates in previous inventory).

Total national N_2O emissions have exhibited a compounded annual growth rate of 3.1% during 1985–2005, which has been gradually declining from 4.7% over 1985–1990 to 2.4% over 2000–2005. The source level emissions have also been growing slowly over the years. For instance, N_2O emissions from synthetic N fertilizer use

Table 10 N_2O emissions from various source categories, 1985–2005

Source category	Emissions (Gg)					% CAGR,1985–2005
	1985	1990	1995	2000	2005	
Direct N_2O emissions	78	104	124	139	159	3.6%
Synthetic fertilizer use[a]	58	82	101	112	131	4.1%
N from crop residue left[a]	10	12	14	16	17	2.6%
Organic N applied to the soil[a]	10	9	9	11	12	0.8%
Indirect N_2O emissions	17	22	27	30	34	3.7%
Field burning of agriculture residue	4	5	7	8	8	3.2%
Biomass burning	21	22	24	26	26	1.1%
Coal consumption	6	8	10	12	13	4.1%
Petroleum fuels consumption	1	1	2	3	3	4.7%
Gas consumption	0.01	0.04	0.05	0.08	0.09	9.6%
Industrial processes	8	8	11	9	9	1.1%
Waste	9	9	11	12	14	2.0%
Total N_2O Emissions	144	181	215	238	267	3.1%

[a] These three are sub-source categories of direct N_2O emissions as per IPCC (2006) categorization

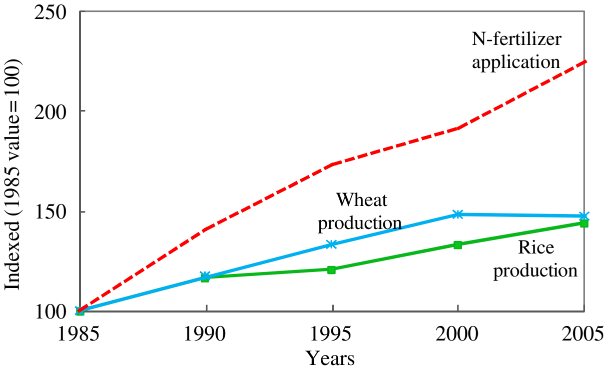
increased by 7.2% per year over 1985-1990, while by only 3.2% over 2000–2005. This does not necessarily mean that N fertilizer use efficiency has been increasing. It may be the reverse case. To clarify, the corresponding increase in crop production has been 5.6% per year over 1985–1990, while by only 0.5% over 2000–2005. All India average crop yields for rice were 1.46 tons ha^{-1} in 1985 and it changed to 1.69 tons ha^{-1} (1990), 1.89 tons ha^{-1} (1995), 1.92 tons ha^{-1} (2000) and 2.08 tons ha^{-1} (2005). Similarly, wheat yields were 0.84 tons ha^{-1} (1985), 2.24 tons ha^{-1} (1990), 2.38 tons ha^{-1} (1995), 2.59 tons ha^{-1} (2000) and 2.71 tons ha^{-1} (2005). It implies that at national level, while crop productivity per unit area is moving towards saturation levels for existing technology applications, N fertilizer application is increasing year-on-year (Fig. 2). There are wide variations in sub-regional trends. These are discussed in later sections and implications thereof.

4.2 Sector emissions trends

Agriculture sector accounts for around 75% of total N_2O emissions in 2005, including around 49% from nitrogen fertilizer use, 13% from indirect soil emissions, 6% from decaying of crop residue, 4% from livestock manure used as organic fertilizer and 3% from (onsite) agriculture residue burning (Table 10). Sources other than agriculture sector namely biomass (offsite) burning, fossil fuel combustion, municipal waste management and nitric acid production contribute 10%, 6%, 5% and 4% respectively.

There has been significant growth of Indian agriculture sector during last several decades. Food grain production in 1951–1952 (52 Tg) rose to above 232 Tg in 2004–2005 (DoF 2006). Mainly after the severe drought of 1965–1966 and food aid cessation due to the Indo-Pakistan war of 1965, increase in food-production remained under major focus of Indian policymakers. Such tremendous success in the agricultural sector was not possible without a significant role of chemical fertilizer. During the same period, use of synthetic fertilizer (63% share of N-fertilizer) grew from 0.066 to 20.34 Tg with 11.4% CAGR (FAI 2006). Besides higher application of N fertilizer, increased area under different crops and increase in animal population also increased the N_2O emissions from agriculture sector.

Fig. 2 Total rice, wheat production and N-fertilizer application in India over the years



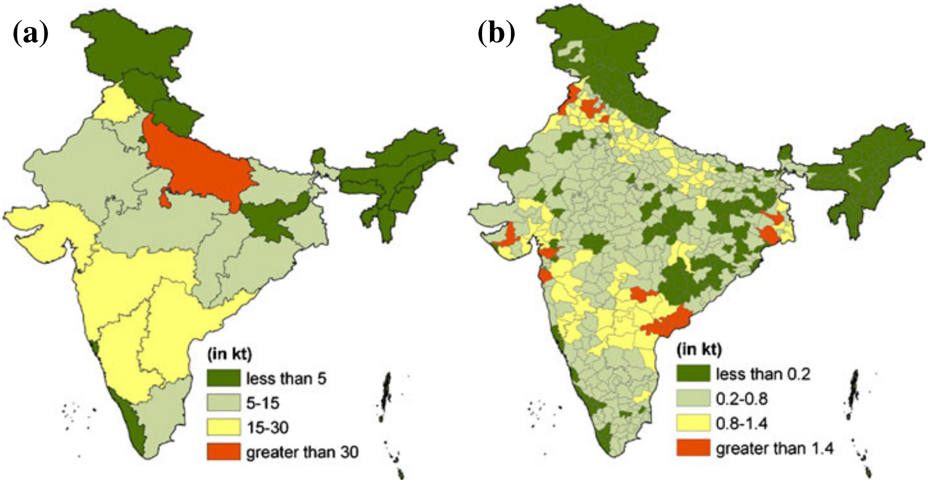


Fig. 3 **a** State level N_2O emissions from India, 2005 **b** District level N_2O emissions from India, 2005

5 Regional emission analysis

Figure 3(a, b) illustrate state and district level N_2O emission in 2005. Out of total 35 states and union territories in India, twelve states contributed more than 10 Gg each in 2005 accounting for 90% of total Indian N_2O emissions, with Uttar Pradesh (UP) being the largest contributor at 52 Gg, followed by Maharashtra, Andhra Pradesh

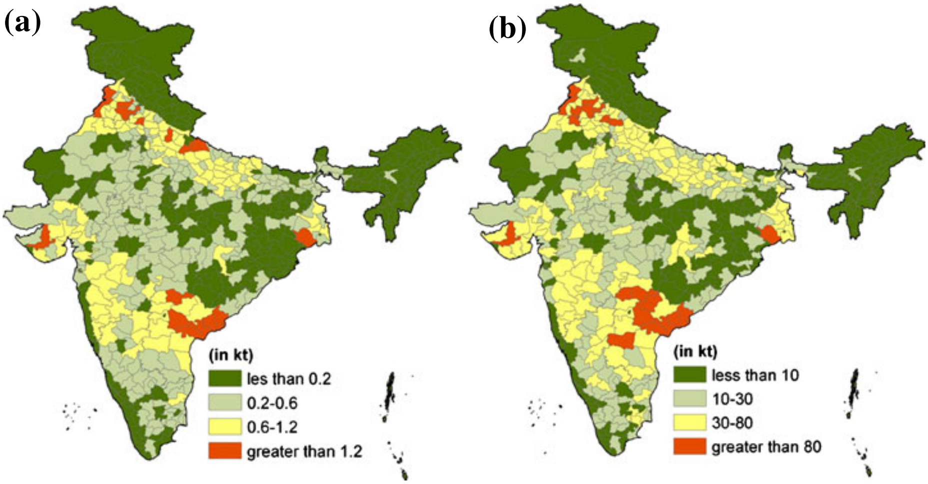


Fig. 4 **a** N_2O emissions from Agriculture activities in India, 2005 **b** Nitrogenous fertilizer application in India, 2005

Table 11 Food grain production and use of nitrogenous fertilizer in 2005

States	N-fertilizer applied ($\mathrm{kg\ km^{-2}\ year^{-1}}$)	Food grain production ($\mathrm{kg\ km^{-2}\ year^{-1}}$)	Annual food grain production/ nitrogen applied ($\mathrm{kg\ kg^{-1}}$)	Composition and share of food grain produced
Punjab	15550	398636	25.64	Rice (40%), wheat (58%)
Haryana	13190	304491	23.08	Rice (25%), wheat (68%)
West Bengal	6500	242291	37.28	Rice (93%)
Andhra Pradesh	12160	236491	19.45	Rice (69%), Maize (18%)
Pondicherry	57150	217958	3.81	Rice (97%)
Uttar Pradesh	9910	205745	20.76	Rice (28%), wheat (60%)
Gujarat	7530	155130	20.60	Rice (21%), wheat (40%), Bajra (17%)
Bihar	8820	131128	14.87	Rice (41%), wheat (38%)
INDIA	6665	171589	25.74	Rice (44%), wheat (33%)

Estimated using FAI (2006), CMIE (2008b)

(AP) and Punjab contributing 30, 26 and 20 Gg respectively. The 50 largest N_2O emitting districts (including 12 from UP, 10 from Punjab, nine from AP, and five each from Gujarat and West Bengal and four from Maharashtra) contributed more than one fourth of the Indian national emissions in 2005. UP is the most populous state in India, almost equal to combined population of France, Germany and Spain. Its N_2O emissions were however only one-ninth of combined N_2O emissions from these three countries in 2005 (UNFCCC 2008).

Around 70% of the synthetic N-fertilizer is used for food grain production in India followed by oilseeds (8%) and remaining for other crops (FAI 2006). This is the main reason why higher grain producing states like Uttar Pradesh, Punjab and Andhra Pradesh are top N-fertilizer consumers and in-turn top N_2O emitters (Fig. 4a, b). Synthetic N-fertilizer use efficiency (food grains produced per unit of fertilizer applied) varies across districts based on crop-mix, agriculture practices and other agricultural inputs. On an average, 25.7 kg food grains were produced per kg of N-fertilizer applied in India in 2005 (Table 11). West Bengal had a high average of 37.3, while large grain producers such as Punjab, Haryana and Uttar Pradesh had it in the range 20–25 kg grains per kg fertilizer. West Bengal mainly produces rice paddy which consumes lower nitrogen fertilizer as compared to wheat. West Bengal is also high in other agriculture inputs such as organic fertilizer and water, off-setting need for N fertilizer to some extent.

N-fertilizer applied per unit cropped area and crop yield have wide differences across the Indian states and districts (Fig. 5). Such differences and high fertilizer use in several regions are found mainly due to unsustainable practices such as excessive use of water along with imbalanced use of chemical fertilizers, decreased use of organic fertilizer, decreasing carbon/organic matter content, deficiency of micro nutrient etc. Such effect is found very strongly in the 'green revolution' areas of northern and northwestern parts of India, where fertilizer consumption is comparatively high, and the response ratio of grain output to fertilizer input has declined over recent years.

The district level distribution has also undergone a substantial change over 1990–2005. Efficiency of fertilizer application vis-à-vis grain production has gone down in many districts during 1990–2005. This resulted in an increase in N_2O emissions per unit area without corresponding gain in food grain yield per hectare, indicating

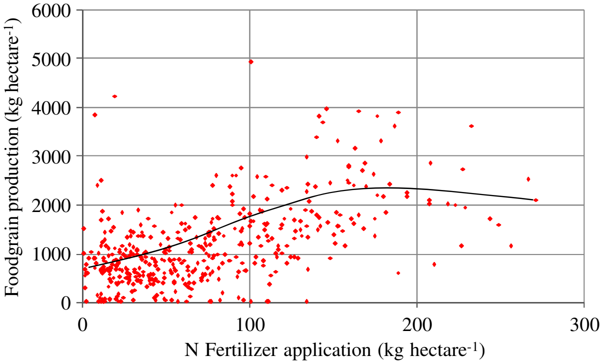


Fig. 5 Fertilizer use efficiency of Indian districts, 2005

Table 12 Sector N_2O emissions and some driving parameters of highest emitter states in India, 2005

State	% share of concerned state's N_2O emissions				All India % share of				
	N-fertilizer used	Organic N applied to soil	Indirect	Others	Total N_2O emissions	Livestock population	N-Fertilizer used	Rice grown	Wheat grown
Uttar Pradesh	49%	3%	17%	31%	19%	13%	19%	12%	35%
Maharashtra	37%	3%	5%	55%	11%	8%	8%	3%	2%
Andhra Pradesh	61%	4%	8%	27%	10%	12%	12%	13%	–
Punjab	66%	2%	20%	13%	7%	2%	10%	11%	21%
Gujarat	48%	3%	16%	33%	7%	5%	7%	1%	4%
Karnataka	51%	4%	7%	38%	6%	5%	6%	6%	0.3%
West Bengal	44%	6%	15%	35%	5%	9%	5%	16%	1%
Haryana	62%	2%	20%	16%	5%	2%	7%	3%	13%
Tamil Nadu	43%	5%	6%	45%	5%	5%	4%	6%	–
Bihar	54%	5%	18%	23%	5%	5%	5%	–	5%
India (Tg)	0.131	0.012	0.035	0.090	0.267	470.5[a]	12.72	91.79	69.35

[a] Million number

Table 13 Distribution of N_2O emissions from Indian districts

No. of largest emitter districts	% of total emissions	
	1995	2005
1 to 5	5.0	6.4
1 to 15	13.8	12.7
1 to 25	21.3	17.8
1 to 47	34.2	27.7
1 to 233	86.1	77.0
1 to 350		91.3
Total (1–594)	100	100

a possible over application of synthetic fertilizers. Subsidized fertilizer prices could be one reason for this trend as well as lack of proper and sufficient knowledge with farmers in optimizing the integrated use of fertilizers and other farm inputs for higher crop yields.

Table 12 provides sector N_2O emissions and some driving parameters of highest emitter states. N-fertilizer application is the main source of emissions. Wheat–rice cultivation, in that order, appears to drive this. Though the food grain production of Punjab is higher than Andhra Pradesh, it's N_2O emissions are lower. This is because of higher N-fertilizer use efficiency of Punjab (25.6 kg kg^{-1}) than that of Andhra Pradesh (19.5 kg kg^{-1}) as well as higher population of livestock in Andhra Pradesh (12%). Other food-grain producing states with high N-fertilizer use efficiency are Orissa (48.3 kg kg^{-1}), Madhya Pradesh (40.8 kg kg^{-1}), West Bengal (37.3 kg kg^{-1}), Rajasthan (31.3 kg kg^{-1}) and Karnataka (30.1 kg kg^{-1}), thus having lower N_2O emissions.

The district level N_2O emission range analysis indicates decline in percentage share of largest emitter districts over 1995–2005 (Table 13). Thane (Maharashtra), Firozpur (Punjab), West Godavari and Guntur (Andhra Pradesh) and Amritsar (Punjab) are the highest emitting five districts across India and contribute about 6.4% of national N_2O emissions. 85% of all India nitric acid production happens in Thane contributing about 3% of the national N_2O emissions.

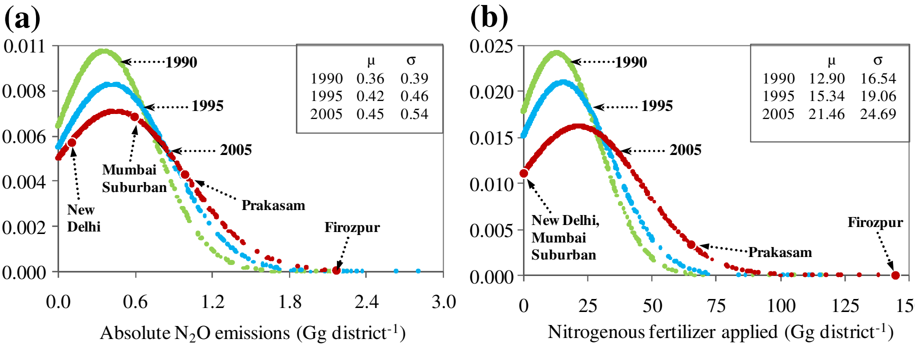


Fig. 6 **a** District level absolute N_2O emissions during 1990, 1995 and 2005 **b** District level nitrogenous fertilizer applied during 1990, 1995 and 2005

The standard deviation of district level N_2O emissions during 2005 has increased 38% with respect to that in 1990 and 17% from 1995 (Fig. 6a). This indicates an upward shift in annual N_2O emissions from more and more districts with time. The main reason for such growth pattern can be noticed from Fig. 6(b) showing almost a similar change in N-fertilizer use across districts. The small emitter districts lie in states such as Bihar, Jharkhand, Orissa, Chhattisgarh, Rajasthan and north-eastern states. These districts have less agriculture development and had mostly missed the first green revolution wave. Bihar could be a sleeping giant in agriculture revolution with availability of fertile soil, laborious work force and an awakening society. Its agriculture transformation could lead India to a second green revolution or an evergreen revolution. Major barriers include regular floods and draughts, slow land reform implementation, low adoption of new farming technologies, and low resource utilization.

In view of per unit area emission, New Delhi is the largest with 45 times higher per area emissions than Indian average, mainly due to its smaller size but considerable coal and gas consumption. For a per capita emission analysis, Indian N_2O emissions were 0.26 kg capita^{-1} year^{-1} in 2005, which converts to 0.08 tCO_2e capita^{-1} year^{-1}. It has increased annually by 1.5% over 1995–2005 (Fig. 7). Muktasar (1.38 kg N_2O capita^{-1} year^{-1}), Mansa and Firozpur from Punjab, Karnal and Faridkot from Haryana are the five highest emitter districts on per capita basis. However only a few Indian districts reach anywhere near the average Chinese per capita emissions (0.88 kg N_2O capita^{-1} year^{-1}), while they are far away than the per capita USA emissions (4.96 kg N_2O capita^{-1} year^{-1}).

Table 14 represents India's hot spot emitter districts in each source category in 2005. Absolute as well as per capita N_2O emissions from state capital district can be seen in Fig. 8. Raipur and Pondicherry are the highest in terms of absolute and per capita N_2O emissions respectively; both are having highest contribution of emissions from N fertilizer use.

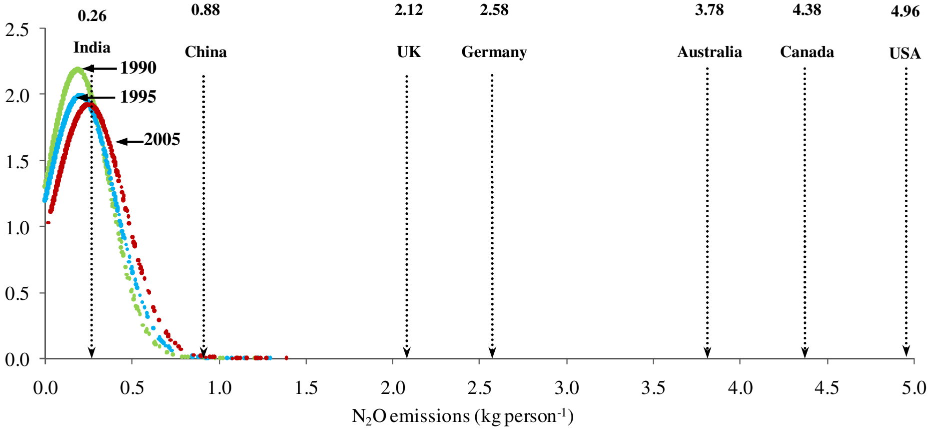
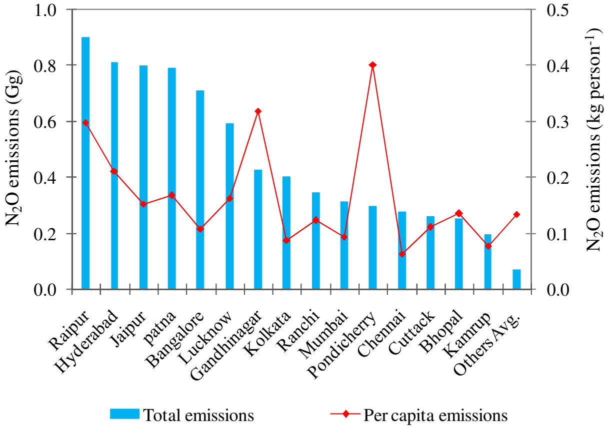


Fig. 7 Per capita N_2O emission distributions (kg person^{-1} year^{-1}) of India during 1990, 1995 and 2005 as compared to some other countries in 2005

Table 14 N_2O emitter hotspot districts for different source categories, 2005

Source Categories	Largest	Second	Third	Fourth	Fifth
Synthetic fertilizer use	Firozpur	West Godavari	Guntur	Sangrur	Amritsar
N from crop residue left	Uttar Kannada	Viluppuram	Erode	Allahabad	Azamgarh
Organic N applied to the soil	Coimbatore	Cuddapah	Barddhaman	Murshidabad	South Twenty Four Parganas
Indirect N_2O emissions	Firozpur	Sangrur	Amritsar	Patiala	Karnal
Agriculture residue burning	Uttar Kannada	Viluppuram	West Godavari	Allahabad	Erode
Coal combustion	Sonbhadra	Anugul	Korba	Bokaro	East Godavari
Oil combustion	Mumbai	Jamnagar	Mumbai (Suburban)	Vadodara	Thane
Nitric acid production	Thane	Bharuch	Hyderabad	Ernakulam	Kupwara
All India	Thane	Firozpur	Guntur	West Godavari	Amritsar

Fig. 8 N_2O emissions from state capital districts, 2005

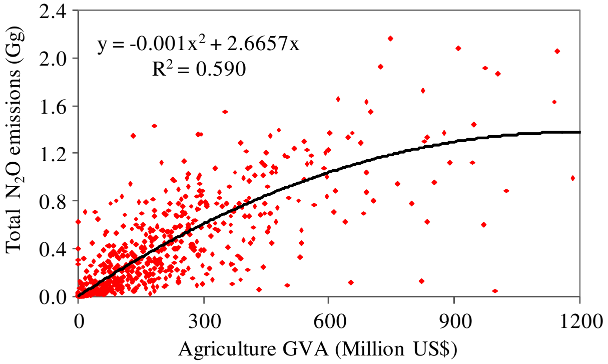


6 Emission efficiency

6.1 N_2O emissions and economic value addition

Agriculture sector's contribution to India's GDP has been declining over the years, from 23% in 1985 to 18.5% in 2005 (Economic survey 2006–2007). Figure 9 plots district level N_2O emissions as a function of agriculture gross value added (GVA) from the corresponding district in 2005. Analyzing the correlation of N_2O intensity and agriculture GVA offers some interesting insights. About 42% of total N_2O emission variation is explained by district level agriculture GVA. This improves to 47% if some outlier districts are excluded. If we take only agriculture related N_2O emissions versus agriculture sector GVA, this improves to 59%. The outlier districts are way below the regression line, with less than 10,000 tons N fertilizer used per year and annual agriculture GVA of more than US$ 300 million. These are districts that have considerable tea plantations and spice cultivation, such as Darrang, Dibrugarh, Sibsagar districts (all in Assam); and Idukki, Wayanand and Malappuram districts (all in Kerala). These crops do not contribute much N_2O emissions due to lower need for N fertilizers, continuous nature of crops, and cultivation practices such as

Fig. 9 Relationship between total N_2O emissions and agriculture GVA



minimal crop residue burning etc. (Saseendran et al. 2000). On the other hand (above the regression line) we have districts in grain dominant states such as Punjab and Andhra Pradesh that consume over 100,000 tons N fertilizer per annum along with annual agriculture GVA of more than US$ 300 million. These include Firozepur, Sangrur, Amritsar, Ludhiana and Amritsar districts (all in Punjab); and Guntur, East and West Godavari, Karimnagar and Krishna districts (all in Andhra Pradesh). These districts produce almost 10-times more N_2O per unit cropped area than the former set of outliers, even though the share of economic value addition by agriculture sector to concerned district's gross annual product is almost the same for both groups. Crop selection therefore plays an important role in N_2O emissions. Figure 10 provides N_2O emission efficiency of net state domestic products (NSDP) for some states in 2005 (in kg N_2O per million US$). The insight drawn is that agriculture sector could contribute considerably to GDP even with very low N_2O emissions.

6.2 N_2O emissions and agriculture sector productivity

The second insight correlates agriculture sector productivity with N-fertilizer application. Indian districts can be classified into modern, transitional and traditional in agriculture technology based on tilling practices, fertilizer (NPK) application, irrigation availability, seed quality, soil quality management, and other scientific crop management practices (Moulik et al. 1991). Resultant crop yields per hectare would be different for the three categories. Let us consider two main staple crops in India—rice and wheat. Table 15 provides N-fertilizer application per unit of cropped area and corresponding average rice-wheat productivity for all the Indian districts lying in specific fertilizer application range. It may be noted that the national average hides the state level variability in distribution for each category. Table 16 provides the

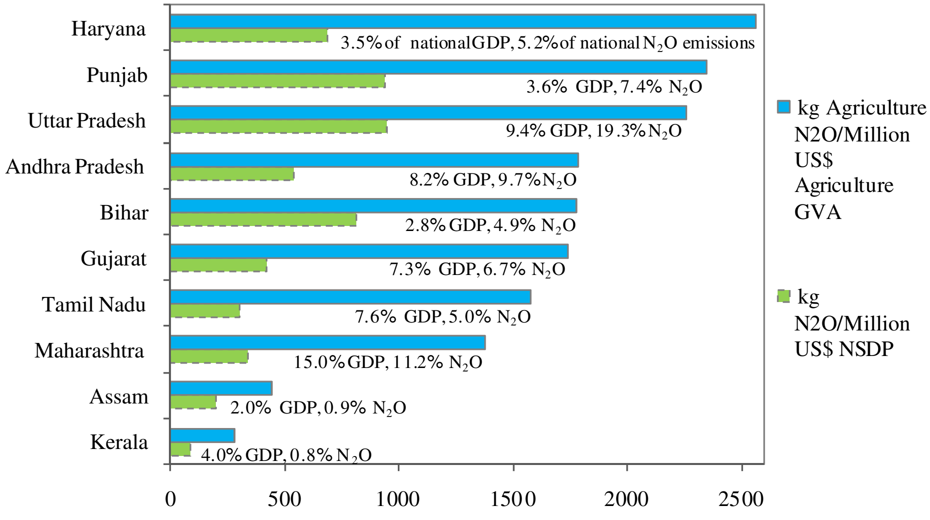


Fig. 10 N_2O emission efficiency of net state domestic products (NSDP) for some states in 2005 (in kg N_2O per million US$)

Table 15 N-fertilizer use, rice and wheat productivity

Avg N-fertilizer (kg ha^{-1})	Number of districts	Average rice productivity (ton ha^{-1})	Average wheat productivity (ton ha^{-1})	States where these districts are located (with number of districts)
>300	3			Tripura (2), Pondicherry (1)
200–300	16	3.31	3.20	Haryana (5), TN (3)
150–200	37	3.99	3.27	Punjab (12), UP (9), AP (5), Bihar (1)
100–150	78	2.88	3.39	UP (24), Bihar (15), TN (9), AP (5), Haryana (5), Punjab (5)
75–100	59	2.94	2.88	UP (19), Mah (7), Bihar (6), Raj (6), Kar (5)
50–75	68	2.69	2.14	Mah (8), Raj (8), 6 each – AP, Bihar, Gujarat, Kar, MP, TN and UP
25–50	94	3.01	2.51	MP (20), Mah (12), HP (9), Kar (8), Orissa (8), Bihar (4)
10–25	73	2.68	2.20	Orissa (16), MP (13), Raj (9), Bihar (4)
<10	166	2.32	2.36	Nagaland, Uttaranchal, Sikkim, Arunachal Pradesh, Manipur, Assam, WB, Jharkhand, Pondicherry, Andaman & Nicobar Islands

AP Andhra Pradesh, *HP* Himachal Pradesh, *Kar* Karnataka, *Mah* Maharashtra, *MP* Madhya Pradesh, *TN* Tamil Nadu, *UP* Uttar Pradesh, *Raj* Rajasthan, *WB* West Bengal

Table 16 Rice productivity and N-fertilizer use, 2005

Rice productivity range (ton ha^{-1})[a]	Area cultivated (Million ha)	Average productivity (ton ha^{-1})	Avg N-fertilizer/total food grain production (kg ton^{-1})[b]	Number of districts	Main states and % of their districts in the specific range
>2.5	12.06	4.40	68	231	Punjab (15/17 districts, i.e. 88%), AP (83%), WB (72%), TN (67%), Mah (63%), Kar (59%), Haryana (58%), MP (56%), UP (42%),
>2–2.5	7.77	2.22	73	51	Tripura (50%)
>1.5–2	7.54	1.75	43	86	Nagaland (88%), Orissa (53%)
1–1.5	11.58	1.28	48	90	Chhattisgarh (69%), Bihar (46%), Assam (43%)
<1	5.93	0.55	54	68	HP (50%)

AP Andhra Pradesh, *HP* Himachal Pradesh, *Kar* Karnataka, *Mah* Maharashtra, *MP* Madhya Pradesh, *TN* Tamil Nadu, *UP* Uttar Pradesh, *WB* West Bengal

This table captures districts for which rice cultivation area data was available for the year 2005. In fact there are a total of 552 districts in India where rice is grown

[a] Adapted for 2005 based on 1999–2001 data from Directorate of Rice Development, Ministry of Agriculture, Government of India (http://dacnet.nic.in/Rice/Productivity%20Analysis%20-%2001.htm)

[b] Total N-fertilizer applied and total food grain production (≥200 kg ton^{-1} taken as outliers)

rice productivity groups while Table 17 provides wheat production zones in India. Punjab has one of the highest rice and wheat production per hectare at 3.7 and 4.1 tons ha^{-1} respectively for 2005. Haryana is also in the same range. In contrast, Bihar is a state with low rice and wheat productivity in 2005, which stood at 1.8 and 1.7 tons ha^{-1} respectively. Districts from Bihar are generally at lower end of productivity distribution in each category in Table 15. As Indian districts move up to higher crop yields, N-fertilizer application, and therefore N_2O emissions, are expected to increase (Aggarwal and Mall 2002). Cropping intensity could be another surrogate indicator for agriculture technology. Its value for Punjab was 186.9% for the year 2003–2004, the highest in India (FAI 2006). Bihar stood at 138%, higher than a few other states of reasonable size and total crop production. If we consider percentage of net irrigated area to net cultivated area, Punjab is again the highest at 95.4% while Bihar is much lower at 60.1%. Of course there are many states with lower irrigation coverage. In terms of N-fertilizer application, Punjab applied 156 kg N-fertilizer ha^{-1} year^{-1} while Bihar applied 88 kg N-fertilizer ha^{-1} year^{-1} in 2005, implying that the relationship between crop yields and fertilizer applications are non-linear (Fig. 5). Bihar could therefore be classified as traditional and Punjab as modern as far as agriculture technology is concerned. Other large Indian states mostly lie somewhere in between these two states, indicating a transition from traditional to modern agriculture.

6.3 N_2O intensity of crop production

The third insight is based on a related parameter—N_2O intensity of crop production. It is the amount of N_2O emitted for one ton crop produced. N-fertilizer application is the main source of N_2O emissions from crops, and fertilizers are applied in different quantities for different types of crops. Crop level fertilizer application data was not available at district level. The average N-fertilizer applied per unit of crop produced in Tables 16 and 17 therefore reflect total fertilizer applied and total crop produced per district. Farmers tend to develop an individual tendency to use fertilizers to a certain extent which could be different for different crops but would also reflect a general trend in their community behavior. Modern technology districts use around 50–70 kg N-fertilizer ton^{-1} total food grain produced, while traditional

Table 17 Wheat productivity and N-fertilizer use, 2005

Productivity groups	Area cultivated (Million ha)	Average productivity (ton ha^{-1})	Average N-fertilizer/ total food grain production (kg ton^{-1})[a]	Number of districts
Northern hill zone	0.8	1.77	19	31
North west plains zone	9.5	4.17	69	66
North east plains zone	9.5	1.58	46	168
Central zone	4.5	2.86	63	89
Peninsular zone	1.5	2.32	82	69
Southern hill zone	0.2	1.00	105	19

This table captures districts for which wheat cultivation area data was available for the year 2005. In fact there are a total of 423 districts in India where wheat is grown

[a] Total N-fertilizer applied and total food grain production ($\geq$200 kg ton^{-1} taken as outliers)

districts use around 25–40 kg. Therefore as these traditional districts move up on crop productivity closer to modern districts, total N-fertilizer application is most likely to increase in India. This is a reasonable possibility. For instance, for wheat production the soil conditions in north east plains and north west plains are quite similar, spread over the Indo-Gangetic plains (Singh and Sontakke 2002; Aggarwal 2008). Water and labor availability are also similar. New technology adoption and land reform implementation could be different currently, which could change in future. It may be noted here that there are also some traditional technology districts that have high N-fertilizer application per ton of food grain production since their crop yield (ton ha^{-1}) is much lower. These districts may not increase their fertilizer application per unit area, but would need to enhance other agriculture inputs to increase crop yields.

6.4 Elasticity

A simple correlation based on 1985–2005 trends shows that, *ceteris paribus,* a 10% increase in total crop production is accompanied with a 12.4% increase in N-fertilizer application and a 9.7% increase in total N_2O emissions from India. The corresponding arc elasticity's are shown in Table 18. It indicates that N-fertilizer application has been rising over the years without a proportionate increase in crop production (Fig. 2). May be, on an average, the Indian agriculture is reaching a plateau as far as effectiveness of fertilizer inputs are concerned. There are still many districts with deficient fertilizer application where more application could lead to much enhanced crop yields, such as districts following traditional and transitional agriculture technologies. However there are also many districts, those practicing modern agriculture, where use of more fertilizer would not result in enhanced crop yields. A high elasticity of N-fertilizer application vis-à-vis total crop production during 2000–2005 shows that may be Indian agriculture is reaching a sort of an efficiency frontier and it needs to expand the input frontiers beyond existing considerations to enter a second green-revolution. This could also mean that the policymakers and agriculture scientific community have to send a signal to the farmers that excessive fertilizer application alone may not always result in enhanced crop yield—everywhere and every year (Aggarwal 2008). This could be done through awareness generation, extension services or also through a market signal, such as reducing the fertilizer subsidy.

Table 18 Some elasticity related to N_2O emissions in India

Time period	Elasticity of total N_2O emissions with regard to total crop production	Elasticity of total N-fertilizer application with regard to total crop production	Elasticity of total N-fertilizer application with regard to combined rice and wheat production
1985–1990	0.84	1.27	2.22
1990–1995	0.85	1.01	2.67
1995–2000	0.72	0.72	0.99
2000–2005	4.50	6.10	3.84
1985–2005	0.97	1.24	2.08

7 Conclusion

This research has updated N_2O emission estimates from India incorporating the latest methodologies (IPCC 2006), the latest activity data for 2005 and most recent Indian emission factor measurements. Time-series emissions over 1985–2005 have also been re-calculated using these, improving our own previous estimates (Garg et al. 2006). The current research, Indian N_2O emissions have grown from 144 Gg in 1985 to 267 Gg in 2005.

The sectoral share indicates that N-fertilizer application was the largest contributor to N_2O emissions in 2005 at 49% of all India N_2O emissions. Sub-regional distribution indicates an upward shift in annual N_2O emissions from more and more districts over time. The main reason being increased use of N-fertilizer. However crop selection plays an important role in N_2O emissions and there are crops providing high economic returns but low N-fertilizer requirements.

Various strategies are available to mitigate N_2O emissions, such as use of nitrification inhibitors, matching crop demand and fertilizer supply, reducing mineral nitrogen accumulation by minimizing fallow periods, optimal irrigation, using more organic fertilizers and micronutrients. Indian agriculture encompasses a wide variability in input application technology and crop yields, manifested in states like Punjab as modern and states like Bihar as traditional. As states like Bihar and districts therein move up on crop productivity, N-fertilizer application is most likely to increase. A simple correlation based on 1985–2005 trends shows that, *ceteris paribus*, a 10% increase in total crop production is accompanied with a 12.4% increase in N-fertilizer application and a 9.7% increase in total N_2O emissions from India. The small N_2O emitter districts in states such as Bihar, Jharkhand, Orissa, Chhattisgarh, Rajasthan and north-eastern states have less agriculture development. Bihar could be a sleeping giant in agriculture revolution with availability of fertile soil, laborious work force and an awakening society. Its agriculture transformation could lead India to a second green revolution or an evergreen revolution. N_2O emissions from India could rise in future subsequently, if appropriate mitigation measures are not adopted simultaneously.

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