Estimates of emission and deposition of reactive nitrogenous species for India

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Anthropogenic activities are responsible for the enhanced emission of reactive nitrogenous species like nitrous oxide (N_2O), oxides of nitrogen (NO_x) and ammonia (NH_3) into the atmosphere from the biosphere. This article reviews the available estimates of emissions of these reactive nitrogenous species for India. In addition, it reviews the estimates of depositional fluxes of ammonia and nitrate through dry and wet precipitation over India. Agriculture soils are the largest emitter of N_2O in India due to increasing application of nitrogenous fertilizers in agriculture fields. The contributions of other sources like biomass burning and energy activities are rather small in the overall N_2O emissions in India. However, total contribution of Indian agriculture to the global N_2O emissions is merely 2.7%. On the other hand, energy activities are a major source of NO_x emissions in India, which include both mobile and stationary combustion processes. The agriculture sector has a small contribution in the total NO_x emissions in India. The ammonia emissions are primarily contributed from the agriculture sector in India. The depositional fluxes of ammonia have so far been reported to be higher for sub-urban areas while the nitrate depositional fluxes have been reported to be higher over rural areas, which can have significant impacts on the agriculture productivity. However, the present article reveals large uncertainties in all these estimates which need to be addressed through systematic nation-wide studies.

Keywords: Depositional fluxes, emission, greenhouse gas, inventories, nitrogeneous species.

THE natural biogeochemical cycle of nitrogen (N) in the post-industrial era has been greatly influenced by the anthropogenic activities through enhanced emission of reactive nitrogenous species from various sectors like energy, industries, agriculture and waste. A major consequence of this human-driven change in the global nitrogen cycle is the increased emission of N-based trace gases, such as nitrous oxide (N_2O) and NO_x ($NO + NO_2$) and ammonia (NH_3) that has impacted regional and global atmospheric chemistry[1]. Although the diatomic nitrogen (N_2) constitutes the major portion of atmospheric nitrogen (78%), the role of other nitrogenous species in the atmosphere, present in trace quantities, is important in the modification of the earth's radiation balance and atmospheric chemistry. Nitrous oxide is effective at trapping heat in the atmosphere and triggers reactions leading to destruction of ozone in the stratosphere. Nitrogen oxides (NO_x) play an important role in the chemistry of the lower atmosphere by catalysing the photochemical formation of ground-level ozone, causing detrimental effects with regard to human health and crop productivity[2]. Nitrous oxide is also important in the photochemical formation of NO_x, a component of acid rain[3]. Ammonia is the major gaseous base in the atmosphere and serves to neutralize about 30% of the hydrogen ions in the atmosphere[4].

Over evolutionary history, only a limited number of species of bacteria and archaea have evolved the ability to convert N_2 to reactive nitrogen. Reactive nitrogen (N_r) is usually referred to all the nitrogen species that are biologically active, photo-chemically reactive and radiatively important in the atmosphere and biosphere of the earth[5]. Thus, N_r includes reduced inorganic forms of N (NH_3, NH_4^+), oxidized inorganic forms (NO_x, HNO_2, N_2O and NO_3^-) and organic compounds (urea, amines, proteins and nucleic acids). The impact of N_r on the environment can occur in series. Referred to as the N-cascade[6], one atom of N can, in sequence, (i) increase tropospheric O_3 (human health impact), (ii) increase fine particulate matter (visibility impact), (iii) alter forest productivity, (iv) acidify surface waters (biodiversity loss), (v) increase coastal ecosystem productivity, (vi) promote coastal eutrophication and (vii) increase greenhouse effect in the atmosphere (N_2O production).

Among the trace nitrogenous species, the nitrous oxide (N_2O), being an important greenhouse gas, has the largest concentration in the atmosphere and this species also has a strong bearing on the earth's radiation balance. According to the recent Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report[7], the global N_2O concentrations have increased from about 270 ppb during the pre-industrial period to about 319 ppb in 2005. The growth rate of N_2O has been reported to be approximately constant since 1980, but more than a third of the total N_2O emission has been attributed to anthropogenic activities, including agriculture, which is the largest contributing sector.

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The other important trace N-species in the atmosphere are oxides of nitrogen (NO_x) and ammonia (NH_3) which are highly reactive and thus have short atmospheric residence time, unlike N_2O which has a longer atmospheric residence time, but they also play an important role in the chemistry of the atmosphere. NH_3 in the atmosphere acts as a neutralizing agent for the acidic aerosols, besides directly affecting the vegetation and forming nitrate and N_2O. Similarly, NO_x in the atmosphere acts as a precursor of ozone (O_3) and also forms nitric acid (HNO_3), thus contributing not only to the acidity of the atmosphere, but also indirectly contributing to greenhouse effects. The ammonium and nitrate species formed during the atmospheric chemical processes are eventually returned back to the earth surface in the form of aerosols or ions through wet and dry depositions.

The IPCC has developed methodologies for countries to estimate national greenhouse gas emissions (GHG) from different sectors, e.g. nitrous oxide (N_2O) emission from agriculture. Each agricultural activity has a magnitude and emission factor and their product is summed over all included activities to generate a national total[8]. Nitrogen fertilization of agricultural soils is responsible for emission of the greatest amount of N_2O of all the anthropogenic sources. Besides mineral N fertilizers, compost and green manure also contribute towards N_2O emission. In order to support the global food production, N fertilizer use is likely to increase in future[9] and as a result N_2O emissions are also expected to go up.

The present article reviews the estimates for emission of different trace nitrogen species (viz. N_2O, NO_x and NH_3) and information on deposition fluxes of nitrogenous species reported so far for India.

Nitrous oxide emission

N_2O is emitted into the atmosphere from both natural (like waterbodies and soils) as well as from anthropogenic activities like agriculture, transport, industries and waste-management practices. Measurement of N_2O emission from Indian agriculture started only in the 1990s. The closed-chamber technique[10] was employed for these measurements. Results of N_2O emission from agricultural soils based on actual field measurements are summarized in Table 1. These experiments reveal average N_2O-N emission of 0.0025 and 0.0055 kg kg^{-1} N applied from rice and wheat fields respectively. Results indicate that N_2O emission is more in aerated crops such as wheat than in rice, which is grown in flooded anaerobic soil condition. As rice and wheat are the major crops in India, covering about 45 and 27 mha of cultivated area respectively, and consume maximum amounts of N fertilizer, an average N_2O emission can be taken as 0.004 kg kg^{-1} N applied. Earlier, some attempts have been made to estimate N_2O emission from Indian soils for different time periods (Table 2). For example, it is estimated[11] that 199–279 Gg N_2O-N yr^{-1} is emitted from agricultural soils in India. In another study[12], N_2O-N emission from Indian agricultural soils was estimated to be 240 Gg yr^{-1}. Garg *et al.*[13] using the IPCC methodology and emission coefficients[14] have given an estimate of 170 Gg N_2O-N from Indian soils. The estimate included emission from biological N fixation, N fertilizer and indirect emission from soils. These estimates do not match, as adequate coverage of all sources of N_2O emission has not been made and there were too many assumptions without the actual measurement data. Recently[15], it has been estimated that 79.94 Gg N_2O-N is emitted for the base year 1994–95 from Indian agricultural soils using some measured emission coefficients (Table 3). However, using the IPCC default emission coefficients, the emission was 145 Gg N_2O N yr^{-1}. Uttar Pradesh (including Uttarakhand) emitted the highest amount of N_2O-N (15.53 Gg) followed by Andhra Pradesh (9.50 Gg) and Maharashtra (7.50 Gg). Larger area under cultivation, higher use of N fertilizer and greater animal population are responsible for higher emission in these states. Estimates of N_2O-N emission in

Table 1. Emission of N_2O from agricultural fields in India

Crop	Fertilizer[†]	N dose (kg ha^{-1})	Irrigation[‡]	Duration (day)	N_2O emission (kg N ha^{-1})	Emission coefficient (kg N_2O-N kg^{-1} N)	Reference
Rice	Urea	140	CF	70	0.06	0.0004	47
Rice	Urea	140	IF	90	0.16	0.0011	48
Rice	AS	140	IF	90	0.23	0.0016	48
Rice	Urea	120	SS	105	0.17	0.0014	49
Rice	AS	120	SS	105	0.15	0.0012	49
Rice	PN	120	SS	105	0.19	0.0016	49
Rice	Urea	120	SS	90	0.74	0.0050	50
Rice	Urea	120	IF	90	0.93	0.0050	50
Wheat	Urea	140	3 irrig.	125	0.71	0.0052	50
Wheat	Urea	120	5 irrig.	125	0.77	0.0052	50
Wheat	Urea	120	5 irrig.	95	0.55	0.0045	51

[†] AS, Ammonium sulphate; PN, Potassium nitrate.

[‡] CF, Continuously flooded; IF, Intermittently flooded; SS, Saturated soil.

Table 2. Estimates of N_2O emission from Indian agriculture

Source	Estimate (Gg N_2O-N yr^{-1})	Domain	Methodology used
Parashar *et al.*[11]	199–279	India	Extrapolated from some measurements all over India
ALGAS[12]	248	India	Extrapolated from some measurements all over India
Garg *et al.*[13]	170	India	IPCC methodology and IPCC emission coefficients
Bhatia *et al.*[15]	80	India	IPCC methodology and measured emission coefficients
Bhatia *et al.*[15]	145	India	IPCC methodology and IPCC emission coefficients
INC[16]	146	India	IPCC methodology and IPCC emission coefficients
Pathak *et al.*[18]	50	Indian rice fields	DNDC simulation model

Table 3. Emission of nitrous oxide from agricultural soils in different states of India during 1994–95

State	N_2O emission (Gg)
Andaman and Nicobar Islands	0.02
Andhra Pradesh	9.50
Arunachal Pradesh	0.01
Assam	0.21
Bihar	3.90
Chandigarh	0.03
Dadra and Nagar Haveli	0.01
Delhi	0.10
Goa, Daman and Diu	0.03
Gujarat	4.49
Haryana	4.38
Himachal Pradesh	0.26
Jammu and Kashmir	0.32
Karnataka	4.35
Kerala	0.71
Madhya Pradesh	6.78
Maharashtra	7.50
Manipur	0.06
Meghalaya	0.02
Mizoram	0.00
Nagaland	0.53
Orissa	1.34
Puducherry	0.09
Punjab	7.69
Rajasthan	4.31
Sikkim	0.01
Tamil Nadu	4.36
Tripura	0.04
Uttar Pradesh	15.53
West Bengal	3.38
Total	79.94

Source: Bhatia *et al.*[15].

India from 1980–81 onwards ranged from 32.84 Gg (1980–81) to 93.82 Gg (2000–01) per year. There was a linear increase in emission due to increased area under different crops, higher use of N fertilizers and also increase in animal population. It was observed that inorganic fertilizer is the major source (72%) of nitrous oxide. Other sources like crop residues and manure contribute 11 and 3% respectively, to the total emission[15].

India's Initial National Communication to UNFCCC[16] has reported that the total N_2O emission from the country was 178 Gg for the year 1994, which is only 4% of the total GHG emission from the country. The agriculture sector is the largest contributor to it, which accounts for 85% of this emission. The direct emission from soils due to the use of nitrogenous fertilizers is the major source of N_2O emission contributing about 146 Gg for the year 1994, which is about 81% of the total N_2O in terms of CO_2 equivalent. The other small sources of N_2O emission in agriculture sector are manure management and the agriculture crop residue burning[16], which have been estimated to contribute about 1 and 4 Gg respectively, for the year 1994.

Simulation models are efficient tools to quantify the effects of climate, soil, crop and agriculture management on emission of nitrous oxide from the soil. This can reduce the need for expensive and time-consuming field experimentation and can be used to extrapolate the results of research to other larger areas, where similar conditions are observed. Recently, attempts have been made to calculate detailed regional N_2O emission using simulation models[17–19]. A recent study[18] used the simulation modelling approach for estimation of nitrous oxide emission from rice fields in India, using a newly compiled soil/climate/land-use database. Continuous flooding of rice fields (21 mha) resulted in annual net emission of 40–50 Gg of N_2O-N. Intermittent flooding of rice fields increased emission to 50–60 Gg N_2O-N. Emission of N_2O-N was higher from the southeastern (Andhra Pradesh) and northern (Punjab) states of the country. The high emission was due to larger area under rice and higher use of N fertilizers. Moreover, in northern India, rice is generally grown under intermittent drying conditions and considerable amounts of nitrous oxide emission could occur because of alternate wetting and drying of rice fields, resulting in the repetition of nitrification and denitrification processes. In terms of global nitrous oxide emissions, the contribution of Indian agriculture is miniscule (Table 4). Estimates have shown that the Indian agricultural soils are contributing only 0.88% of the world's nitrous oxide emission and nitrous oxide from Indian agricultural soils is responsible for only about 0.1% of the global warming caused by the world's nitrous oxide emission.

N_2O is also produced during the fuel combustion process due to the reaction between nitrogen and oxygen in both mobile as well as stationary combustion processes. The quantities of N_2O emission during combustion depend upon several factors like fuel type, nitrogen content of fuel, combustion type, operating conditions, technologies, etc. For India, the NATCOM report[16] has estimated a total of about 11.4 Gg N_2O emissions from the energy sector for the year 1994. The energy sector includes subsectors like energy and transformation industries contributing 4.9 Gg N_2O, industry (mainly nitric acid production) contributing 2.8 Gg N_2O, transport contributing 0.7 Gg N_2O, commercial–institutional contributing 0.2 Gg N_2O, residential contributing 0.4 Gg N_2O, other sectors contributing 0.4 Gg N_2O and biomass burnt for energy contributing 2.0 Gg N_2O. The waste sector has been estimated to contribute about 7 Gg N_2O in the year 1994.

Estimates[20] using the IPCC methodologies have yielded the total N_2O emission from India for the years 1985, 1990, 1995, 2000 and 2005 as 134, 158, 185, 217 and 253 Gg respectively, which has yielded a compounded annual growth rate (CAGR) of 3.2% for the period 1985–2005. This observed CAGR essentially follows a similar CAGR of 3.2% observed for the N_2O emission due to synthetic fertilizer use during the corresponding period[20], because of its largest contribution in the total national N_2O emission. For other sectors like field burning of agriculture residue, indirect soil emission, manure management, fossil-fuel combustion, industrial processes and waste, the reported[20] CAGR values are 1.4, 2.9, 3.9, 4.9, 5.0 and 2.8 respectively, for the period 1985–2005. The observed higher CAGR for manure management, fossil-fuel combustion and industrial processes reflects that in future these sectors may also become significant contributors in the national total emissions of N_2O.

Nitrogen oxide emission

The release of nitrogen oxides (NO_x) has been accelerated during the last few decades, primarily through the increase in fossil-fuel combustion[21]. The NO_x emissions are predominantly contributed by sources such as vehicular exhaust, coal combustion and biomass burning. The higher temperatures in the flame during combustion are generally responsible for the formation of NO_x, as it helps in breaking down the molecular nitrogen and oxygen of the air, that recombine to form NO_x, which includes both nitric oxide (NO) and nitrogen dioxide (NO_2). In addition, the nitrogen content of the fuel also gets oxidized during the combustion and releases NO_x. Among the above-mentioned three sources, vehicular exhaust is the largest contributor of NO_x emission in India. Singh *et al.*[22], using the default IPCC emission factors, have estimated that the Indian road transport sector contributed about 0.3 Tg NO_x emission in 1980, which has increased to 1.1 Tg in 2000. Diesel-powered vehicles have been estimated to be the dominant contributors and account for about 84% of the total NO_x emission for the road transport sector. This could possibly be due to higher consumption of diesel in freight and passenger (mass transport) transport vehicles, which are mostly powered by diesel engines only. The CAGR of these NO_x emissions have been estimated at about 8% for the period 1980–1990. However, for the period 1990–2000, CAGR has been estimated as about 6% only. This decrease in the growth rate during the last decade has been attributed to relatively lower increase in the consumption rate of diesel from 1997 onwards, though the absolute value of the consumption has increased four times between 1980 and the later period of 1990s. Other available estimates for NO_x emission from the Indian transport sector show wide variation due to the use of different emission factors. For example, a study[23] using a modelling approach to compute emission factors has estimated total NO emission from all vehicles in India for the year 1997 as 4.8 Tg. However, others[24] have estimated NO_x emission as 1.9 Tg for the year 2001–02. The reasons for such large variations in the emission estimates are due to the emission factors used in these estimates. In order to reduce such large uncertainties, development of country-specific emission factors for different activities is required.

Table 4. Contribution of Indian agriculture towards global N_2O emission

Domain	N_2O emission (Tg)	N_2O (% of world)
World*	8.96	100
India*	0.26	2.8
World agriculture†	3.5	39.1
Indian agriculture*	0.24	2.7
Indian agricultural soils‡	0.08	0.88

Source: *ALGAS[12]; †IPCC[14]; ‡Bhatia *et al.*[15].

In the thermal power plants, NO formation largely depends upon the excess air used during combustion and the gas temperature in the boiler. NO is formed by the oxidation of atmospheric nitrogen during combustion of the fuel. The contribution of nitrogen that is chemically bound within the fuel is small. A study[25] using the modelling approach has estimated average NO emission per unit of electricity as approximately 4.8 g/kWh. This compares to a US average 3.5 g/kWh for the year 1995. Total NO emission due to thermal power generation in India has been estimated by them as 5.3 Tg for the year 1997.

The 'field burning of agricultural residue' is established as an important sub-sector of the 'agriculture' sector in the IPCC methodology for national GHG inventory preparation[8]. Northern India is among the most productive regions for agriculture in Asia and post-harvest field burning of rice straw is common practice in the area. In these areas farmers normally resort to burning of left-over agriculture residue as a cost-effective post-harvest field management practice. The increasing use of combine harvesters in the region usually leaves behind a large quantity of straw in the field that is often subjected to burning[26]. In a recent survey it was observed that 60 and

Table 5. Volatilization of ammonia from various land use types and locations of India

Location	Crop	Organic C (%)	pH	Texture†	N added (kg ha^{-1})	N source	Volatilization loss (kg ha^{-1})	Reference‡
New Delhi	Rice	0.48	7.7	SCL	120	Urea	10.1	52
New Delhi	Rice	0.48	7.7	SCL	120	USG	4.0	52
New Delhi	Wheat	0.41	8.2	L	100	Urea	8.0	53
Kalyani, WB	Rice	1.23	8.4	SiCL	90	Urea	15.6	54
Kalyani, WB	Rice	1.23	8.4	SiCL	90	Neem + urea	12.0	54
Kalyani, WB	Rice	1.23	8.4	SiCL	90	Urea + GM	7.2	54
Cuttack	Rice	0.70	6.0	SiL	90	Urea	2.9	55
Pantnagar	Rice	–	7.6	–	120	Urea	22.8	56
Pantnagar	Rice	–	7.6	–	120	USG	1.0	56

†SCL, Sandy clay loam; L, Loam; SiCL, Silty clay loam; SiL, Silty loam; S, Sandy; CL, Clay loam; USG, Urea super granule.

82% of rice straw produced in the northwestern states of Haryana and Punjab respectively, is burned in the field. Some estimates of NO_x emission from this source are available, like 0.1 Tg yr^{-1} field burning of crop residue[27] for the year 1985 and 0.54 Tg yr^{-1} from all types of biomass burning[28]. Another study[29] has estimated 47.6 Gg of NO_x emission for the year 1989–90 and others[30] have reported 40 Gg of NO_x emission for the year 1994 from field burning of wheat residue. A recent study[31] has estimated that the field burning of wheat residue is responsible for emission of 14 ± 9, 33 ± 32, 15 ± 14 and 11 ± 9 Gg of N_2O, NO_x, NO and NO_2, respectively, for the year 2000 in India.

NO_x emission from soils is primarily a result of NO production by the microbial oxidation of ammonium, the process known as nitrification[32]. NO production in the soils also occurs through microbial reduction of nitrate (denitrification). This reaction only occurs in water-saturated soils where little NO is released from the soil to the atmosphere[33]. Davidson and Kingerlee[34] estimated that about 5 Tg of NO_x-N is emitted annually from cultivated soils globally, through an analysis of published NO_x flux measurements in agricultural fields. Estimates[35] exist that about 0.5% of fertilizer-N applied to agricultural fields was emitted to the atmosphere as NO. Others[36] observed that although field measurements are lacking, NO emission from paddy fields during the rice-growing season could be assumed to be non-negligible and a fertilizer-induced emission factor of 0.13% for NO from paddy fields as proposed[37] could be considered.

Ammonia emission

Agriculture is the major sector responsible for NH_3 emission. Application of fertilizers in the agriculture fields and the livestock population are mainly responsible for NH_3 emission. The emission estimates of NH_3 are highly uncertain in India, as no country-specific emission factor for NH_3 is available as yet. Estimates of ammonia emission from various land-use types and locations in India have been summarized in Table 5. The loss rates vary from 1 to 22.8 kg ha^{-1} depending upon soil type, crop and fertilizer material. Some studies have shown leaching loss of N from soils in the Indo-Gangetic-Plains (IGP) as 10–15 kg N ha^{-1}, while ammonia volatilization loss is 20–30 kg N ha^{-1} with application of 120 kg N ha^{-1} in rice and wheat[38,39]. In a study on the loss of N as NH_3 from the rice–wheat system of North India, volatilization losses ranged from 38.6 kg N ha^{-1} in unfertilized soil to 69.0 kg N ha^{-1} with urea plus DCD treatments have been reported[40]. Daily emission of NH_3-N was as high as 0.45 kg N ha^{-1} d^{-1} in rice and 0.5 kg N ha^{-1} d^{-1} in wheat. Substitution of 50% urea-N by farmyard manure reduced NH_3-N emission by 10% in rice and wheat compared to urea-N alone. Studies[11] have estimated using proposed[41] emission factors that fertilizer application was responsible for about 1.17 Tg NH_3 emission in India for 1993–94.

Among all the fertilizers, urea application is responsible for contribution of more than 90% of these emissions. Other types of fertilizers like ammonium sulphate, calcium ammonium sulphate, diammonium phosphate, ammonium phosphate, nitrophosphate and NPK, have been estimated to contribute only a small amount of NH_3 emission. The reason for highest contribution from urea is not only because of its highest usage in Indian agriculture, but also due to the large emission factor for NH_3 emission (as per cent loss of N). However, none of these emission estimates has taken into account the organic manure applications in the agriculture fields in India so far. A recent study[42] simulated N loss from rice–wheat cropping systems of the IGP through ammonia volatilization. Total loss of N was 16–62 kg N ha^{-1} in the various states of the IGP. Average N loss was 30 kg N ha^{-1}, with average fertilizer application of 98 kg N ha^{-1}. Thus, about 30.4% of N applied through fertilizer and manure was lost from the system. Volatilization accounted for 15 kg ha^{-1} loss of N. Ammonia volatilization was larger in Punjab and West Bengal because of a larger amount of N use through fertilizer and manure and also because of higher soil pH (Figure 1).

The livestock in India has been estimated to contribute about 1.43 Tg of NH_3 emission[11]. Among these emissions, cattle have been estimated to have the largest con-

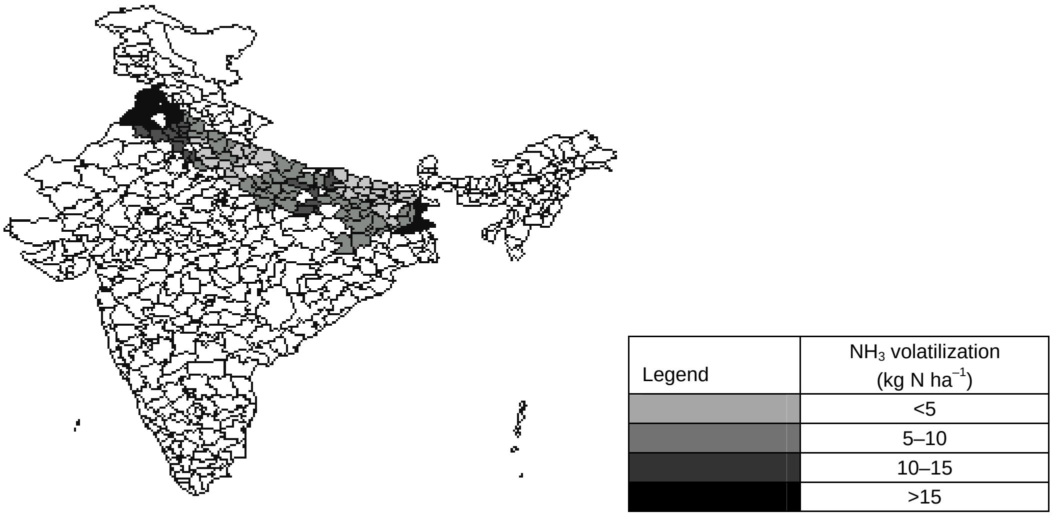

Figure 1. Annual loss of N through volatilization in the rice–wheat systems of the IGP (source Pathak *et al.*[42]).

tribution amounting to 1.05 Tg, followed by buffaloes which have been estimated to contribute about 0.28 Tg NH$_3$. The other categories of livestock like pigs, poultry, horses and sheep have small contributions in the total national NH$_3$ emission. These emission estimates are again based on the emission factors proposed by Asman[41], which have been developed using the feed intake ratios of West European cattle and therefore, may not truly represent Indian conditions, where the feed intake ratios are generally low.

Depositional fluxes of NH$_4^+$ and NO$_3^-$

Nitrogen species like NH$_4^+$ and NO$_3^-$ present in the atmosphere due to direct emission or as resultant products of the atmospheric chemical process are normally removed from the atmosphere through wet and dry precipitations and brought back to the earth's surface. The dry and wet depositions constitute an important input to the soil and vegetation on the earth and, therefore, need to be quantified adequately to ascertain the total nitrogen cycle with more certainty. However, limited estimates of these species are available so far, especially in most of the developing countries, including India, which makes it almost impossible to accurately quantify the depositional fluxes. There is an increasing concern about the enhanced depositions of these nitrogenous species due to anthropogenic reasons, especially in regions like India and China, where the emission rates of nitrogen compounds are estimated to be increasing at a fast rate[43,44].

A study on India[45] reviewed the precipitation-monitoring studies to synthesize regional patterns based on the available data from different monitoring stations in the country. This study indicates that the NH$_4^+$ median concentrations of about 9 μ eq l^{-1} (range from 25 to 75 percentile = 4–16 μ eq l^{-1}) are the lowest in the precipitation samples measured over rural areas in India and the concentration is about 14 μ eq l^{-1} (range from 25 to 75 percentile = 11–18 μ eq l^{-1}) in the samples collected over sub-urban areas. Precipitation in the urban areas showed highest NH$_4^+$ median value concentration of 22 μ eq l^{-1} (range from 25 to 75 percentile = 15–27 μ eq l^{-1}), while precipitation samples collected over industrial areas in India showed NH$_4^+$ median value of 18 μ eq l^{-1} (range from 25 to 75 percentile = 11–37 μ eq l^{-1}). For the NO$_3^-$ concentrations in the precipitation samples collected over rural, suburban, urban and industrial areas[45], median values of 22 (range from 25 to 75 percentile = 10–34 μ eq l^{-1}), 11 (range from 25 to 75 percentile = 9–18 μ eq l^{-1}), 28 (range from 25 to 75 percentile = 10–46 μ eq l^{-1}) and 21 μ eq l^{-1} (range from 25 to 75 percentile = 12–28 μ eq l^{-1}) respectively, were obtained. On the basis of these observed concentrations, the median depositional fluxes of NH$_4^+$ species over rural, suburban, urban and industrial areas have been estimated to be 10, 13, 18 and 26 μ eq m^{-2} yr^{-1} respectively and for NO$_3^-$ species the depositional fluxes have been estimated to be 18, 14, 26 and 29 μeq m^{-2} yr^{-1} respectively[45].

It is quite evident from these data that, so far, the urban areas are observed to have the highest depositional fluxes of both of NH$_4^+$ and NO$_3^-$ species, but the NO$_3^-$ concentrations in the precipitations over rural areas have also been found to be quite high, which is expected to significantly influence the total input quantities of nitrogen species in the agriculture eco-systems. However, this is more of indicative in nature at present, as pointed out by Kulshrestha *et al.*[45] that the problems related to rather low monitoring stations density which is lower by a factor of 10 compared to monitoring stations in Europe and uneven coverage of various regions in the country. This makes the deciphering of regional depositional patterns of NH$_4^+$

and NO_3^- fluxes rather difficult. Recently[46], a multi-model evaluation made for nitrogen and sulphur deposition on regional and global scales through twenty-three atmospheric chemistry transport models, found that the models strongly over-estimated the NH_4 depositions for the Indian region by an average 350 mg (N) m^{-2} yr^{-1}. This was attributed due to over-estimation of NH_4 emissions for the region or due to biological degradation of unstabilized samples collected by monitoring stations. On the other hand, the modelled nitrate depositions are strongly underestimated by 130 mg (N) m^{-2} yr^{-1}. These evaluations point out the extent of uncertainties that exist in depositional fluxes of ammonia and nitrate for the Indian region.

Conclusion

The estimation of emission and deposition of reactive nitrogenous species for the Indian region, reported so far, has been covered in this article; but data are still scarce and suffers from various deficiencies like non-availability of country-specific emission factors, lack of adequate monitoring stations and data quality. The uncertainties in N_2O emission estimation from Indian agriculture are also because of diverse soil and climatic conditions, different management practices and socio-economic status of the farmers. Therefore, an appropriate national exercise is needed to formulate and address the deficiencies and gaps in order to make quantitative estimations of emission of various reactive nitrogenous species and their depositional fluxes, to clearly understand the nitrogen cycle at a national level. This will not only improve estimates of emission and related impact assessments, but also provide a baseline from which future emission trajectories may be developed to identify and evaluate mitigation strategies.

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