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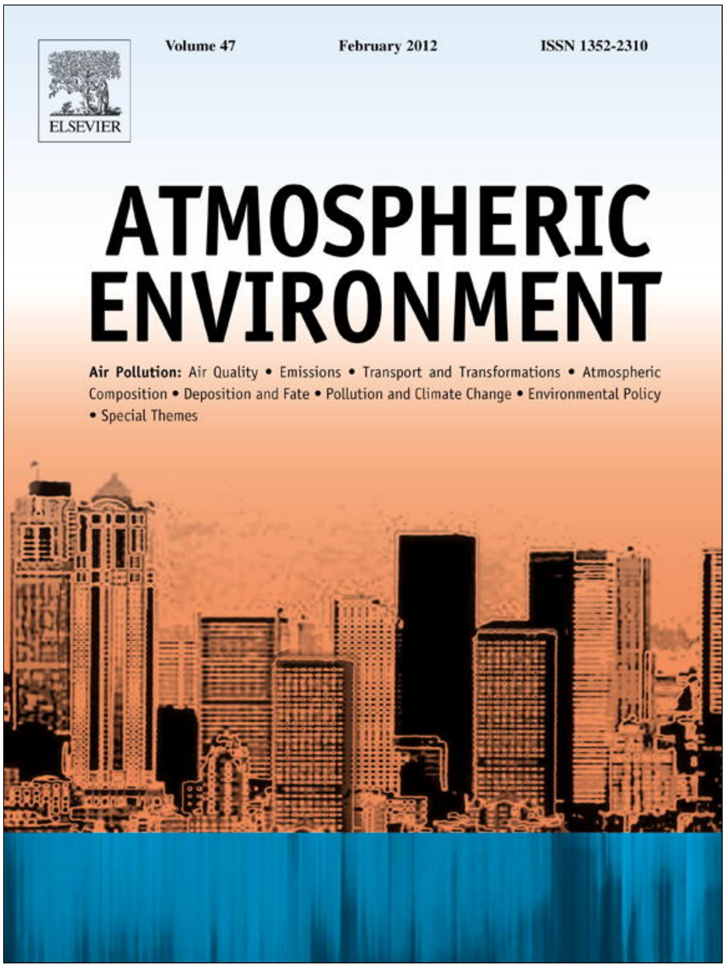
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ABSTRACT

The rapid increase in anthropogenic nitrogen emissions to the atmosphere is matter of concern for the environment, as these may lead to photochemical air pollution, reduced visibility, eutrophication of surface waters, changes in biodiversity, acid rain, stratospheric ozone depletion, and global warming. In this study, ambient emissions of reactive nitrogen (ammonia and nitrous oxide) from animal and crop farming are analyzed for the base year 2003. This objective was achieved by the systematic development of a spatially resolved emissions inventory on a Geographic Information System (GIS) platform. Emissions of ammonia (NH_3) and nitrous oxide (N_2O) were estimated: (i) from livestock; 1705 Gg/yr and 214 Gg yr^{-1} and (ii) fertilizer applications; 2697 Gg yr^{-1} and 326 Gg yr^{-1}. These estimated emissions were compared and contrasted with global, U.S., and European emissions of reactive nitrogen; emissions from India were second only to China. From the spatially resolved emission inventory, it was observed that the state of Uttar Pradesh has the highest NH_3 emission (522 Gg yr^{-1}) followed by the state of Maharashtra (425 Gg yr^{-1}) both from animal and crop farming. Similarly the State of Uttar Pradesh has the highest N_2O emission (70 Gg yr^{-1}) followed by the state of Maharashtra (47 Gg yr^{-1}).

1. Introduction

With its triple covalent bond, nitrogen gas (N_2) is very unreactive, accounting for nearly all of the nitrogen present at the surface of the Earth. Other N compounds are present only in trace concentrations; however, these trace N species play a vital role for life. Biologically-active, photochemically-reactive, and radiatively-active nitrogen compounds in the atmosphere, hydrosphere, and biosphere are collectively referred to as reactive nitrogen (Nr) (Galloway et al., 2003; EPA, 2011). The Nr includes inorganic chemically-reduced forms of nitrogen [e.g., ammonia (NH_3) and ammonium ion (NH_4^+)], inorganic chemically-oxidized forms of N [e.g., nitrogen oxides (NO_x), nitric acid (HNO_3), nitrous oxide (N_2O), nitrogen pentaoxide (N_2O_5), nitrous acid (HONO), peroxy acetyl compounds such as peroxyacytyl nitrate (PAN), and the nitrate ion (NO_3^-)] and organic compounds (e.g., urea, amines, amino acids, and proteins). Over the past few decades, human activities leading to the production of reactive nitrogen from diatomic nitrogen (N_2) have exceeded the natural rate of nitrogen fixation on land at the global scale (Galloway et al., 2004; Schlesinger, 2009; EPA, 2011). Although nitrogen (N) is a major nutrient that governs growth and reproduction of organisms, accumulations of reactive nitrogen from various sources have profound effects on air and water quality, leading to human disease and respiratory failure (Bell et al., 2004; Aneja et al., 2006a, 2006b, 2008a, 2009; Singh and Singh, 2008; Erisman et al., 2008; EPA, 2011).

The world's population has grown from about 1.5 billion at the beginning of the 20th century to 7.0 billion today. This population increase has been accompanied by the advent and growth of "intensive" agriculture, with associated impacts to the environment (Aneja et al., 2001, 2008a, 2009; Erisman et al., 2008). Over the past few decades, the number of domestic animals in the world has increased faster than the human population. Between 1960 and 2000, while the human population roughly doubled, the number of domestic animals roughly tripled (Oenema, 2006). Increases in livestock populations are particularly large in developing countries such as India and China (Gerber et al., 2005; Galloway et al., 2008).

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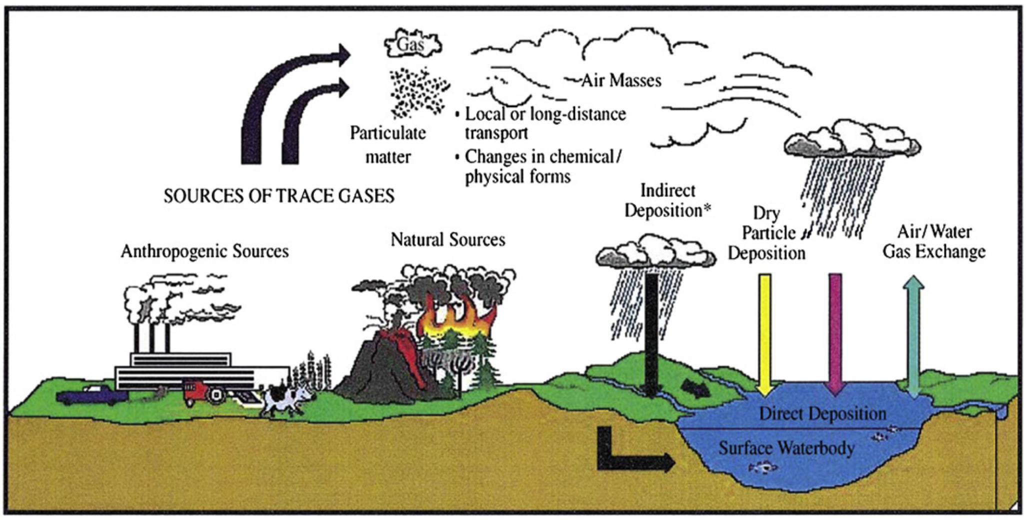

*Indirect deposition is direct to land followed by runoff or seepage through groundwater to a surface water-body.

Fig. 1. Atmospheric emissions, transport, transformation and deposition of reactive nitrogen (Source: Aneja et al., 2008a). *Indirect deposition is direct to land followed by runoff or seepage through groundwater to a surface water-body.

Greater food requirements to meet nutritional requirements of a growing population result in agricultural emissions of NH_3, and N_2O, as well as losses of nitrate to water bodies due to leaching and runoff. Once released to the atmosphere by either man-made (anthropogenic) or natural processes, these Nr compounds undergo transformation in various reactions e.g., in gas phase (Crutzen, 1970, 1979; NRC, 1991) and gas-to-particle conversion (Baek and Aneja, 2004; Baek et al., 2004; and Baek et al., 2006; Behera and Sharma, 2010a, 2011a, 2011b), transport associated with wind, and finally wet and dry deposition (Fig. 1). Reactive nitrogen lost from agricultural systems can enter groundwater, streams, lakes, estuaries, and coastal waters where the Nr can undergo further transformation in a wide range of biotic and abiotic processes (Schlesinger, 2009). Unusual accumulations of reactive N can perturb the environment with a host of beneficial and detrimental effects, for example increased crop yields from nitrogen fertilizer or decreased human health by the respiration of nitrogen-derived aerosols (Aneja et al., 2009). Substantial evidence points to perturbation of the global nitrogen cycle, but the exact quantification of the magnitude and spatial distribution of this perturbation is presently unknown.

Table 1 presents global estimates for sources and sinks of N_2O and NH_3. Emissions from agricultural activities, both crop and animal, are known to contain reactive nitrogen compounds, especially NH_3 and N_2O. N_2O is one of the important greenhouse gases in Earth's atmosphere (Bouwman et al., 1995); it has approximately 300 times the global warming potential of carbon dioxide (Olivier et al., 1998; Shindell et al., 2009). It is now also the major species contributing to the depletion of stratospheric ozone (Ravishankara et al., 2009). Ammonia is the most abundant alkaline constituent in the atmosphere (Aneja et al., 2008a, 2008b, 2008c), where it regulates atmospheric acidity (Brasseur et al., 1999). In addition, NH_3 is also an important source of atmospheric aerosols (PM_{fine}), because it facilitates gas-to-particle conversion (Baek and Aneja, 2004; Baek et al., 2004; Sharma et al., 2007; Behera and Sharma, 2010b). Its deposition contributes to soil acidification through oxidation of the deposited ammonia to acidic compounds (Roelofs et al., 1987).

While developed nations are concerned with reducing emissions of Nr to the environment, developing nations are far away from such initiatives. This paper provides estimates of NH_3 and N_2O emissions from farming (both crop and livestock) in India using emission factors with regional specificity, livestock species characteristics, and regional inventories of the types of fertilizers applied. Emissions to the atmosphere via waste management systems for livestock (non-dairy cattle, dairy cattle, buffaloes, sheep, goats, pigs, horses, asses and mules, camels, and poultry)

Table 1
Global atmospheric budgets of N_2O and NH_3.

Particulars of sources	N_2O[a]	NH_3[b]
	($Tg\ Nyr^{-1}$)[c]	
Fossil fuel combustion	1.9	0.1
Biofuel combustion		
Non-road transport (e.g., ships)		
Industrial emission		0.2
Aircraft		
Biomass burning		5.7[g]
Sea surface	4–5[e]	8.2
Domestic animal waste	3.8	21.7
Human excrement	–[d]	2.6
Lightning	–	–
Natural burning at high latitudes	–	–
Atmospheric chemistry	<1	–
Stratospheric input	–	–
Soil emissions	7.1–8.1[f]	12.6[h]
Undisturbed ecosystem	–	2.4
Other[g]		
Total sources[h]	18.3	53.6

[a] Source: Syakila and Kroeze (2011).
[b] Source: Bouwman et al. (1997).
[c] 1 Tg = 10^{12} g.
[d] (–) Indicates insignificant values.
[e] Ocean emissions for N_2O include: natural sources (3–4 Tg Nyr^{-1}) and anthropogenic sources (1 Tg Nyr^{-1}).
[f] Soil emissions for N_2O include: natural sources (6–7 Tg Nyr^{-1}) and agricultural soils (1.1 Tg Nyr^{-1}).
[g] includes biomass burning and biofuels.
[h] Soil emissions for NH_3 include: croplands (3.6 Tg Nyr^{-1}) and fertilizers (9.0 Tg Nyr^{-1}).

and fertilizer usage are estimated. This paper uses a Geographic Information System (GIS) to provide spatially resolved state-wide estimates of NH_3 and N_2O emissions from animal farming and fertilizer applications in India for the base year 2003. We compare and contrast these estimates with the estimates from previous studies in other regions of the world.

2. Study area and methodology

The methodology adopted in this study has three steps. In the first step, identification of the sources responsible for Nr emissions and collection of source information including location, livestock population (of nine livestock types) and fertilizer consumption (four fertilizers types) were undertaken. In the second step, emission factors for different sources were adopted on the basis of literature appropriate for the region. In the final step, an emission inventory for the district level was developed with spatially resolved emission maps generated for NH_3 and N_2O on a GIS platform. These steps are described in detail in subsequent sections.

2.1. Study area characteristics

India hosts land in six major climatic subtypes, ranging from the desert in the west, to alpine tundra and glaciers in the north, to humid tropical regions supporting rainforests in the southwest and on the island territories in the south. Many regions have starkly different microclimates. With a total land area of 3,287,263 km^2, India measures 3214 km from north to south and 2993 km from east to west. It has a land frontier of 15,200 km and a coastline of 7517 km. India's unique geography and geology strongly influence

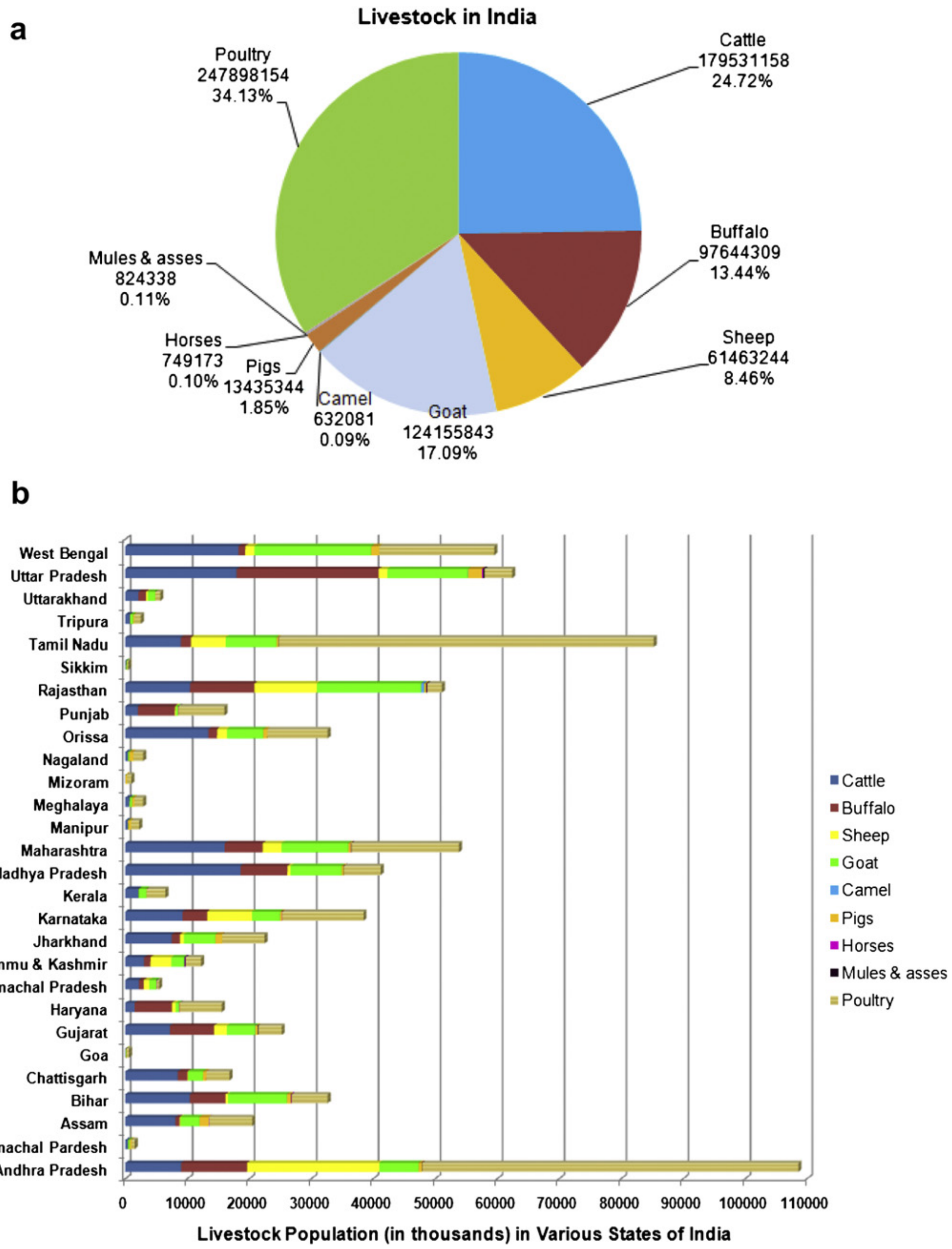

Fig. 2. Livestock in India 2003: (a) overall population, and (b) with state-wise distribution (Source: the data were taken from 'Department of Animal Husbandry, Dairying and Fisheries, India' and compiled to desired form).

its climate; this is particularly true for the Himalayas in the north and the Thar Desert in the northwest.

India ranks second worldwide in farm output today. Agriculture and allied sectors, such as forestry and logging, accounted for 16.6% of the gross domestic product (GDP) in 2007, and employed 52% of the total workforce. India is the world's largest producer of milk, cashew nuts, coconuts, tea, ginger, turmeric and black pepper. It also has the world's largest cattle population (281 million). It is the second largest producer of wheat, rice, sugar, groundnut and inland fish. It is the third largest producer of tobacco and accounts for 10% of the world fruit production, with first rank in the production of banana and sapota.

2.2. Activity data collection and emission calculation

The district-wise data for livestock numbers were obtained from the 17th Indian livestock census in 2003 (States in India are further divided into districts, equivalent to counties in the U.S.) from the website of The Department of Animal Husbandry, Dairying and Fisheries, India (Annual Report, 2003). The database was prepared for various types of livestock (e.g. cattle, buffalo, sheep, goats, horses, asses and mules, camels, pigs and poultry) for each state and district of the country (Fig. 2). District-wise consumption of various fertilizers (urea, diammonium phosphate, ammonium sulfate, and NPK fertizers) was obtained from the Ministry of Chemicals and Fertilizers, India for the year of 2003.

NH_3 or N_2O emissions E_L (kg/yr), from livestock in each district, were estimated from Eq (1):

$$E_L = \sum(\mathrm{EF}_i \times \mathrm{LP}_i) \quad (1)$$

Where,

E_L is the emission of NH_3 or N_2O in kg/yr from livestock in a district,
EF is the emission factor of livestock in kg/head/yr,
i is the livestock type (e.g., cattle),
LP is the population of livestock in a district.

NH_3 or N_2O emissions E_F (kg/yr), from fertilizer applications in each district, were estimated as follows:

$$E_F = \sum(\mathrm{EF}_j \times N_j \times A_j) \quad (2)$$

Where,

E_F is the emission of NH_3 or N_2O from fertilizer application in a district in kg-N/yr,
EF is the emission factor of fertilizer application in % loss of N applied,
j is the type of fertilizer application (e.g. urea application),
N is the N content (%) in fertilizer,
A is fertilizer consumption in kg/yr in a district.

2.3. Selection of emission factors

Earlier studies have estimated NH_3 emissions from livestock in Europe and the US (USEPA (2006), Battye, et al. (2003), Bouwman et al. (1997), Misselbrook et al. (2000), and Van Der Hoek (1998)). The most recent U.S. emissions inventory was computed using a process-based model, which takes into account different animal sizes, husbandry practices, and waste management practices (EPA, 2006). The IPCC has also developed emission equations which take these factors into account. The IPCC provides default factors tailored to animal size distributions in different world regions (IPCC, 2006).

Some research groups have presented NH_3 inventories for Asia (Zhao and Wang, 1994; Lee and Park, 2002), but these studies have relied on emission factors based on animal-farming conditions in European countries (Klaassen, 1991; Asman, 1992; European Environment Agency (EEA), 1999), because they did not have enough information on Asian-specific emission factors. The latest study done by Yamaji et al. (2004) has estimated the NH_3 emission from the livestock farming for Asian countries. They estimated NH_3 emissions by taking into account the N-excretion values from the livestock combined with coefficients for NH_3 volatilization in different breeding periods.

We used Yamaji et al. (2004) for emission factors of NH_3 for livestock in India. The livestock considered for this study are cattle, buffalo, sheep, goat, camel, pigs, horse, mules and asses, and poultry. Table 2b shows the NH_3 emission factors used for animals in this study, and compares these with the IPCC guidelines for the South Asia region, and the average emission factors for the U.S. inventory. The IPCC recommendations cover a range of possible animal waste management practices. As the table shows, the emission factors for this study are within the range of the IPCC guidelines for major animal categories, with the exception of poultry, where the emission factor for this study is somewhat lower than the IPCC values. Emission factors for this study are generally lower than the average factors for the U.S. reflecting the differences in the nitrogen contents of animal diets. Ammonia emissions depend on meteorological conditions, especially temperature. As described in Section 2.1, there are six climatic regions in India having different mean temperature, and there is a need to use emission factors that account for these temperature differences. A study, Steenvoorden et al. (1999) (reported in USEPA (2002)), has established an empirical relation between ambient temperature and NH_3 emission factors (Eq (3)) for cattles:

$$\mathrm{EF} = 12.434e^{0.0626t} \quad (3)$$

Where EF (g NH_3–N/animal/day) is the emission factor and t is the temperature in degree centigrade.

We have modified this equation for use in our context. For example, the EF of 11.8 g NH_3–N/animal/day (4.3 kg NH_3–N head^{-1} yr^{-1}; Table 2a) for cows, applicable for India, is assumed to correspond to the average temperature of 24.6 deg centigrade (annual average temperature). Given that EF and keeping the exponential term the same as in Eq (3), the modified temperature dependent EF for our study is EF = 2.54 exp

Table 2a
Livestock NH_3 and N_2O emission factors for the current study compared with IPCC guidelines for the South Asia region and average U.S. emission factors.

Livestock	This study (overall for India)	IPCC-South Asia	U.S. average[a]	This study (overall for India)	IPCC-South Asia
	kg NH_3–N head^{-1} yr^{-1}			kg N_2O–N head^{-1} yr^{-1}	
Cattle	4.3	3.3–19	5.6	0.32	0–0.94
Buffalo	3.4	4.1–8.6		0.39	0–0.27
Sheep	1.4	1.4–3.0	2.8	0.21	0–0.69
Goat	1.1	1.8–3.8	5.3	0.17	0–0.24
Camel	7.0	4.4–9.1		1.06	0–0.30
Pigs	1.5	1.3–2.5	5.8	0.18	0–0.73
Horses	7.0	4.8–10	10.1	0.87	0–0.10
Mules & assess	7.0	2.6–5.5		0.87	0–0.80
Poultry	0.1	0.2–0.3	0.5	0.01	0–0.44

Table 2b
Livestock NH_3 emission factors (kg NH_3–N head^{-1} yr^{-1}) with region specific of India used for the current study.

Climatic region of India	Cattle	Buffalo	Sheep	Goat	Camel	Pigs	Horses	Mules & assess	Poultry
North	3.61	2.86	1.18	0.92	5.88	1.26	5.88	5.88	0.08
Central	4.49	3.55	1.46	1.15	7.31	1.57	7.31	7.31	0.10
East	4.63	3.66	1.51	1.18	7.54	1.62	7.54	7.54	0.11
West	4.65	3.69	1.54	1.21	7.56	1.67	7.56	7.51	0.11
North-eastern	3.10	2.45	1.01	0.79	5.04	1.08	5.04	5.04	0.07
South	4.66	3.69	1.52	1.19	7.59	1.63	7.59	7.59	0.11

[a] U.S. emissions estimates for animal husbandry include the application of animal wastes to cropland.

(0.062t). Similarly, the Eq (3) is modified for other livestock animals and revised EFs for various climatic regions are given in Table 2b.

The IPCC guidelines show N_2O emission from animal waste management systems in each region of the world, using values for N-excretion per head of six different types of livestock; cattle (beef), cattle (dairy), poultry, sheep, pigs, and other animals (Houghton et al., 1997). In addition to these recommended values, N_2O emission factors were estimated from the N-excretion values of the other four types of livestock; buffaloes, camels, horses, and goats, obtained from Van der Hoek (1994). Table 2 provides the emission factors used in this study to estimate the emission of N_2O from various livestock types in India, and compares these factors with the IPCC guidelines for South Asia. The emission factors (Table 2a) for various livestock are expressed as 'kg NH_3–N head^{-1} yr^{-1}' for NH_3 emission and 'kg N_2O–N head^{-1} yr^{-1}' for N_2O emission. NH_3 and N_2O emissions were estimated from Eq (1) by multiplying these individual emission factors with respective livestock population. It is to be noted that the reported results were translated from NH_3–N to NH_3 and N_2O–N to N_2O with suitable conversion factors.

Several research groups in the past have estimated NH_3 emission from synthetic fertilizer applied on agricultural land in the world (e.g. Bouwman et al., 1997; Misselbrook et al., 2000; Lee and Park, 2002). The emission factors vary as a function of the chemical composition of the fertilizer, soil properties (pH, calcium content, water content, buffering capacity, porosity, etc.), meteorological conditions (temperature, wind speed, precipitation), mode of application, and soil and water management (Bouwman et al., 1997). The most recent U.S. emissions inventory uses a process model which takes into account soil and meteorological conditions in different U.S. regions (EPA, 2006). However, due to lack of data, the NH_3 emission from fertilizers cannot generally be presented as a function of all the above factors. For instance, IPCC guidelines give a flat emission factor of 10% of the nitrogen content for all synthetic fertilizers. We have adopted the emission factors from the studies by Bouwman et al. (1997) for NH_3, as they have been compiled for different regions of the world. In India the most common synthetic nitrogen fertilizers applied on the agricultural land are urea, diammonium phosphate, ammonium sulfate and NPK fertilizers. Table 3 lists the emission factors used in this study and compares them to the ranges of factors used in the U.S. The factor used for urea is somewhat higher than the factors used in the U.S., while factors for other fertilizers fall within the ranges used in the U.S.

Table 3
Synthetic fertilizer NH_3 emission factors used in this study compared with the ranges of factors used in the U.S.

Fertilizer	N content (%)	This study NH_3–N (% loss of N applied)	US	This study N_2O–N (% loss of N applied)
Urea	46	25	15–20	1.4
Diammonium phosphate	21	5	5	0.25
Ammonium sulfate	21	8	5–15	0.35
NPK fertilizer	17	4	6–8	0.2

The IPCC assumed an N_2O emission factor of 1.25 ± 1.0% of fertilizer N applied. No allowance was made for different fertilizer types, for different soil management and cropping systems, and for variations in rainfall, which are important variables. U.S. emissions of nitrous oxide were estimated using the DayCent model (EPA, 2010; Del Grosso et al., 2008), which takes into account nitrification and denitrification reactions and other competing removal mechanisms for nitrogen. The emissions inventory does not report simplified emission factors for N_2O; however, estimated emissions amounted to about 1.5% of the available nitrogen from anthropogenic and natural sources of nitrogen. We have adopted the emission factors from Smith et al. (1997), which are listed in Table 3. The emission factor used for urea (1.4%) is higher than the IPCC guidelines and similar to the 1.5% emission rate obtained for the U.S. Our emission factors for other fertilizers are somewhat lower than either the IPCC guidelines or the U.S. modeling results. Table 3 presents the N_2O emission from the fertilizer application through direct pathways. To estimate N_2O emission from indirect pathways, we have used the emission factors of one Indian study done by Bhatia et al. (2004). In the indirect pathways, N_2O emissions from volatilized N of fertilizer and manure, and emission from leached and runoff N from fertilizer and manure were considered. For the indirect pathways from fertilizer application, we assumed an emission factor as 0.5% of N applied.

2.4. Development of spatially resolved emission inventory

A GIS tool, Geostatistical Analyst extension of ArcGIS (ArcMap, version 9.2; ESRI Inc., Redlands, WA, USA) was used to develop a base map of India. The map was digitized to extract the district, state and national boundaries in the form of polygons, as per the procedures in Behera et al. (2011). These vector data (polygon information) were converted to different thematic layers to determine the locations of areas of specific interest and also for further editing. These thematic layers were used for computing emissions and extracting inventories. The different thematic layers include maps of activity data, population, area boundaries etc. The attribute values (of livestock population, fertilizer consumption in each district) stored in map tables were utilized to generate the maps of the desired emission. Finally, a spatially-resolved emission inventory was developed for each district.

3. Results and discussion

3.1. Scenarios of the sources in India

The livestock population of India is large, and animals play an important role in the agricultural economy even though they often

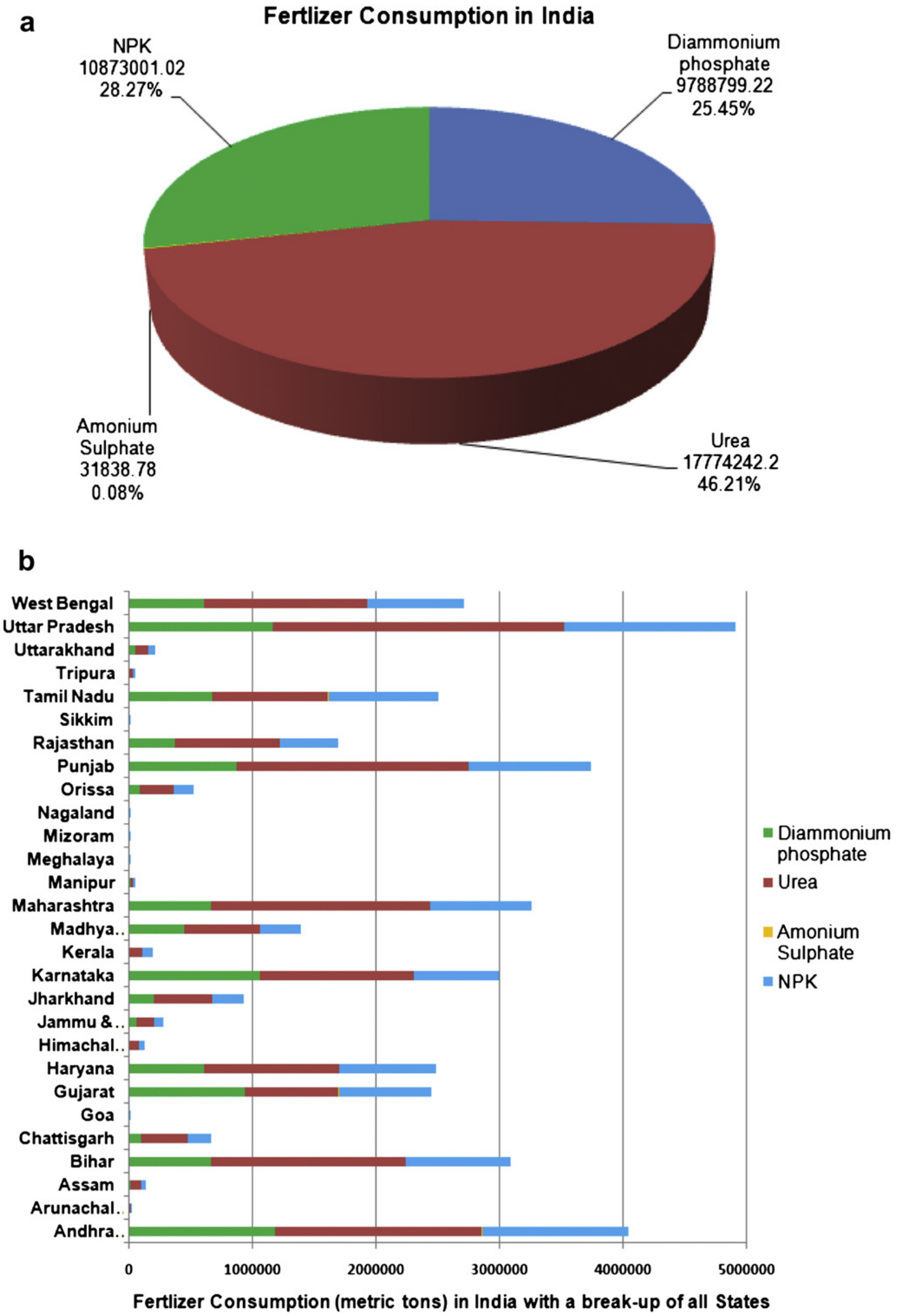

Fig. 3. Fertilizer Consumption in India 2003: (a) Overall consumption, and (b) with state-wise distribution (Source: the data were taken from 'Ministry of Chemicals and Fertilizers, India' and compiled to desired form).

receive inadequate nourishment. In 2001 there were an estimated 219.6 million cattle, more than in any other country and representing about 15% of the world's total. For 2003, India's livestock population as a proportion of the world's total is: cattle 13.5%, buffaloes 55.1%, sheep 5.7%, goats 16.1%, pigs 1.8% and horses 1.4% (Annual Report, 2003) (http://dms.nic.in/ami/home.htm). The overall highest livestock population is found in the state of Andhra Pradesh, followed by Tamil Nadu, Uttar Pradesh and West Bengal. The greatest individual population of livestock is found for cattle in Madhya Pradesh (18.58 million), buffalo in Uttar Pradesh (22.91

Table 4a
Emissions of NH_3 and N_2O from different livestock.

Category	Emission of NH_3		Emission of N_2O	
	Gg/yr	%	Gg/yr	%
Cattle	956.9	56.1	90.2	42.3
Buffalo	403.0	23.6	59.9	28.1
Sheep	101.8	6.0	20.3	9.5
Goat	171.3	10.0	33.1	15.5
Camel	5.7	0.3	1.1	0.5
Pigs	23.4	1.4	3.8	1.8
Horses	6.2	0.4	1.1	0.5
Mules and asses	7.1	0.4	1.1	0.5
Poultry	29.4	1.7	2.7	1.3

million), sheep in Andhra Pradesh (21.37 million), goats in West Bengal (18.77 million), camels in Rajasthan (0.49 million), pigs in Uttar Pradesh (2.28 million), horses in Jammu and Kashmir (0.17 million), mules and asses in Uttar Pradesh (0.23 million) and poultry in Andhra Pradesh (60.70 million).

Fig. 3 shows the fertilizer consumption, applied on land for agriculture purposes in India for the year 2003. Urea accounts for the greatest use (46.21%), followed by NPK (28.27%), diammonium phosphate (25.45%) and ammonium sulfate (0.08%). The percentage of each fertilizer used was based on its consumption relative to total

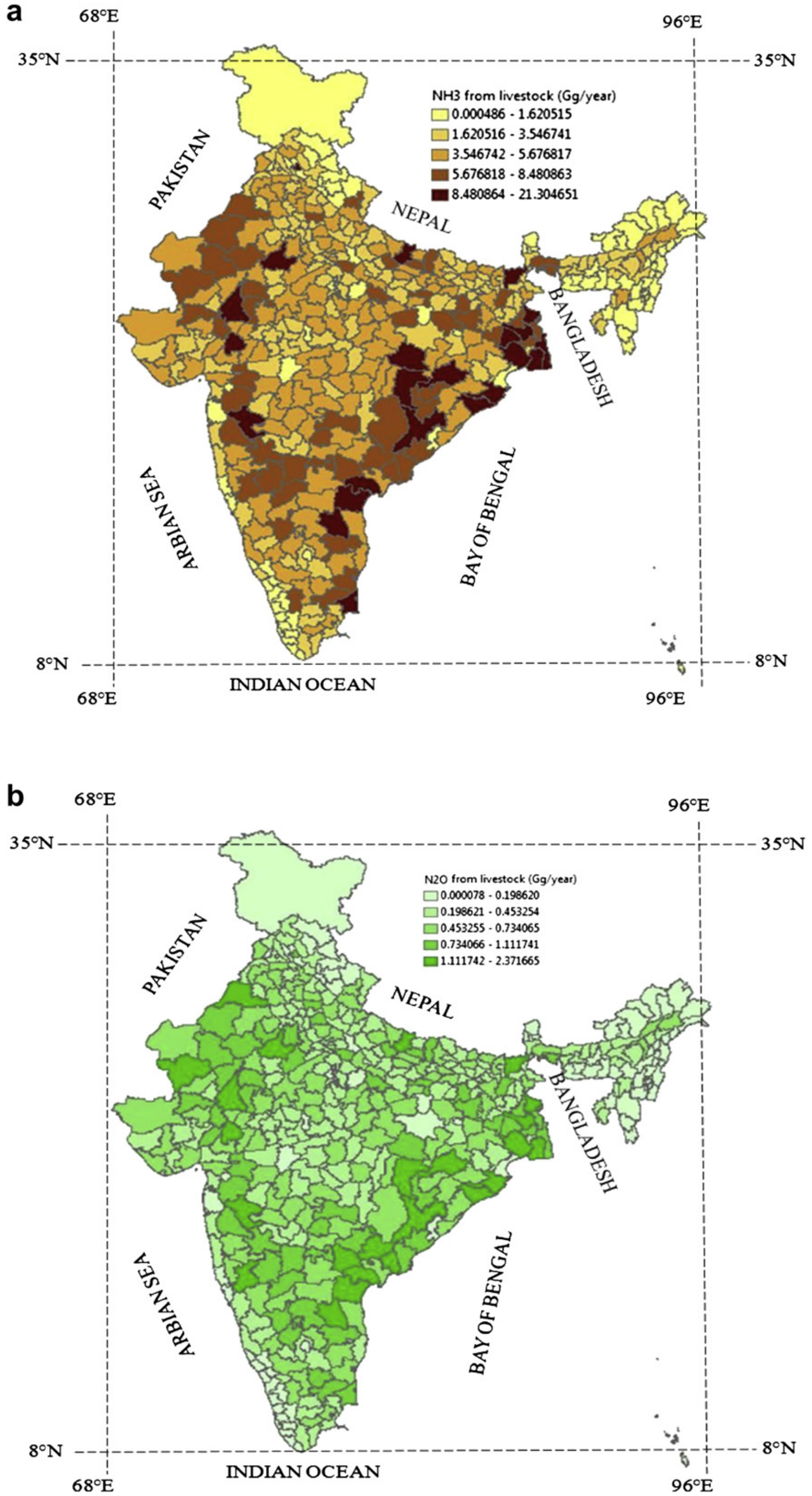

Fig. 4. District-wise spatially resolved emissions from livestock in India: (a) NH_3, and (b) N_2O.

Table 4b
Emissions of NH_3 and N_2O from fertilizer application.

Category	Emission of NH_3		Emission of N_2O (Gg/yr)			
	Gg/yr	%	Direct[a]	Indirect[b]	Total	%
Diammonium phosphate	124.8	4.6	45.2	16.1	61.3	18.8
Urea	2481.5	92.0	179.9	64.2	244.1	74.8
Ammonium sulfate	0.6	0.02	0.04	0.50	0.5	0.2
NPK	89.7	3.3	5.8	14.5	20.3	6.2

[a] emission direct pathways of fertilizer application.
[b] emission is from indirect pathways of fertilizer application.

consumption (i.e., sum of diammonium phosphate, urea, ammonium sulfate and NPK fertilizers). The highest fertilizer consumption was in the state of Uttar Pradesh followed by Andhra Pradesh, Punjab, Maharashtra and West Bengal. The highest individual fertilizer consumption is: diammonium phosphate in Andhra Pradesh (1.18 million metric tons), urea in Uttar Pradesh (2.36 million metric tons), ammonium sulphate in Andhra Pradesh (6339 metric tons) and NPK in Uttar Pradesh (1.39 million metric tons).

3.2. Emission inventory for India

The NH_3 and N_2O from the waste for each type of livestock, was estimated at state and district levels by multiplying the specific emission factor by the livestock population, taking into account the N-excretion value from each livestock. Table 4a presents the emissions of NH_3 and N_2O from livestock excretion (from waste management process excluding the application of these wastes on land). For NH_3, cattle contributed the highest emission (56.1%) of the total emission from livestock; followed by the buffalo (23.6%). Although the population of poultry was highest, their contributions towards the NH_3 pollution were low owing to their low emission factors. For N_2O, cattle also contributed the highest proportion (42.3%), followed by buffalo (28.1%) and goats (15.5%), towards the total emission from the livestock sector. Uttar Pradesh has the greatest NH_3 emission from livestock (215.9 Gg yr^{-1}), followed by Madhya Pradesh (148.4 Gg yr^{-1}) and West Bengal (142.5 Gg yr^{-1}). Similarly the greatest contributor to N_2O emission from livestock is Uttar Pradesh (28 Gg yr^{-1}), followed by Madhya Pradesh (17 Gg yr^{-1}) and Maharashtra (16 Gg yr^{-1}). Fig. 4a and b show district-wise spatially-resolved emissions of NH_3 and N_2O from livestock. From these maps, it has been observed that the regions comprising states of West Bengal, Maharashtra, Andhra Pradesh, Orissa, and Bihar have the greatest areas with emissions of NH_3 and N_2O per unit area (Gg/yr/km^2) from livestock.

NH_3 and N_2O from fertilizer applications on agricultural land for each type of fertilizer were estimated at state and district levels by multiplying the specific emission factor for each fertilizer by fertilizer type consumption (as described in Section 3). Table 4b presents the emissions of NH_3 and N_2O from the application from various fertilizers. It can be observed that for NH_3, urea contributed highest emission (92.0%) among fertilizers. Similarly for N_2O, urea also contributed the highest emission (74.8%). Uttar Pradesh has the greatest NH_3 emission from fertilizer (306 Gg yr^{-1}) followed by Punjab (294 Gg yr^{-1}) and Maharashtra (283 Gg yr^{-1}). Similarly the highest contributors of N_2O emission from fertilizer are Uttar Pradesh (42 Gg yr^{-1}) followed by Punjab (33 Gg yr^{-1}) and Andhra Pradesh (32 Gg yr^{-1}). Fig. 5a and b show the district-wise spatially resolved emissions of NH_3 and N_2O from fertilizer applications. From these maps, it has been observed that the regions comprising states of Punjab, Haryana, Gujarat, Maharashtra, Bihar, Andhra Pradesh, Karnataka, and Tamil Nadu have the largest areas having emissions of NH_3 and N_2O per unit area (Gg/yr/km^2) from fertilizer applications.

For assessing uncertainty in the agricultural NH_3 emissions, ranges for all input parameters (e.g. activity date, emission factor) were used in the emission inventory for calculating NH_3 volatilization (Beusen et al., 2008). In this study, the activity level data used are accurate, as these data are recorded at the district level. However the uncertainty in emission factors is potentially significant, as there are no published experimental data on the emissions for individual sources in India. Therefore, the uncertainty in the range of emission estimates of NH_3 and N_2O from livestock and fertilizer application were calculated based on different emission factors available in the literature. In this task, suitable lower- and upper-limit estimates for emission factors (Tables 2 and 3) were utilized for estimates for emissions inventories. With this approach, the range of NH_3 emission was estimated to be from 3158 to 9124 Gg yr^{-1} (our NH_3 estimate was 4454 Gg yr^{-1}). Similarly the range of N_2O emission was estimated to be between 424 and 859 Gg yr^{-1} (our N_2O estimate was 550 Gg yr^{-1}).

3.3. Comparison of emission estimates with previous studies

The total amount of NH_3 and N_2O emissions from livestock were estimated at 1705 Gg/yr and 214 Gg yr^{-1}, respectively, for the base year 2003 (Table 5a). Our estimate of NH_3 emissions cannot be compared directly with previous studies (Olivier et al., 1998; Zhao and Wang, 1994) since their values included NH_3 emissions after the application of manure as fertilizer. But it can be compared with Yamaji et al. (2004), where they calculated NH_3 as 1578 Gg yr^{-1}, similar to our value of 1705 Gg yr^{-1}. Table 5a also presents the NH_3 emissions from animal excreta used as manure which were estimated by Yan et al. (2003). Due to the lack of reported region-specific emission factors and activity level data for manure application from each livestock type, we have taken the total estimated value from Yan et al. (2003) for comparison of our values with earlier studies. Our result for NH_3 emission (from waste generation and application) is 17% less than by Olivier et al. (1998) and is 24% less than by Zhao and Wang (1994) for India. Though our results are lower than these earlier estimates, our approach has finer resolutions for the emissions inventory and has more appropriate activity data. We also generated regional specific emission factors based on earlier empirical relationship between meteorology and emission factor. For N_2O, our results matched well with Yamaji et al. (2004).

Table 5b presents the NH_3 and N_2O emissions from fertilizer application in comparison with the earlier studies (e.g. Olivier et al., 1998; Parashar et al., 1998). Our values for NH_3 are higher than the values by Olivier et al. (1998), perhaps due to greater consumption of fertilizer in recent years. In comparing our results with Parashar et al. (1998) for the year 1993 in India, our results are higher for NH_3; perhaps due to rising fertilizer consumption during the past 10 years. Our results are also higher than the results of Garg et al. (2006) and Sharma et al. (2011). The reason might be due to the selection of higher emission factors in our study. Overall, we believe that our work is more appropriate in the sense that we had the activity level data at district levels and chose the emission factors suitable for Asian context.

3.4. Reactive nitrogen emissions in India compared to global, U.S., and European emissions

Table 6 presents NH_3 and N_2O emission for India, China, European Union countries and the USA. The emission for India is from this study, including animal waste management and fertilizer application from direct and indirect pathways. The values for the livestock manure application have been taken from Yan et al. (2003)). The emission values in Table 6 for all regions are from sources including livestock manure and its application, and fertilizer application. Overall, comparing the data from this study with other regions reported by earlier studies, India stands second after China for emission of both NH_3 and N_2O from the agricultural sector.

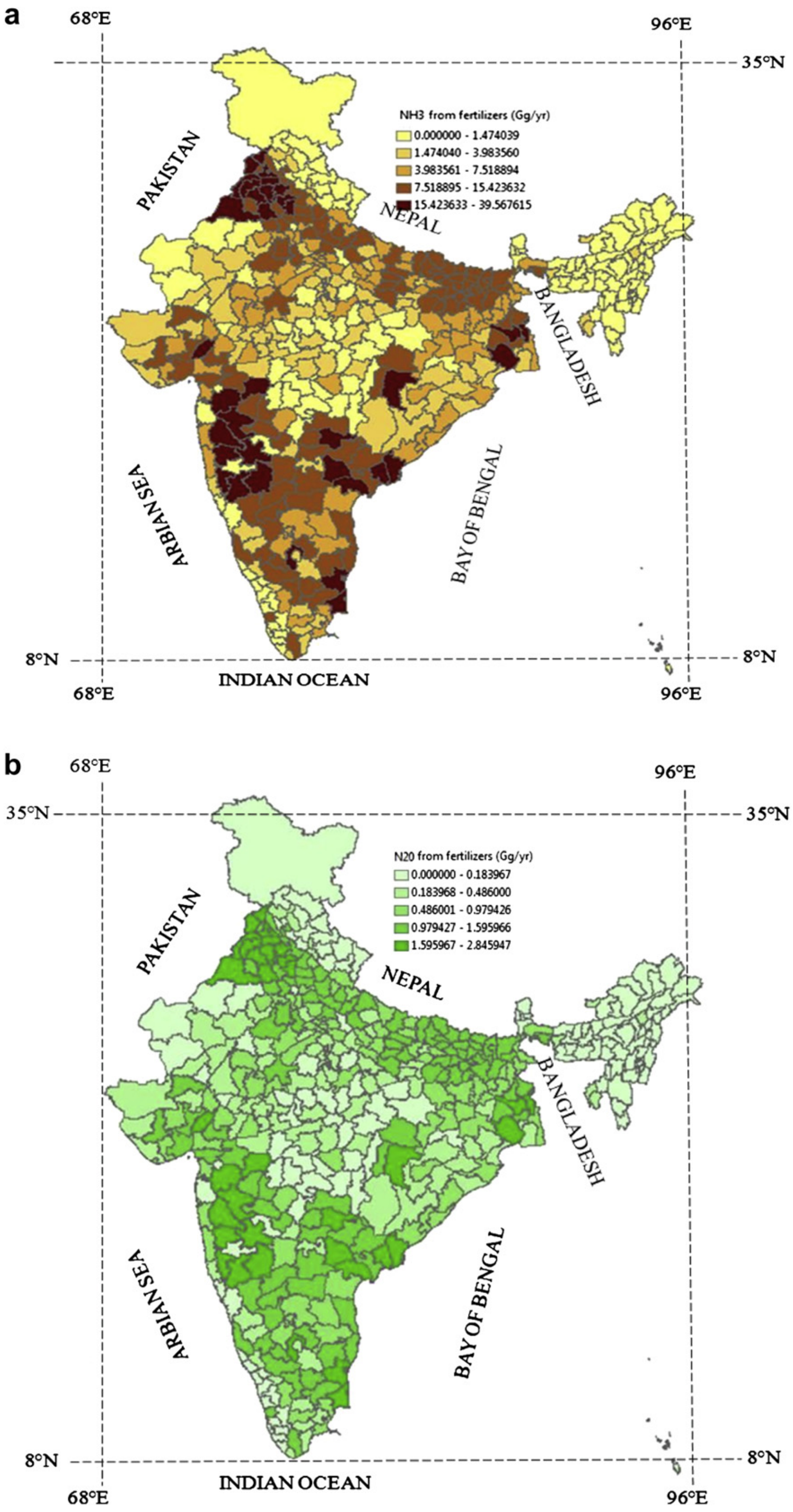

Fig. 5. District-wise spatially resolved emissions from fertilizer application in India: (a) NH_3, and (b) N_2O.

Table 5a
Comparison of NH_3 and N_2O from livestock waste emission (Gg/yr) with previous studies in Indian perspectives.

Pollutant	Category	This study 2003	Yamaji et al. (2004) 2000	Olivier et al. (1998) [c] 1990	Zhao and Wang (1994) [c] 1990	EDGAR[c] (EDGAR: Emissions Database for Global Atmospheric Research (EDGAR), 1995)
NH_3	Livestock waste	1705	1578	4560	4992	–
	Application[a]	2064[a]	–			
N_2O	Livestock waste	214	225	291	–	314
	Application[b]	130[b]	–			

Based on these estimates, agricultural emissions in India contribute significantly to global agricultural emissions of N_2O. The impacts of NH_3 are of more concern on local and regional scales than on a global scale; however, NH_3 emissions from India contribute to regional transport of fine particulate matter (Dentener et al., 2011). As the estimates in Table 6 show, NH_3 emissions from agriculture in India represent a significant portion of agricultural NH_3 emissions in the Northern Hemisphere.

3.5. *Reactive nitrogen in Indian context*

Over half of the world's population is centered in Asia (primarily China and India) and thus agricultural drivers of change are also centered there. While other regions of the world have led the global economy in the 20th century, causing global-scale changes (e.g., in rising CO_2 in the atmosphere), their dominance will soon diminish – over the next few decades, Asia is projected to be the dominant force in the alteration of the global environment (Galloway et al., 2008). Assessments of the nitrogen cycle of Asia over the past decade have revealed that: (i) human activities are the major source of new Nr in Asia, (ii) Asia is the largest consumer of fertilizer N on a global basis, (iii) there are major ecosystem and human health impacts due to increased Nr in the Asian environment, (iv) Asia is predicted to become an even larger creator of Nr over the next few decades as both population and per-capita resource use continue to grow (Galloway et al., 2008, 2004; Galloway, 2000).

While the developed countries of the world and China seem to be conscious about the need to reduce of Nr; India lacks a unified study of Nr on either a regional or national scale. Hence it is imperative to study Nr with respect to monitoring, emission inventory, and control options to be implemented and legislated in India. The need for an integrative approach to research and policy regarding Nr in Indian agriculture, industry and environment was realized in 2004, when the Society for Conservation of Nature (SCON), a voluntary body of scientists, brought together some concerned Indian experts from diverse backgrounds to discuss the issue. This was followed by a series of nationwide consultations in association with the National Academy of Agricultural Sciences (NAAS) in 2005 and with the Union Government's Department of Biotechnology and Indian National Science Academy (INSA) in 2006, with active support from other agencies. These discussions led to the adoption of a policy paper on Nr and N-use efficiency in Indian agriculture (NAAS, 2005). A network of nitrogen researchers and experts called 'Indian Nitrogen Group' (ING), has also been formalized as an outcome of the INSA workshop in 2006.

India is currently the third largest producer and consumer of fertilizers (after China and USA), and fertilizer usage is bound to increase with further intensification of agriculture. We need a precise understanding of the scale of nitrogen use/misuse/release through various agricultural, industrial, vehicular and other activities and their contribution to the pollution of waters and air, with special reference to various point and non-point sources, contributing to the biogeochemical N cycle. In this respect, one of the major challenges before the scientific community is to provide policy makers with reliable estimates of Nr transfers to different ecosystems and to describe balanced, cost-effective and feasible strategies and policies to reduce the amount of reactive nitrogen where it is not wanted. In this regard, this paper is meant to address the issues related to Nr emission (specifically NH_3 and N_2O) from agricultural sector in India.

Table 5b
Comparison of NH_3 and N_2O from fertilizer application emission (Gg/yr) with previous studies in Indian perspectives.

Pollutant	This study 2003	Olivier et al. (1998) 1990	Parashar et al. (1998) 1993	Garg et al. (2006) 2005	Sharma et al. (2011) 2007
NH_3	2697	2418	1174	–	–
N_2O	326[d]	193	199	151	226

IPCC emissions estimates for agricultural sources in India in 2000.
Ammonia: 3450 Gg NH_3/yr (or 2840 Gg NH_3–N/yr).
Nitrous oxide: 465 Gg N_2O/yr (or 296 Gg N_2O–N/yr).
Based on IPCC, 2009, RCP Database, version 2.0.5. http://www.iiasa.ac.at/web-apps/tnt/RcpDb.

[a] Ammonia emissions from application of wastes to agricultural lands (Yan et al., 2003).
[b] Nitrous oxide emissions from application of wastes to agricultural lands (Yan et al., 2003).
[c] Emissions from all stage of animal wastes treatment. These values are equal to the sum of waste and application (http://www.rivm.nl/bibliotheek/rapporten/773301001.pdf).
[d] the emission is from both the direct and indirect pathways.

Table 6
Comparison of NH_3 and N_2O Emission (Gg/yr) India with other regions of the world.

Pollutant	This study	Olivier et al. (1998)			EDGARv4 (2005)		
	India[a]	China	USA	EU[b]	China	USA	EU[c]
NH_3[e]	6466	8353	2362	3919	9211	2729	4753
N_2O[e]	670[d]	608	302	451	778	506	474

Other U.S. agricultural emissions estimates for 2005: For ammonia: 2980 Gg NH_3/yr (or 2450 Gg NH_3–N/yr) Based on USEPA, 2008, 2005 National Emissions Inventory. http://www.epa.gov/ttn/chief/net/2005inventory.html.
Other U.S. agricultural emissions estimates for 2005: For nitrous oxide: 752 Gg N_2O/yr (or 458 Gg N_2O–N/yr) Based on USEPA, April 2010, INVENTORY OF U.S. GREENHOUSE GAS EMISSIONS AND SINKS: 1990–2008, U.S. EPA # 430-R-10-006. http://epa.gov/climatechange/emissions/usinventoryreport.html.

[a] Values are after adding application of livestock wastes in the field from Yan et al. (2003) with our results for NH_3 and N_2O.
[b] European Union excluding former Soviet Union.
[c] European Union except Malta and Cyprus.
[d] emission from both direct and indirect pathways.
[e] Values indicate the emissions from livestock waste, its application and fertilizer application.

4. Summary and conclusions

This study estimates the emissions of atmospheric reactive nitrogen, NH_3 and N_2O, which are produced from animal farming and fertilizer application for agricultural purposes in India. For NH_3 we suggest that among livestock, cattle contributed highest emission, inasmuch as 56.1% of the total emissions of NH_3 stems from cattle, followed by buffalo (23.6%). For N_2O, cattle also contributed highest proportion (42.3%), followed by buffalo (28.1%) and goats (15.5%), relative to the total pollution from the livestock sector. It can be observed that for fertilizers, urea contributed the highest proportion of emission of NH_3 (92.0%) and N_2O (74.8%) among the fertilizers. The total amount of NH_3 and N_2O emission from livestock was estimated at 1705 Gg yr^{-1} and 214 Gg yr^{-1}, respectively for the base year 2003. The emission loads from fertilizer application were, 2697 Gg NH_3/yr and 326 Gg N_2O/yr.

These emissions estimates are subject to considerable uncertainty, stemming from a number of factors. As illustrated in Tables 2 and 3, there are large variations in measured NH_3 emissions from animal husbandry and fertilizer usage. Based on the ranges of potential emission factors for South Asia, NH_3 emissions from livestock could be a factor of 2–3 higher than we have estimated, and NH_3 emissions from fertilizer application could be up to 40% lower than we have estimated. In the case of N_2O, there are limited emissions data for many processes. Variations in animal husbandry practices and fertilizer application techniques from farm to farm also contribute to uncertainties in emissions estimates.

In Western European countries and the U.S. (to some extent), health and environmental concerns about air pollutants from agriculture have prompted regulators and policy makers to implement mitigation strategies. In the Netherlands, for example, livestock production must meet stringent standards for ammonia emission based on deposition reduction targets. Since the introduction of a mineral bookkeeping system in the Netherlands, along with regulations to incorporate manure into the soil, modifications to animal housing systems and the introduction of end-of-pipe scrubbers, the ammonia emissions have decreased by more than 40%, since 1995 and particulate emissions decreased also (Erisman et al., 2008).

Emission reduction policy should not be hindered by technology limitations; effective techniques are already available, e.g., an engineered solution i.e. ammonia emissions from swine manure are reduced as it passes through a treatment plant with solid–liquid separation (Aneja et al., 2008b) and as emission-free housing systems, nutrient management systems, including precision fertilization, are adopted. Substantial reductions in emissions from fertilizers can also be achieved by matching fertilizer type to environmental conditions and by adjusting overall nitrogen application rates to meet, but not exceed, crop requirements. Policy incentives that could be used to encourage increased on-farm nutrient efficiencies include: tax incentives or financial grants, targets for nitrogen losses, carbon credits, and cap–and-trade of GHG emissions.

Agriculture has adopted modern technologies and science to maximize productivity, but it has not as yet been subjected to the same environmental regulations that other modern industries must obey. The potential health and environmental risks of intensified modern agriculture demand that we develop emission abatement policies based on best available science (Aneja et al., 2008a, 2008b, 2008c, 2009).

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References

Aneja, V.P., Roelle, P.A., Murray, G.C., Southerland, J., Erisman, J.W., Fowler, D., Asman, W.A.H., Patni, N., 2001. Atmospheric nitrogen compounds II: emissions, transport, transformation, deposition and assessment. Atmospheric Environment 35, 1903–1911.

Aneja, V.P., Schlesinger, W., Knighton, R., Jennings, G., Niyogi, D., Gilliam, W., Duke, C. (Eds.), 2006a. Workshop on Agricultural Air Quality: State of the Science. North Carolina State University, Raleigh, NC 27695–37603, ISBN 0-9669770-4-1, 314p.

Aneja, V.P., Schlesinger, W.H., Niyogi, D., Jennings, G., Gilliam, W., Knighton, R.E., Duke, C.S., Blunden, J., Krishnan, S., 2006b. Emerging national research needs for agricultural air quality. Eos. transactions. American Geophysical Union 87, 25–29.

Aneja, V.P., Schlesinger, W., Erisman, J.W., 2008a. Farming pollution. Nature Geoscience 1, 409–411.

Aneja, V.P., Arya, S.P., Rumsey, I.C., Kim, D.-S., Bajwa, K.S., Williams, C.M., 2008b. Characterizing ammonia emissions from swine farms in eastern North Carolina: reduction of emissions from water-holding structures at two candidate superior technologies for waste treatment. Atmospheric Environment 42, 3291–3300.

Aneja, V.P., Blunden, J., James, K., Schlesinger, W.H., Knighton, R., Gilliam, W., Jennings, G., Niyogi, D., Cole, S., 2008c. Ammonia assessment from agriculture: U.S. status and needs. Journal of Environmental Quality 37, 515–520.

Aneja, V.P., Schlesinger, W., Erisman, J.W., 2009. Effects of agriculture upon the air quality and climate: research, policy, and regulations. Environmental Science and Technology 43, 4234–4240.

Annual Report, Department of Animal Husbandry, Dairying and Fisheries, 17th Indian Livestock Census 2003- District Wise: http://dms.nic.in/ami/home.htm.

Asman, W.A.H., 1992. Ammonia Emission in Europe: Updated Emission and Emission Variations. Report 228471008. National Institute of Public Health and Environmental Protection, The Netherlands.

Baek, B.H., Aneja, V.P., 2004. Measurement and analysis of the relationship between ammonia, acid gases, and fine particles in Eastern North Carolina. Journal of Air and Waste Management Association 54, 623–633.

Baek, B.H., Aneja, V.P., Tong, Q., 2004. Chemical coupling between ammonia, acid gases, and fine particles. Environmental Pollution 129, 89–98.

Baek, B.H., Koziel, J., Aneja, V.P., 2006. A preliminary review of gas-to-particle conversion, monitoring, and modeling efforts in the USA. International Journal of Global Environmental Issues 6, 204–230.

Battye, W., Aneja, V.P., Roelle, P.A., 2003. Evaluation and improvement of ammonia emissions inventories. Atmospheric Environment 37, 3873–3883.

Behera, S.N., Sharma, M., 2010a. Investigating the potential role of ammonia in ion chemistry of fine particulate matter formation for an urban environment. Science of the Total Environment 408, 3569–3575.

Behera, S.N., Sharma, M., 2010b. Reconstructing primary and secondary components of $PM_{2.5}$ aerosol composition for an urban atmosphere. Aerosol Science and Technology 44, 983–992.

Behera, S.N., Sharma, M., 2011a. Degradation of SO_2, NO_2 and NH_3 leading to formation of secondary inorganic aerosols: an environmental chamber study. Atmospheric Environment 45, 4015–4024.

Behera, S.N., Sharma, M., 2011b. Transformation of atmospheric ammonia and acid gases into components of $PM_{2.5}$: an environmental chamber study. Environmental Science and Pollution Research. doi:10.1007/s11356-011-0635-9.

Behera, S.N., Sharma, M., Dikshit, O., Shukla, S.P., 2011. GIS-based emission inventory, dispersion modeling, and assessment for source contributions of particulate matter in an urban environment. Water, Air, & Soil Pollution 218, 423–436.

Beusen, A.H.W., Bouwman, A.F.P., Heuberger, S.C., Van Drecht, G., Van Der Hoek, K.W., 2008. Bottom-up uncertainty estimates of global ammonia emissions from global agricultural production systems. Atmospheric Environment 42, 6067–6077.

Bhatia, A., Pathak, H., Aggarwal, P.K., 2004. Inventory of methane and nitrous oxide emissions from agricultural soils of India and their global warming potential. Current Science 87, 317–324.

Bell, M.L., McDermott, A., Zeger, S.L., Samet, J.M., Dominici, F., 2004. Ozone and short-term mortality in 95 urban communities, 1987–2000. Journal of the American Medical Association 292, 2372–2378.

Bouwman, A.F., Lee, D.S., Asman, W.A.H., Dentener, F.J., Van der Hoeck, K.W., Olivier, J.G.J., 1997. A global high-resolution emission inventory for ammonia. Global Biogeochemical Cycles 11, 561–587.

Bouwman, A.F., Van der Hoeck, K.W., Olivier, J.G.J., 1995. Uncertainties in the global source distribution of nitrous oxide. Journal of Geophysical Research 100, 2785–2800.

Brasseur, G.P., Orlando, J.J., Tyndall, G.S., 1999. Atomospheric Chemistry and Global Change. Oxford University Press, New York.

Crutzen, P.J., 1970. The influence of nitrogen oxides on the atmospheric ozone content. Quarterly Journal of the Royal Meteorological Society 96, 320–325.

Crutzen, P.J., 1979. The role of NO and NO_2 in the chemistry of the troposphere and stratosphere. Annual Review of Earth and Planetary Sciences 7, 443–472.

Del Grosso, S.J., Wirth, T., Ogle, S.M., Parton, W.J., 2008. Estimating agricultural nitrous oxide emissions. Eos 89, 529–530.

Frank, D., Keating, T., Akimoto, H. (Eds.), 2011. Hemispheric Transport of Air Pollution, 2010–Part A: Ozone and Particulate Matter, Air Pollution Studies No. 17. Task Force on Hemispheric Transport of Air Pollution acting within the framework of the Convention on Long-range Transboundary Air Pollution, United Nations, New York, NY and Geneva, Switzerland.
EDGAR: Emissions Database for Global Atmospheric Research (EDGAR): 1995. http://www.rivm.nl/bibliotheek/rapporten/773301001.pdf.
EDGAR: Emissions Database for Global Atmospheric Research (EDGAR): 2005. http://edgar.jrc.ec.europa.eu/, EDGAR v4, EDGAR FT32, EDGAR Hyde datasets.
EEA (European Environment Agency), 1999. Atmospheric emission inventory guidebook, Second edition. EEA, Copenhagen emissions inventories. Atmospheric Environment, 37, pp. 3873–3883.
EPA (Environmental Protection Agency), 2006. Documentation for the Final 2002 Nonpoint Sector National Emission Inventory for Criteria and Hazardous Air Pollutants. http://www.epa.gov/ttn/chief/net/2002inventory.html.
EPA, 2010. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2008. EPA 430-R-10-006. http://www.epa.gov/climatechange/emissions/usinventoryreport.html.
EPA, 2011. Reactive Nitrogen in the United States: An Analysis of Inputs, Flows, Consequences, and Management Options. EPA-SAB-11-013/August 2011/. www.epa.gov/sab. http://yosemite.epa.gov/sab/sabproduct.nsf/67057225CC780623852578F10059533D/$File/EPA-SAB-11-013-unsigned.pdf.
Erisman, J.W., Bleeker, A., Hensen, A., Vermeulen, A., 2008. Agricultural air quality in Europe and the future perspectives. Atmospheric Environment 42, 3209–3217.
Galloway, J.N., 2000. Nitrogen mobilization in Asia. Nutrient Cycling in Agroecosystem 57, 1–12.
Galloway, J.N., Aber, J.D., Erisman, J.W., Seitzinger, S.P., Howarth, R.W., Cowling, E.B., Cosby, B.J., 2003. The nitrogen cascade. Bioscience 53, 341–356.
Galloway, J.N., Dentener, F.J., Capone, D.G., Boyer, E.W., Howarth, R.W., Seitzinger, S.P., Asner, G.P., Cleveland, C.C., Green, P.A., Holland, E.A., Karl, D.M., Michaels, A.F., Porter, J.H., Townsend, A.R., Vorosmarty, C.J., 2004. Nitrogen cycles: past, present and future. Biogeochemistry 70, 153–226.
Galloway, J., Raghuram, N., Abrol, Y.P., 2008. A perspective on reactive nitrogen in a global, Asian and Indian context. Current Science 94, 1375–1381.
Garg, A., Shukla, P.R., Kapshe, M., 2006. The sectoral trends of multigas emissions inventory of India. Atmospheric Environment 40, 4608–4620.
Gerber, P., Chilonda, P., Franceschini, G., Menzi, H., 2005. Geographical determinants and environmental implications of livestock production intensification in Asia. Bioresource Technology 96, 263–276.
Houghton, J.T., Meira Filho, L.G., Lim, B., Treanton, K., Mamaty, I., Bonduki, Y., Griggs, D.J., Callender, B.A. (Eds.), 1997. Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Greenhouse Gas Inventory Reference Manual, vol. 3. UK Meteorological Office, Bracknell.
IPCC (Intergovernmental Panel on Climate Change), 2006. Guidelines for National Greenhouse Gas Inventories. http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html.
Klaassen, G., 1991. Past and Future Emissions of Ammonia in Europe. Part 1 of a Report to: Ministry for Public Housing, Physical Planning and Environment. International Institute for Applied Systems Analysis, Laxenburg, Austria.
Lee, Y.-H., Park, S.-U., 2002. Estimation of ammonia emission in South Korea. Water, Air and Soil Pollution 135, 23–37.
Misselbrook, T.H., Van Der Weerden, T.J., Pain, B.F., Jarvis, S.C., Chambers, B.J., Smith, K.A., Phillips, V.R., Demmers, T.G.M., 2000. Ammonia emission factors for UK agriculture. Atmospheric Environment 34, 871–880.
NAAS, 2005. Policy Options for Efficient Nitrogen Use. Policy Paper No. 33. National Academy of Agricultural Sciences, New Delhi, p. 12.
National Research Council (NRC), 1991. Rethinking the Ozone Problem in Urban and Regional Air Pollution. National Academy Press, Washington, DC.
Oenema, O., 2006. Nitrogen budgets and losses in livestock systems. International Congress Series 1293, 262–271.
Olivier, J.G.J., Bouwman, A.F., Van der Hoek, K.W., Berdowski, J.J.M., 1998. Global air emission inventories for anthropogenic sources of NO_x, NH_3 and N_2O in 1990. Environmental Pollution 102 (S1), 135–148.
Parashar, D.C., Kushrestha, U.C., Sharma, C., 1998. Anthropogenic emissions of NO_x, NH_3 and N_2O in India. Nutrient Cycling Agroecosystem 52, 255–259.
Ravishankara, A.R., Daniel, J.S., Portmann, R.W., 2009. Nitrous oxide (N_2O): the dominant ozone-depleting substance emitted in the 21st century. Science, 123–125. doi:10.1126/science.1176985.
Roelofs, J.G.M., Boxman, A.W., Van Dijk, H.F.G., 1987. Effect of ammonium on natural vegetation and forest. In: Asman, W.H., Diederen, H.S.M.A. (Eds.), Ammonia and Acidification, pp. 266–276.
Schlesinger, W.H., 2009. On the fate of anthropogenic nitrogen. Proceedings of the National Acdemy of Sciences, U.S 106, 203–208.
Sharma, M., Kishore, S., Tripathi, S.N., Behera, S.N., 2007. Role of atmospheric ammonia in the formation of inorganic secondary particulate matter: a study at Kanpur, India. Journal of Atmospheric Chemistry 58, 1–17.
Sharma, S.K., Choudhury, A., Sarkar, P., Biswas, S., Singh, A., Dadhich, P.K., Singh, A.K., Majumdar, S., Bhatia, A., Mohini, M., Kumar, R., Jha, C.S., Murthy, M.S.R., Ravindranath, N.H., Bhattacharya, J.K., Karthik, M., 2011. Greenhouse gas inventory estimates for India. Current Science 101, 1–11.
Shindell, D.T., Faluvegi, G., Koch, D.M., Schmidt, G.A., Unger, N., Bauer, S.E., 2009. Improved attribution of climate forcing to emissions. Science 326 (5953), 716–718. doi:10.1126/science.1174760.
Singh, B., Singh, Y., 2008. Reactive nitrogen in Indian agriculture: inputs, use efficiency and leakages. Current Science 94, 1382–1393.
Smith, K.A., McTaggart, I.P., Tsuruta, H., 1997. Emissions of N_2O and NO associated with nitrogen fertilization in intensive agriculture, and the potential for mitigation. Soil Use and Management 13, 296–304.
Steenvoorden, J.H.A.M., Bruins, W.J., van Eerdt, M.M., Hoogeveen, M.W., Hoogervorst, N., Huijsmans, J.F.M., Leneman, H., van der Meer, H.G., Monteney, G.J., de Ruiter, F.J., 1999. Monitoring van nationale ammoniakemissies uit de landbouw. Reeks Milieuplanning 6. DLO-Staring Centrum, Wageningen, The Netherlands.
Syakila, A., Kroeze, C., 2011. The global nitrous oxide budget revisited. Greenhouse Gas Measurement and Management 1, 17–26.
US EPA, 2002. Review of Emission Factors and Methodologies to Estimate Ammonia Emissions from Animal Waste Handling. EPA/600/R-02/017. U.S. EPA, Office of Research and Development, Research Triangle Park, North Carolina.
Van der Hoek, K.W., 1994. Calculation of N Excretion and NH_3 Emissions by Greenhouse Gases in the Netherlands. Technical Report 222901003. National Institute of Public Health and Environmental Protection, The Netherlands.
Van Der Hoek, K.W., 1998. Estimating ammonia emission factors in Europe: summary of the work of the UNECE ammonia expert panel. Atmospheric Environment 32, 315–316.
Yamaji, K., Ohara, T., Akimoto, H., 2004. Regional-specific emission inventory for NH_3, N_2O, and CH_4 via animal farming in South, Southeast, and East Asia. Atmospheric Environment 38, 7111–7121.
Yan, X., Akimoto, H., Ohara, T., 2003. Estimation of nitrous oxide, nitric oxide, and ammonia emissions from croplands in East, Southeast, and South Asia. Global Change Biology 9, 1080–1096.
Zhao, D., Wang, A., 1994. Emission of anthropogenic ammonia emission in Asia. Atmospheric Environment 28, 689–694.