Regional nitrogen cycle: An Indian perspective

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During the past century through food and energy production, human activities have altered the world's nitrogen cycle by accelerating the rate of reactive nitrogen creation. India has made impressive strides in the agricultural front, in which N fertilizer plays a major role. There has been a marked change in the supply and use of land, water, fertilizers, seeds and livestock, but the N use efficiency remained at a low level. Exploring the nature of these changes and quantification of the impacts on the N cycle has become essential. Hence we have presented data on various N pools and fluxes based on a conceptual N model. In India, efforts should focus on understanding the fate and consequences of the applied N and to increase the efficiency of N use.

Keywords: Anthropogenic changes, regional nitrogen cycle, remote sensing and GIS, quantification approaches.

COMPARED with other essential elements, nitrogen is only a minor constituent of living matter; but why is nitrogen so important? There has been an increased recognition of the importance of the nitrogen cycle to global climate and primary productivity, which has drawn attention to the value of large-scale element models for assessing the effects of human activity on the N cycle. Nitrogen remains largely locked in the atmosphere (gaseous nitrogen, N_2), and only a fraction (reactive nitrogen, Nr) enters into the growing plants, animal and ultimately human beings. According to Galloway *et al.*[1], reactive nitrogen includes all biologically, photochemically and radiatively active nitrogen compounds in the atmosphere and biosphere of the earth, and does not include N_2. Legumes, through symbiotic association with N-fixing bacteria and some free-living microorganisms, can fix atmospheric nitrogen into available form, whereas grasses are largely dependent upon outside sources. The amount of nitrogen in available forms in the soil is small, while the quantity withdrawn annually by crops is comparatively large, particularly in agro-ecosystems. As its effects on plants are conspicuous and rapid, in several agro-ecosystems and across different regions over-application or mismanagement of nitrogen, which may be harmful, sometimes occurs. Moreover, due to industrial activities and fossil-fuel burning, greenhouse gases (Nr compounds, i.e. N_2O among others) are released into the atmosphere, resulting in detrimental effects on ecosystems and human health. At present, detailed regional N budgets for India are lacking and should not be under-represented in future global synthesis. Hence, in this article we describe a detailed model of the nitrogen cycle for India.

Human modifications

The global N cycle is the result of complex interactions of various biological and abiotic processes occurring in various pools of nitrogen. Based on the constancy of the N_2O record, N fixation and denitrification in pre-industrial times were approximately equal[2]. Since the early 20th century, the amount of N fixed by unmanaged ecosystems has not been sufficient to meet the human dietary needs; hence industrial N fixation and human modified biological N fixation (BNF) have become essential.

Galloway and Cowling[3] have estimated the global human modification of the N cycle. Humans currently ingest ~20 tera gram ($Tg = 10^{12}$ g) of N yr^{-1} in their food and ~100 Tg of N yr^{-1} into the environment through food production. In addition, ~25 Tg of N yr^{-1} was created by fossil fuel combustion and ~20 Tg of N yr^{-1} by other activities. Nr creation through natural terrestrial BNF is ~90 Tg of N yr^{-1}. 'Human activity is radically altering the world's nitrogen cycle by producing increasing amounts of Nr through food and energy production. While some important food-producing systems of the world are nitrogen deficient, others are generating excess nitrogen, affecting air, land and freshwater, and ultimately environmental and human health[4].' Thus, there is substantial regional variability in Nr creation, distribution and effects that range from terrestrial ecology to atmospheric chemistry and global climate change.

Importance of N cycle estimates for India

In India, as a result of anthropogenic-related developmental activities, land degradation, deforestation and changes in water and atmospheric chemical composition have been occurring, which result in the alteration of the N fluxes in and out of the major N reservoirs. Exploring the nature of these changes and quantification of the impacts on the N cycle have become essential to address the concern of human and animal health and to ensure sustainable development. However, estimation of N cycle in India is

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in its infancy. A few discrete studies of the terrestrial N cycle have been made to estimate its major pools and fluxes in agro-ecosystems and anthropogenic N emissions.

The agro-ecosystem forms the most dominant terrestrial ecosystem in India and is predominantly controlled by human activities aimed to produce food, fodder and fibre. Nitrogen fertilizer use in Indian agriculture has increased to 11.31 million tonnes (mt) in 2001–02 from 0.065 mt in the early 1950s. The increase in fertilizer consumption is related to the introduction of high-yielding and fertilizer-responsive cultivars of cereal crops. Additionally, organic sources of N, such as manure and/or biological N fixation (for example, the symbiotic association between legumes and *Rhizobium* spp.), are also used across different cropping systems. Further, as a result of industrialization and expansion of infrastructure, increasing amount of Nr is being created. This results in the nitrogen cascading effect, which is defined as the sequential effect that a single atom of nitrogen can have in various reservoirs after it has been converted from a non-reactive form to a reactive form[5]. Since these changes have significant local and global consequences, it is important to quantify the regional pattern, integrating natural flows with human food cycle, fossil use and land-use change impacts to improve the understanding as well as highlighting policy issues.

N pools and fluxes estimates for India

Regional-level biogeochemical cycles are valuable for assessing what is known about element cycle processes in a particular ecosystem of a region[6] and for addressing region-specific environmental policy questions[7,8]. India constitutes an important part of the terrestrial biosphere and hence it is essential to quantify N-cycle components. We briefly describe this below.

N cycle in Indian agro-ecosystem

Nitrogen from the atmosphere (N_2 pool) is added to the agro-ecosystem by industrial and biological N fixation and moves out of the system through crop harvest. The data presented in Figure 1 are synthesized for a reference period (1995–96) using various data sources[9–11], which gives a glimpse of the N cycle in the agro-ecosystem with estimates for India.

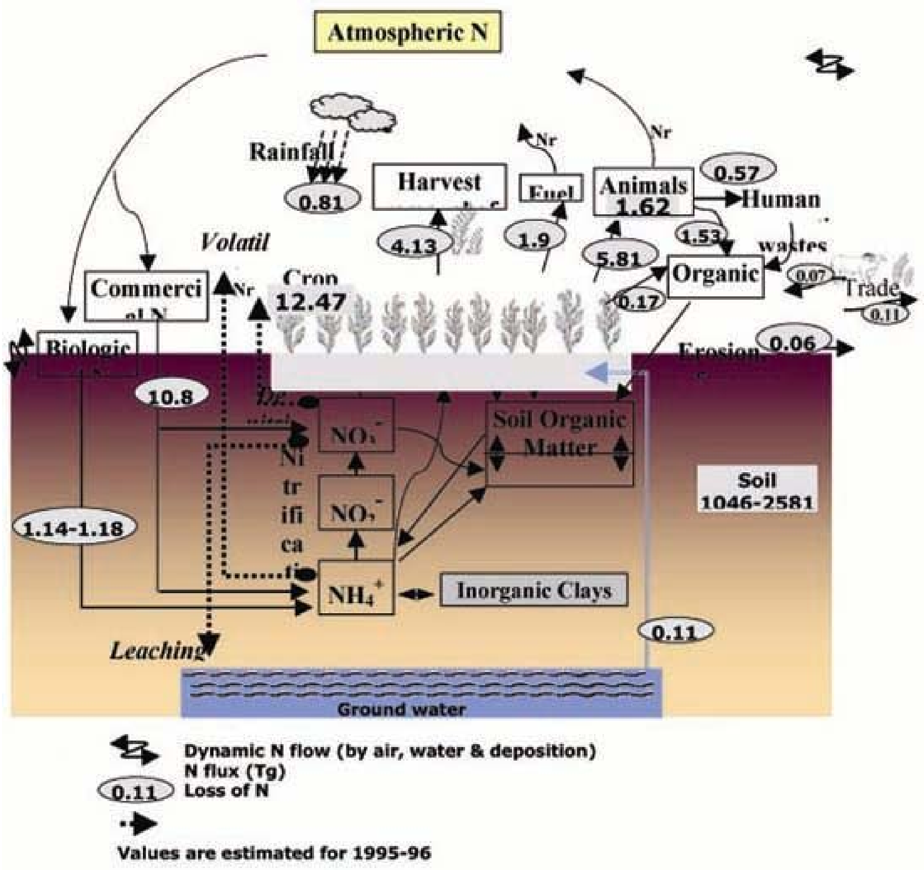

Figure 1. Simplified N cycle in agro-ecosystem of India.

In India, nearly 10.8 Tg N was added through commercial N fertilizers in the recent production cycles and another 1.14–1.18 Tg N was added by BNF into the soil. The bulk of the non-atmospheric N in India is in the soil. The soil N pool other than forest was estimated to be ~1046–2581 Tg N. Recycling (mineralization) of organic N is a means by which inorganic N sources to plants may be increased. But the proportion of this N that actively cycles in the soil–plant system is not known with certainty. In spite of the above fact, it is of critical importance in Indian agricultural systems because this system is usually characterized by a harvest that removes ~4.13 Tg N from the total crop N pool of ~12.47 Tg N. Further, ~1.9 Tg N is removed from the crop N pool and used for fuel, which in turn releases N_2O into the atmosphere.

The plants contain a substantial amount of immobilized N in their tissues, which are either recycled or removed through harvest to supply N to consumers, such as animals (~5.81 Tg N) or people (~0.57 Tg N). India has the largest livestock population in the world and the livestock N pool estimated in live biomass is ~1.62 Tg N. The animals in turn may return a portion of the N to the system as manure, but birds or insects that feed on the crop also harvest some N and may return it to the system as excreta and corpse, which are difficult to estimate. Organic manure is one of the sources of N used in crop production and produced from crop, animal and human waste added ~0.17 Tg N into the soils.

A portion of the atmospheric N is fixed by lightning as NO, which can form NO_2 with the simultaneously produced ozone[12]. However, measurement of NO_x production by lightning flashes is difficult, as it must be concurrent with the thunderstorm. GOME (Global Ozone Monitoring Experiment) measures the lightning NO_x production, however, with random and systemic errors[13]. The wet N deposition (NO_3^- and NH_4^+) over the Indian agro-ecosystem is estimated to be ~0.81 Tg N. Nitrate N is soluble and mobile in soils, which is either used by the plants or is easily leached or removed by run-off (~0.06 Tg N) from the system. This agricultural run-off leads to nitrate pollution of river systems or water bodies. Approximately 25% of applied fertilizer is expected to end up in the sea and nearly 2236 t of nitrogen is discharged into Mahim Bay alone every year from various sources[14]. This may even lead to phytoplankton blooms in coastal areas and carbon and energy become concentrated at lower tropic levels, with potentially significant effects for ecosystem structure and function. These marine regions where phytoplankton blooms occur are located adjacent to rapidly developing agricultural areas in South Asia[15]. The concentration of NO_3, NO_2 and NH_4 in the surface waters of mangroves in the eastern coast of India near Chennai was found to be high (35.3, 23.0 and 157 μg of the chemical species l^{-1} respectively), which is associated with regions receiving agricultural wastewater from land-based sources[16]. Both nitrate and ammonium forms may be absorbed by microorganisms or converted to gaseous N forms (N_2, N_2O or NH_3) and lost to the atmosphere. Excessive irrigation in addition to increased intensity of N fertilizer use have resulted in nitrate (NO_3^-) pollution of groundwater and the survey showed that large areas in Uttar Pradesh (300–694 ppm), Punjab (362–567 ppm) and Haryana (300–1310 ppm) have been affected by NO_3^- pollution of groundwater[17]. The problem of high nitrates in groundwater is both extensive and intensive, posing serious health hazard. However, as irrigation is one of the essential components of the modern agricultural production system, groundwater is utilized to irrigate ~36.25 mha in India. As a result, N in the form of NO_3^- (0.11 Tg N) from groundwater is brought into the agricultural production system.

There is substantial dynamic movement of N in and out of India from neighbouring countries through wind and water flow, the estimates of which are not available. In addition, in 1995–96, trade involved 0.07 Tg N comprising foodgrains (0.02 Tg N) and animal products (0.05 Tg N) as imports and 0.11 Tg N comprising food grains (0.09 Tg N) and animal products (0.02 Tg N) as exports from India. N fertilizer import, which accounts for 2.00 Tg N (1995–96), is not included in this estimate, but added to the N fertilizer addition into the soil. The detailed estimation methodology, individual products and N equivalents are given by Bhatt[9].

The data presented above are based on a conceptual N model; however, there exists a wide variation in N pools and flux distribution. The N cycle in the agro-ecosystem is a unique case as land and water management practices are linked to the local socio-economic and biophysical environments.

Soil surface nitrogen balance

The soil surface nitrogen balance is calculated as the difference between the total quantity of nitrogen inputs entering the soil and the quantity of nitrogen outputs leaving the soil. Total inputs and outputs along with the soil-surface N balance for the entire agricultural land of India as a whole are given in Table 1 (refs 18–20). Nearly 14.6 Tg of nitrogen has been estimated as input from different sources, with output nitrogen of about 12.24–12.71 Tg. Soil-surface N balance estimated as input minus output is found to be about 1.89–2.32 Tg. Inorganic N fertilizer constituted the major percentage of total inputs, and fodder and feed the major percentage of total outputs. Prasad *et al.*[18] estimated the spatial patterns in nitrogen balance for different states of India; it varied from deficit to surplus. The highest nitrogen surplus was found in Uttar Pradesh (2.5 Tg) and negative nitrogen balance was found in Orissa (–0.01 Tg) and the North-eastern states. However, national-level N surplus estimate for unit agricultural area (54.1 kg N/ha) seems high, considering the N input use in rainfed agriculture and the uncertainty of the estimate. In the rice–wheat system, higher N balance (available N) was observed when N was applied at the rate of 180 kg ha^{-1} and the values were higher for organic + inorganic N supply system than organic alone. Available N balance for the inorganic system was found to be low, mainly due to N losses[21]. The uncertainties arising from the above estimates are attributed to the conversion factors used for different agricultural systems, soils, climatic conditions, crop types and management practices[22].

GHG emission

Concerns have been expressed over the potentially harmful environmental impacts associated with N atmospheric emissions of N_2O, NO_x and NH_3. The emission of N_2O results from nitrification/denitrification of anthropogenic nitrogen (e.g. fertilizer, manure) added to the agro-ecosystems[23,24]. N_2O emission from various agricultural activities in India is given in Table 2 (refs 25–29). Fertilizer use[26] contributed 0.012 Tg N, residue burning from 0.011 to 0.03 Tg N and combined agricultural activity 0.24 Tg N as N_2O emission[25]. Total N_2O emissions from India were in the order: 0.23 Gg in 1990 and 0.26 Gg in 1995 (Table 3), indicating marginal growth[27]. The sectoral shares indicate that of the total N_2O emissions, 63% is due to the use of N fertilizer and 12% from crop residue burning (Figure 2). However, the emissions are much dispersed and the values vary widely. National estimate of N_2O emission from manure use is lacking and most of the research focuses on point/experimental field-emission of N_2O. Further, reliable estimates of manure use in agriculture in various districts of the country are hardly available and the existing N_2O emission data at national level are estimated using Inter-governmental Panel on Climate Change (IPCC) emission coefficient. The uncertainty associated with such datasets is high, as single coefficient-based estimate is unreliable and hence, it is essential to develop appropriate emission coefficients through measurements covering different seasons and diverse cropping systems of the country.

At a global scale, the dominant sources of nitrogen oxides – combustion of fossil fuel (~50%) and biomass burning (~20%) are basically anthropogenic. Natural sources, including lightning and microbial activity in soils, represent less than 30% of the total emissions. But, fertilizer use in agriculture constitutes an anthropogenic perturbation to the microbial source[30]. NO_x emission from India in 1995 was estimated to be 3.46 Tg and grew at about 5.6% per annum between 1990 and 1995 (Table 4). The sectoral composition indicated that the transport sector is the predominant source of NO_x emissions in India, contributing 32% (Figure 3). Power generation (28%), industry (19%), biomass consumption (19%) and other industries (2%) follow. The regional distribution also indicated a close relationship with coal as well as oil-products consumption. Uttar Pradesh, Maharashtra, Madhya Pradesh, Andhra Pradesh and Tamil Nadu were the largest[29] five NO_x-emitting states in 1995. However, Streets *et al.*[31] have reported NO_x emission of 4.6 Tg from India in 2000, which is 17.2% of the Asian emission. The national[29,32] as

Table 1. Soil-surface nitrogen balance (Tg) for agricultural land of India (1995 production level)

N source	Tg N
Input	
Inorganic N fertilizer	10.8
Biological N fixation	1.14–1.18
Compost	0.17
Animal waste (manure)	1.53
Wet deposition	0.81
Groundwater	0.11
Total	14.56–14.6
Outputs	
Harvested crop	4.13
Fodder	5.81
Fuel	1.9
Erosion loss	0.06
GHG emission	0.34–0.81
Total	12.24–12.71
Balance	2.32–1.89

Sources: Bhatt[9], Prasad *et al.*[18], IFFCO[19] and FAI[20].

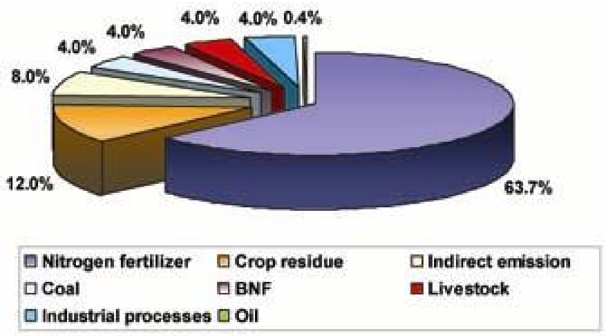

Figure 2. Sectoral distribution of N_2O emission in 1995.

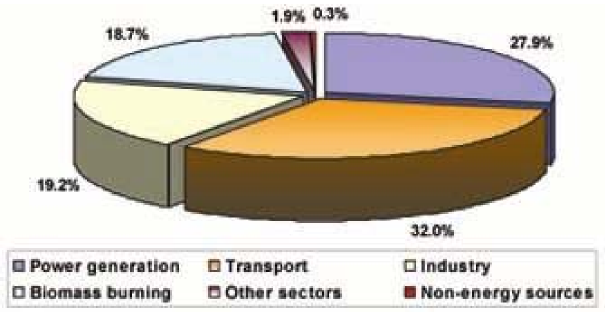

Figure 3. Sectoral share of NO_x emission in 1995.

Table 2. Estimate of N containing GHG from agro-ecosystem of India

N form	Source	Amount Tg N	Estimation year	Reference
N_2O	All agricultural activities	0.24	1990	25
	Fertilizer use	0.012	1989–90	26, 27
		0.16	1995	
	Burning of residues	0.011	1990	27, 28
		0.03	1995	
	Biological N fixation	0.01	1995	27
	Livestock	0.01	1995	27
NO_x ($NO + NO_2$)	Biomass burning	0.1	1990	25, 29
		0.6	1995	

Table 3. Sectoral emission of N_2O (Tg)

Sector	1990	1995
Coal	0.01	0.01
Oil	0.001	0.001
Crop residue	0.02	0.03
BNF	0.01	0.01
Nitrogen fertilizer	0.14	0.16
Livestock	0.01	0.01
Industrial processes	0.01	0.01
Indirect emission	0.02	0.02
Total	0.23	0.26

Source: Garg *et al.*[27].

Table 4. Sectoral emission of NO_x in 1995

Sectors	NO_x (Tg)	Percentage share
Power generation	0.965	27.9
Transport	1.107	32
Industry	0.664	19.2
Biomass burning	0.647	18.7
Other sectors	0.066	1.9
Non-energy sources	0.010	0.3
All-India emissions	3.46	100.000

Source: Garg *et al.*[27].

well as other global estimates of GHG[28,31] have either ignored or are lacking in reliable NO_x emission values from the soil, even though tropical soils have been identified as significant NO_x sources.

NH_3 volatilization values from applied fertilizers and manure may change across various agro-ecosystems, as ammonia lost to the atmosphere from the soil through volatilization is affected by the rate of N application, modified forms of urea, source of N and moisture content of the soil[33]. Cotton crop fertilized with urea has recorded nitrogen loss of 25% as NH_3 and 4.9% as nitrate[34]. Total NH_3 emission in 2000 was reported to be 7.4 Tg, which is 27% of the Asian emission[31]. Volatilization of applied nitrogen as ammonia (NH_3) and oxides of nitrogen (NO_x) is followed by deposition as ammonium (NH_4) and oxides of nitrogen (NO_y) on soils and water, and account for indirect NO_2 emissions from soils[35].

Human modification of the regional N cycle

With 60% of the world's population living in Asia (16.4% in India), human activities are having profound impact on the regional N cycle. Anthropogenic activities introduce three-fold more Nr into Asia than does natural BNF. Agriculture consumes major portions of Nr and also contributes to Nr emission. In India, human perturbation to the N cycle is assessed by considering the effect of the green revolution, present N use situation and future N emission, and the details are presented below.

Effect of the green revolution

The 'green revolution' that started in the mid 1960s led to a tremendous increase in the foodgrain production from 50 to 212 mt, and productivity from 522 to 1707 kg/ha during 1950–51 to 2003–04. At the same time, India has been experiencing high population pressure on the natural resources base of land, water and biodiversity mainly to meet the food and developmental needs. These human activities have disrupted the N cycle to a large degree (Table 5)[36]. Through N fertilizer and BNF nearly 11.4 Tg of Nr was additionally added in 1995–96, compared to the 1950–51 level of Nr use.

Bulk of the nitrogen in soils is present in the organic form as part of the soil organic matter. Reported values[37] of total N in Indian soils (0–15 cm layer) other than the hilly regions, vary from 0.02 to 0.1%. In India gross cropped area and net sown area have increased by bringing new areas under cultivation and intensification of agriculture. This has enhanced the mineralization of organic matter and increased the mineral N, causing more N losses into the surrounding and GHG emission into the atmosphere. As a result, organic N content as a percentage of total N had decreased in 1995–96 compared to the 1950–51 level. The excessive N fertilizer use, increased irrigation facilities and intensification of agriculture have led to more Nr losses, especially leaching losses of NO_3^- and increased the nitrate content in groundwater (Table 6)[38]. Further, nitrogen-rich agricultural run-off into the coastal areas fuels large phytoplankton blooms and eutrophication of water bodies. Beman *et al.*[15] have demonstrated that in 80% of

Table 5. Effect of green revolution and industrialization on Nr creation and GHG emission (Tg N) from India

N pool	1950–51 level	1995–96 level	Magnitude of Nr added/difference
N fertilizer	0.06	10.8	10.74
BNF	0.55	1.14–1.18	0.59–0.63
Crop production	2.94	12.47	9.53
Livestock	0.97	1.62	0.65
Land-use change (mha)[@]			
Net sown area	118	141	23
Gross cropped area	132	188	56
Organic N (as % of total N)*	65–95	55–94	–
GHG production			
N_2O	–	0.26	–
NO_x	–	3.46	–
NH_3	–	7.4	–

*Values are in the range across various regions of India (Srivastava and Singh[36]).
[@]This accelerates N mineralization and increased N fertilizer use.

Table 6. Nitrate-N (mg/l) in water samples from shallow wells (4–10 m deep) in Ludhiana District, Punjab

	1975		1982		1988
Parameter	June	September	June	September	November/December
No. of samples	46	33	26	26	28
Range of nitrate-N	0.04–6.15	0.05–7.90	0.35–10.11	0.23–15.15	0.31–13.30
Geometric mean	0.42	0.42	1.48	2.13	2.29
Correlation coefficient (r) for fertilizer N applied vs NO_3^- N in well water	NS	0.51*	NS	0.51*	0.59*

*Significant at 5% level of significance; Source: Singh and Singh[38].

the cases in the tropical waters blooms are stimulated within days of fertilization and irrigation of agricultural fields. However, detailed studies on the effect of Nr in the coastal regions of India are lacking.

In spite of the profound impact of the green-revolution technologies on Indian agriculture, it is essential to achieve synchrony between N supply and crop demand without excess or deficiency, which is the key to optimizing tradeoffs amongst yield, profit and environmental protection.

Present concerns of Nr production and GHG emission

There are large regional differences in population and per-capita resource use and hence different areas of the country vary in their impact on the nitrogen cycle, and thus on the consequences of the disruption of the nitrogen cycle. It is estimated[39] that by the year 2020 India will need about 300 mt of foodgrains, which can be achieved only if the present consumption of 11 mt of fertilizer nitrogen is increased to 22–25 mt. Nitrogen will thus continue to play an important role in India's efforts for food sufficiency, which further complicates the situation, causing serious concern about the N cycle and its proper management efforts.

In general, Indian soils are low in total N content as well as nitrogen use efficiency (NUE) of major crops. Rice occupies 42–45 mha out of the total cultivated area of 142 ± 1 mha, and consumes about 40% of fertilizer N used in the country. But the NUE is hardly 30–40% (Table 7). NUE by crops, specially rice and other cereals grown during the monsoon season which cover about 70% of the total cultivated area in the country, is only about 20–30%, for wheat it is up to 45–50%. Further, it is to be noted that the adoption of integrated nutrient management (INM) practices varies across various regions as agriculture is practised in various agro-ecosystems. As a consequence, Nr enters into various components of the ecosystem causing an 'N cascade effect', which is defined as the sequential transfer of Nr through the environmental system, that results in environmental changes as Nr moves through or is temporarily stored within each system[1]. The total loss from about 10 mha under rice–wheat cropping system alone is likely to be 0.2 Tg/yr.

Based on the soil and environmental conditions, about one-third of the applied fertilizer N is lost to the atmosphere as ammonia due to ammonia volatilization, or nitrous oxide due to denitrification, or to the underground waters as nitrates due to leaching. Pathak *et al.*[42] predicted on an average ammonia volatilization loss of 12–15%, denitrification loss of 25–30% and leaching loss of 15–

Table 7. Nitrogen use efficiency[#] or recovery of fertility N by crops in India

Crop	Source of N	N rate (kg/ha)	Recovery (apparent or true) (%)
Rice	Sodium nitrate	120	7.5
	Ammonium nitrate	120	13.3
	Ammonium sulphate	120	29.2
	Urea	120	26.7
	Urea	120	26.0*
Maize	Urea	100–120	32.0–18.4
		120	20.1*
Sorghum	Urea	50–100	32.0–25.0
Pearl millet	Urea	40–200	31.5–19.4
Wheat	Urea	50–150	34.8–48.4*

Source: Arora *et al.*[40]; Goswami *et al.*[41]; *^{15}N studies.

Table 8. Simulated and observed average losses of applied N from rice fields

Loss (kg N ha^{-1})	Observed[a]	Simulated[b]
Ammonia volatilization	15	12
Denitrification	30	33
Leaching	15	16

Source: Pathak *et al.*[42]; [a]Mean for 120 kg N ha^{-1}; [b]Simulated mean N loss using CERES-rice model.

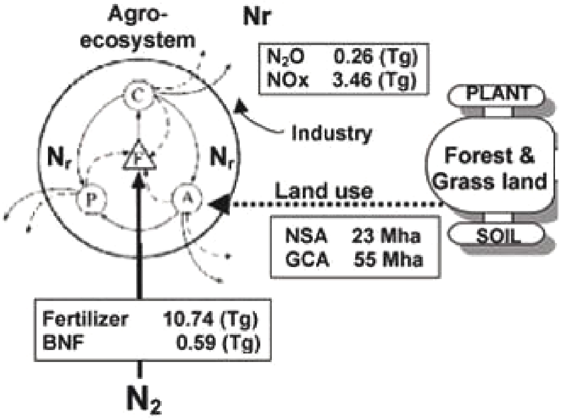

Figure 4. Schematic view of N cycling (magnitude of Nr introduced and GHG produced in 1995 compared to the 1950 level). F, C, A and P refer to N (N pool) in fields, crops, animals and people respectively. The bold, solid arrow represents entry of N_2 as Nr into agro-ecosystems. Solid lines with arrows reflect N transfers between the pools. Dotted lines with arrows from C, A and P to F reflect N-containing waste transferred from N pools back to fields. Dotted lines with arrows from N pools to outside the circle reflect N-containing waste that is lost from the agro-ecosystem. Solid lines with arrows from F, C, A and P reflect atmospheric and hydrologic losses from fields, crops, animal and human waste respectively, within the agro-ecosystem to the outside. Further, Nr is created by land-use change and industrial activity (modified from Galloway[45]).

16% of applied N from rice fields (Table 8), with an application of 120 kg N ha^{-1} as urea from rice fields in northwest India.

India is a fast expanding economy and the third largest consumer of fossil fuels in Asia[43]. As a result, nitrogen oxides (NO_x) are released during combustion of fossil fuel and biomass, and during the production of certain chemicals and products. The Nr that begins in the energy sector cascades through the atmosphere, hydrosphere and soils, before being eventually partially denitrified as nitrous oxide or molecular nitrogen[44].

Depending on its chemical form and source (fertilizer N, biologically fixed N, land-use change-induced N use and accelerated N mineralization and industrial N containing GHG emissions), Nr will enter the ‘N cascade’ at different places (Figure 4)[45]. An important characteristic is that once it starts, the source of Nr becomes irrelevant. Nr species can be rapidly inter-converted from one Nr form to another. Thus, the critical stage in Nr management is in the formation or introduction of Nr by human activity.

The major features of the N cycle and budget have been noted, but there are regional differences within the country in the relative importance of specific effects, depending on the degree of alteration on the regional nitrogen cycle and the geographical location of the region, among other considerations.

Future emission

The reference scenario for future emission projections captures continuation of present Government policies, and forecasts of various macro-economic, demographic and energy-sector indicators. Based on the past 30-yr trends and Government projections, the Indian GDP is assumed to grow by about sixfold during 2000–2035, at an annual average of 5.2%. At the same time the population is expected to reach 1.44 billion in 2035, indicating a fourfold increase in per capita income during that period[46]. On the fuel side, power plants using low-ash imported coal and mandatory washing of coal and use of compressed natural gas for public transport, emission limiting performance standards for passenger vehicles, and stricter enforcement of existing environmental laws would bring down the related emissions[47].

The integrated energy environment analysis projects carbon and local pollutant emission trajectories up to

Table 9. Emission inventory projections for India

Emission (Tg)	1995	2000	2010	2020	2035	CAGR*
Carbon	212	253	411	572	738	3.14
N_2O	0.25	0.25	0.41	0.61	0.84	3.48
NO_x	4.66	5.57	6.08	7.64	8.66	1.87

*Percentage compounded annual growth rate over 1995–2035 (%). Source: Garg *et al.*[48].

2035 (Table 9)[48]. Nitrous-oxide emissions depend more on the agriculture sector and therefore are not direct model outputs. Their emission projections depend on growth of rice paddy cultivation, livestock population, biomass consumption, waste decomposition (solid and water) and use of nitrogen fertilizer. N_2O trajectories have a close correlation with nitrogen fertilizer use and are much more regionally dispersed.

The growth of NO_x emissions from the transport sector slows down as cleaner and efficient technology stocks take over. NO_x control in the power sector is a difficult proposition, as it requires extremely fine temperature control of coal combustion process and also post-combustion NO_x control is quite expensive[49].

Moreover, the multiple and dispersed nature of the transport sector sources makes implementing mitigation measures much more difficult than those for the large point sources in the industry and power sectors.

Mitigation of Nr production in agriculture and related activities will largely depend on crop response to N and NUE, which is low in India. Use of nitrification inhibitors and slow-release nitrogen fertilizers, and efficient crop and fertilizer management can significantly increase NUE. If NUE is increased by 10% and the consumption of N is taken at 20 mt in 2020, the N saving will be equal to the annual production of five moderate-size urea plants involving a capital investment of 25,000 crore rupees at the current prices.

Approaches for quantifying terrestrial N cycle

The understanding of the N pools and fluxes by synthesizing results from various studies has improved significantly since the synthesis by Hutchinson[50–52] and the current understanding is summarized by Galloway *et al.*[1]. The various approaches followed for quantifying N pools and fluxes at local, national and global level are briefly described below.

Site-specific pool and flux measurements

Measurements of Nr concentration in the atmosphere, wet and dry deposition, streams and wetlands, including isotopic techniques[53], nitrogen in soils and measurement of flux/emission of N_2O and NO_x from various land-cover types using chambers constitute the basic dataset on which most of the N cycle synthesis is based.

Mass balance approach

In this approach, conservation of mass, major pathway of N flow and representative measurement of N are used. Bhatt[9] has estimated terrestrial N cycle in India using mass balance approach. However, approach when used alone, this is inadequate for balancing all input and output fluxes or for global long-term change studies.

Emission centric approach (IPCC guidelines)

This approach is suited for depicting human influence on GHG emissions, major human activities and their activity-wise Nr emission coefficients, which are used to estimate fluxes from land to air and sometimes balanced with dry/wet deposition when done globally. NATCOM[35] estimated sectoral GHG emission following IPCC guidelines. Such an inventory has the benefit of simplicity, but reveals no variation with crop or soil, and implies that only a decrease in N use decreases N losses[54].

Models (empirical, process-based)

A large number of models have been used to quantify and understand various components of the terrestrial N cycle. These include models specifically dealing with N or crop/vegetation/land-use/hydrology models that have been supplemented with specific sub-models dealing with N transformations. These can be applied to point as well as spatial datasets.

Combined approach

The combined approach uses two or more of the above-mentioned approaches to assess Nr in various N pools. Remote sensing data-based retrieval models use data collected from ground to validate and estimate various sources of atmospheric N.

Role of remote sensing and GIS

Use of inputs derived from space-borne remote sensing (RS) data and capabilities of GIS would be essential to understand, monitor, model and generate a scenario for the future and suggest policy action based on the nitrogen cycle and its anthropogenic perturbation. The potential and demonstrated case studies to derive N from various N components are briefly mentioned here.

Use of RS data and RS-derived inputs

Atmospheric constituents: Direct measurement of NO_x ($NO + NO_2$) and N_2O containing constituents from space-borne sensors has become possible with sensors such as GOME (on-board ERS-2), SCIAMACHY (Scanning Imaging Absorption Spectrometer for Atmospheric Chartography) on-board ENVISAT[55] and ILAS (Improved Limb Atmospheric Spectrometer) on-board Advanced Earth Observing Satellite[56,57]. The space-borne sensor measures globally, the vertical column distribution of NO_2 and its seasonality is highly correlated with emissions from major cities, power plants, biomass-burning areas and major ship tracks (Figure 5).

Atmospheric processes and interacting constituents: RS data also provide direct measurement of global distribution of atmospheric constituents that interact with N constituents such as ozone, and processes that lead to production/transformation of N constituents such as lightening[58].

Vegetation and leaf constituents: Nitrogen being a key element of the vegetation, can be indirectly inferred from RS-derived inputs on vegetation type, their vigour or canopy characteristics, biomass and leaf area index (LAI). In addition to spatial distribution, RS inputs alone can provide the seasonality of vegetation. Boegh *et al.*[59] retrieved canopy N concentration from remote sensing data after correlating with canopy N estimated from field experiments. Recent advances in sensors, especially hyperspectral sensor such as Hyperion of NASA's EO-1 system, can help in estimating lead N/chlorophyll content of leaf/vegetation.

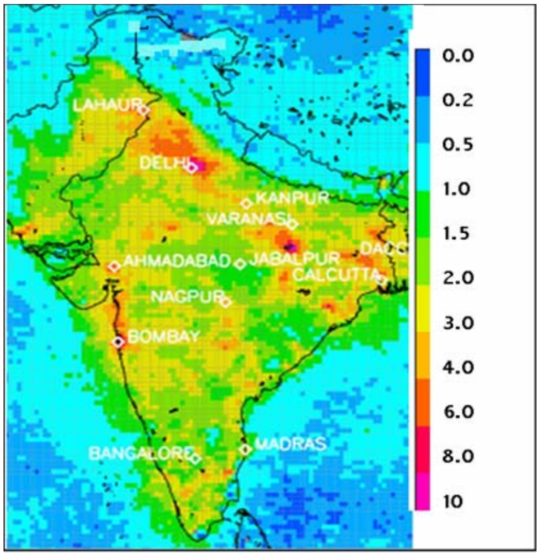

Figure 5. Mean tropospheric NO_2 column density over India (10^{15} molec/cm^2) in 2003. Source: SCIAMACHY/European Space Agency.

Hydrosphere: RS data are useful in modelling hydrologic cycle components such as rainfall, run-off, evapotranspiration (ET) and snow extent, which are needed to study the N cycle. In addition, direct measurement on wetlands and their characteristics, including vegetation, turbidity and eutrophication is possible with RS data. Coles *et. al.*[60] demonstrated the use of RS data to detect global patterns of N_2 fixation from their influence on phytoplankton biomass over the tropical North Atlantic Ocean.

Land use/land-cover change: RS data accurately help in mapping and monitoring land-use and land-cover change, which has a strong influence on N cycling. Reiners *et al.*[61] estimated N_2O and NO emission from a wet tropical region undergoing rapid agricultural development. In India, during the period from 1950–51 to 2000–01, the net sown area increased by 23 mha and 18% increase in cropping intensity, resulting in an increased gross cropped area by 55.58 mha. These intensive and extensive land-use changes have released the N stored in soil organic matter by accelerating the mineralization process, leading to loss of organic matter.

Indirect inference due to C–N coupling: On land, due to close coupling of vegetation C and N cycles and use of RS data for C-cycle vegetation components can thus indirectly help to study the N cycle and parameters in addition to net primary production, litter fall, biomass, and change in biomass/C stock.

Combining RS and collateral information with GIS

The terrestrial N cycle has strong spatial variability, which is related to spatial heterogeneity of human factors as well as natural factors such as climate, physiography, soil, land use and vegetation. Thus, a geographically referenced analysis is needed to study the N cycle and monitor human controls as well as integrate statistical information for administrative regions. GIS helps to estimate vegetation and soil N pool, N addition through fertilizer and manure (Figure 6), hydrological N pool, human and livestock N pool and sectoral N emissions with temporal and spatial extent.

An important consideration for all large-scale biogeochemical models is the scale at which model compartments have to be aggregated[62]. In this presentation we have chosen a level of aggregation for the regional N cycle model that sufficiently provides insight into interactions among most major N pools and fluxes in India.

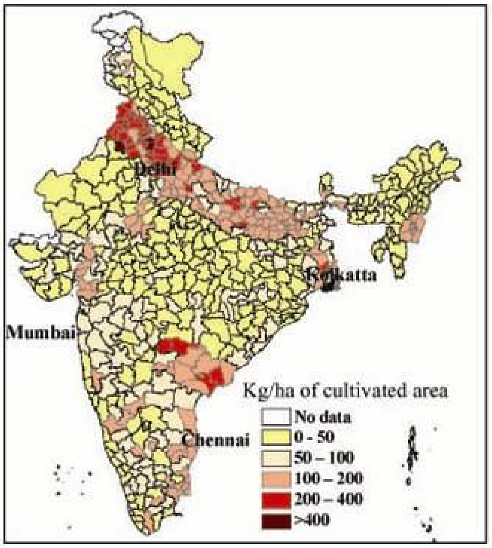

Figure 6. Nitrogen fertilizer used (2003–04) in India. Source: Fertilizer Association of India.

Gaps in measurements and understanding

Considering the possibility of using RS data and different models linked to remote sensing and GIS to estimate various N pools and research efforts to estimate various N pools and fluxes and their inter-links, there seems to be a wide gap between India and recent international studies.

In spite of years of research to estimate the exact amounts of Nr created by human activities and its movement, a poor understanding remains, which is problematic due to the cascading effects of N in the environment, including enhanced rates of atmospheric reactions, fertilization of terrestrial and aquatic ecosystems, loss of ecosystem biodiversity, and increased emission of GHG. The need for necessary efforts to reduce the amount of reactive nitrogen created by human action is also now well understood. The present challenge is to minimize reactive N creation while also maximizing food and energy production[1]. There are still major uncertainties regarding the fate of fertilizer N added to agricultural soils and the potential for reducing emissions to the environment.

The primary reason for loss of N from the soil–plant system and subsequent low N recovery is a lack of synchrony between N demand by the crop and N release from the applied plant residues[63]. Use of the Manure Evaluation Routine (MANNER) model to estimate the amount of N available to crops following livestock manure application after calculating losses due to NH_3 volatilization and NO_3^- leaching, could significantly improve the N use[64]. With proper understanding of this process, the gap between total N added and N loss into the environment can be narrowed down.

In India, the rate of accumulation of Nr (reactive N) in various N reservoirs is not properly understood in its spatial dimension. High degrees of uncertainty are associated with N_2O emission estimates, as most of the activity data, especially in the agricultural sector are dispersed organic sources that have not been well quantified. This is essential before formulating any policy options, as the diversity of Indian agriculture is large to ignore and to develop site-specific N management practices for different crops.

The long-term N emissions could range between half to four times the current levels, indicating large uncertainties in underlying driving forces such as population and economic growth, future developments in agricultural, energy and transport sectors as well as in technology. More research is therefore needed before considering policy interventions to control these gases beyond well-established source categories[65].

Application of RS and GIS techniques to study the N cycle and flux over India has immense potential. However, due to creation of various inputs in different formats and standards, lack of metadata and exchange mechanism is hampering such use.

Research priorities

Reducing uncertainty in estimates of N pools and fluxes

Assessment of various N pools, N-cycling and N mass balance studies on all geographical- and timescales are characterized by high variability and uncertainty[66–68]. The data sources, models/methods adopted, changes in cropping pattern, biomass burning, environmental and climatic factors introduce variability in the measurements at different levels. Since N_2O emission from soils is a key source of N containing GHG emission from India, it is necessary to develop appropriate emission coefficients through measurements covering different seasons in the diverse cropping systems of the country. Hence, it is essential to properly understand the various N fluxes and their considerable variations and inputs and losses have to be presented as ranges rather than as single values.

Food and energy production

In India, the ever-growing need for food and energy to meet the needs of the burgeoning population and to sustain the economic growth, is likely to continue to increase the creation of Nr. Mitigation opportunities for N emissions from agro-ecosystems lie primarily in increasing the efficiency of N fertilizer use and utilization, increased use of organic-farming practices along with decreasing rate of inorganic N addition and appropriate policy thrust. Creating databases on plant residues, their composition and N release patterns on the one side and daily/weekly crop N requirements on the other, will greatly enhance the N management strategies that maximize production and minimize N losses in agro-ecosystems. The organic waste/manure resources need to be updated with respect to quantity, quality and use pattern apart from efficient collection and use of animal waste. RS and GIS inputs can be integrated into the precision-farming technologies suitably modified for the Indian agro-ecosystem to enhance NUE.

Identification of hotspot areas

Blanket application of N fertilizers and manure in a country like India with wide variations in climate, soil, crops, cultivars and management practices, will lead to excess or deficient N application which in turn affects the NUE, and adds more Nr to the environment. Identification of excessive N use/high N balance regions is essential because of the effects of excess N on humans, ecosystems, atmosphere, and their cascading nature[5]. This emphasizes the need for spatial and temporal adjustment of N fertilizer amounts to account for the large difference in the indigenous N supply, also known as Variable Rate Technology, a part of precision farming which has ample scope in India. Focus should also be on denitrification and associated N_2O emissions in terrestrial and aquatic systems with reference to irrigated crops and rice areas in India, and the transport of N from terrestrial to aquatic systems as a result of leaching and run-off.

The human health-related effects of environmental N have attracted much attention. Air pollutants (primarily nitrogen oxides) and dietary nitrate have been issues of concern[24]. Linkage of human activity, health, economic factors and livestock population in GIS is a challenging task, but would be needed for study of hotspots. Urban areas should also remain in focus for these studies.

Spatial and temporal variability of emissions

Human impacts on the N cycle strongly depend upon the rates at which fixed N is denitrified to N_2 in land and aquatic systems. Unfortunately, a quantitative understanding of denitrification rates in various managed and unmanaged terrestrial and aquatic environments is largely missing. This is probably the biggest obstacle thwarting accurate modelling of the N cycle. In addition, in India, climatic conditions (air and soil temperature, precipitation, wind and RH) vary with seasons and strongly influence ammonia volatilization. Hence, accurate estimates can be obtained by means of model simulations in conjunction with observations at large scales and linking of point measurements to spatial datasets (e.g. utilizing sensors on aircraft or spacecraft).

Digital soil datasets

The soil ‘background’ emissions[69] with relatively low rates but from a vast area could have a non-negligible contribution to the global N budget. This emphasizes the need to create national digital soil information at higher resolution, which can be linked to emission models to predict background as well as treatment emission values. More experiments have to be conducted to obtain N_2O data in terrestrial and aquatic systems, particularly long-term measurements to reduce the uncertainty in N_2O estimates.

Atmospheric deposition

Clean Air Status and Trends Network (CASTNet) of the US EPA uses the inferential method[70] to estimate dry deposition. The annual average precision statistics was also calculated for duplicate meteorological and concentration measurements collected at five CASTNet sites. This emphasizes the need to develop a network of dry deposition measurement stations across India, to validate any dry deposition model and the precision of estimates. Further, models should be developed and validated to study changes in the wet and dry deposition fluxes and velocities related to seasonal changes in surface cover, i.e. snow cover, vegetation and micro-meteorology.

Focus on the combined cycles

The carbon and nitrogen cycles are linked through the stoichiometric relationships between C and N. Hence, diagnostic and predictive models must consider the coupled process[71]. The biogeochemical cycle research should also focus on evaluating the potential impacts of human land-use changes on natural ecosystem from the standpoint of these two material balance cycles, especially from the N cycle over India.

RS linked to process-based models

Process-based models need to be considered as alternatives to emission factors. The process-oriented models of soil NH_3 emission[72–74] have incorporated impacts of environmental factors on NH_3 production/deposition, and hence could serve as a basis for improving NH_3 inventory studies. A promising approach to assess the impact of anticipated future climate, and land-use and land-cover conditions on soil-biogenic NO_x emissions is the use of process-based soil N emission models like the CASA model[75], CENTURY/DAYCENT[76] and DNDC[77]. Moreover, the process models can be used to identify the key parameters that are mainly responsible for changes in the soil-biogenic NO_x emissions.

Regional climatic models with inputs from satellite-derived weather parameters along with ground observations in the GIS database which are linked to the nitrogen cycle at the regional scale, can be used to estimate the effect of microclimate change on various N pools and to predict the changes in the future. Estimation involves intensive measurements, GIS databases with characterization of animal waste and other major NH_3 emission sources, and development and application of process-based models. GAIM, a component of the International Geosphere Biosphere Program (IGBP) of the International Council of Scientific Unions (ICSU), is an initiative in this regard. Improved understanding of N cycle using models will promote our ability to manage Nr in the biosphere and to avoid harmful effects of excess reactive nitrogen on water quality, air quality and human health[1].

Creation of a strong research database of N use, hot-spot areas of N pollution along with socio-economic conditions of farmers in various agro-ecosystems of India is essential to support the fertilizer pricing policy of the Government. This will go a long way in stabilizing the N fertilizer use in Indian agriculture.

Conclusion

The N cycle, considering natural to anthropogenic fluxes, is currently under the influence of anthropogenic control. In India, there is paucity of atmospheric Nr measurements and on long-term emission/changes in N pools and fluxes. Using RS and GIS, it is possible to spatially describe dominant controlling factors for the N cycle, such as land use, vegetation type, wet lands, seasonality of vegetation, soil, etc. To the proposed GIS linking of attributes, including admin boundary-based human activity data is an urgent priority.

N-pool and flux studies should adopt a comprehensive and consistent treatment of the reservoirs and cycling of terrestrial N, so as to improve the treatment of N cycling in mathematical models and mass-balance studies. This will facilitate better scientific explanation of historical N-related environmental changes and more closely balance N budgets on a range of geographical and temporal scales, as the N balance surplus is an important indicator for the evaluation of the sustainability of Indian agriculture. RS and GIS-based estimation of various N pools in India, therefore provides a policy linkage with national as well as global priorities, such as environmental management and increasing production along with efficient use of N.

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1. Galloway, J. N., The global nitrogen cycle – Past, present and future. Abstracts of the Plenary Sessions of the Nanjing Declaration, 2004.
2. Ayers, R. U., Schlesinger, W. H. and Socolow, R. H., Human impacts on the carbon and nitrogen cycles. In *Industrial Ecology and Global Change* (eds Socolow, R. H. *et al.*), Cambridge University Press, Cambridge, 1994, pp. 121–155.
3. Galloway, J. N. and Cowling, E. B., Reactive nitrogen and the world. 200 years of change. *Ambio*, 2002, **31**, 64–71.
4. UNEP, *GeoYear Book 2003*, United Nations Environment Programme, 2004.
5. Galloway, J. N., The global nitrogen cycle: Changes and consequences. *Environ. Pollut.*, 1998, **102**, 15–24.
6. Robertson, G. P., Regional nitrogen budgets: Approaches and problems. *Plant Soil*, 1982, **67**, 73–80.
7. Keeney, D. R., A mass balance of nitrogen in Wisconsin. *Arts Lett.*, 1979, **67**, 95–102.
8. Hauck, R. D. and Tanji, K. K., Nitrogen transfers and mass balances. In *Nitrogen in Agricultural Soils* (ed. Stevenson, F. J.), American Society of Agronomy, Madison, Wisconsin, USA, 1982, pp. 891–925.
9. Bhatt, A study on terrestrial nitrogen cycle in India. Ph D thesis, North Gujarat University, Patan, 2002.
10. FAI, Fertilizer statistics 2000–01, Fertilizer Association of India, New Delhi, 2000.
11. DES, Agricultural statistics at a glance. Directorate of Economics and Statistics, Ministry of Agriculture, Govt of India, New Delhi, 1999.
12. Tuck, A. F., Production of nitrogen oxides by lightning discharges, *Q. J. R. Meteorol. Soc.*, 1976, **102**, 749–755.
13. Boersma, K. F., Eskes, H. J., Meijer, E. W. and Kelder, H. M., Estimates of lightning NO_x production from GOME satellite observations. *Atmos. Chem. Phys.*, 2005, **5**, 2311–2331.
14. Sen Gupta, R., Naik, S. and Varadachari, V. V. R., Environmental pollution in coastal areas of India. In *Eco-toxicology and Climate* (eds Bourdeau, P. *et al.*), SCOPE, John Wiley, USA, 1989.
15. Beman, J. M., Arrigo, K. R. and Matson, P. A., Agricultural runoff fuels large phytoplankton blooms in vulnerable areas of the ocean. *Nature*, 2005, **434**, 211–214.
16. Ramesh, Nitrogen cycling and fluxes in coastal ecosystems. Institute for Ocean Management, Anna University, Chennai, 2006 (pers. commun.).
17. Agriculture and Environment, Block 1. Environment: Agriculture Relationships, Indira Gandhi National Open University, School of Sciences, New Delhi, 2004, pp. 47–50.
18. Prasad, K. V., Badarinath, K. V. S., Yonemura, S. and Tsuruta, H., Regional inventory of soil surface nitrogen balances in Indian agriculture. *J. Environ. Manage.*, 2004, **73**, 209–218.
19. IFFCO, Agricultural statistics at a glance. Indian Farmers Fertilizer Cooperative Limited, New Delhi, 2004.
20. FAI, Fertilizer statistics 2003–04. Fertilizer Association of India, New Delhi, 2004.
21. Velmurugan, A., Assessment of soil quality parameters for sustainable production in rice–wheat cropping system. Ph D thesis. IARI, New Delhi, 2000.
22. Silgram, M. and Chambers, B. J., Effects of long-term straw management and fertilizer nitrogen additions on soil nitrogen supply and crop yields at two sites in eastern England. *J. Agric. Sci.*, 2002, **139**, 115–127.
23. Smil, V., Nitrogen in crop production: An account of global flows. *Global Biogeochem. Cycles*, 1999, **13**, 647–662.
24. Mosier, A. R., Syers, K. J. and Freney, J. R., Nitrogen fertilizer: An essential component of increased food, feed and fibre production. In *Agriculture and Nitrogen Cycle* (eds Mosier, A. R., Syers, J. K. and Freney, J. R.), Scope, 65, Island Press, Washington DC, USA, 2004.
25. ALGAS, Asia Least-cost Greenhouse gas Abatement Strategy. Asian Development Bank, Global Environment Facility, United Nations Environment Programme, Asian Development Bank, Manila, Philippines, 1999, p. 260.
26. Tata Energy Research Institute, TERI Energy Data Directory and Year book, TERI, New Delhi, 1993, p. 250.

27. Garg, A., Bhattarcharya, S., Shukla, P. R. and Dadhwal, V. K., Regional and sectoral assessment of greenhouse gas emission in India. *Atmos. Environ.*, 2001, **35**, 2679–2695.
28. ADB, ALGAS-India (Asia Least-cost Green house Gas Abatement Strategy), Asian Development Bank, Manila, 1998; http://www.teriin.org/climate/ghg.htm# ADB94
29. Garg, A., Shukla, P. R., Bhattarcharya, S. and Dadhwal, V. K., Sub-region (district) and sector level SO_2 and NO_x emissions for India: Assessment of inventories and mitigation flexibility. *Atmos. Environ*., 2001, **35**, 703–713.
30. Delmas, R., Serça1, D. and Jambert, C., Global inventory of NO_x sources. *Nutr. Cycl. Agroecosyst.*, 1997, **48**, 51–60.
31. Streets, D. G. *et al.*, An inventory of gaseous and primary aerosol emissions in Asia in the year 2000. *J. Geophys. Res.*, TRACE-P Spl Issue, 2003.
32. Sharma, S., Bhattacharya, S. and Garg, A., Greenhouse gas emissions from India: A perspective. *Curr. Sci.*, 2006, **90**, 326–333.
33. Sharma, S. K., Kumar, V. and Singh, M., Effect of different factors on ammonia volatilization losses in soils. *J. Indian Soc. Soil Sci*., 1992, **40**, 251–256.
34. Shinde, J. S., Varade, S. B., Ramakrishna Rao, G. and Bharambe, P. R., Evaluation of percolation and leaching loss of nitrogen applied through urea in a *vertisol*. *Indian J. Agric. Sci*., 1982, **52**, 319–323.
35. NATCOM, India's initial national communication to the United Nations Framework Convention on Climate Change (UNFCCC), Ministry of Environment and Forests, Govt of India, New Delhi, 2004.
36. Srivastava, P. C. and Singh, T. A., Nitrogen in soil and transformation of fertilizer N. In *Nitrogen Research and Crop Production* (ed. Tandon, H. L. S.), FDCO, New Delhi, 1966, pp. 104–115.
37. Krishnamoorthy, P. and Govindarajan, S. V., Genesis and classification of associated red and black soils under Rajolibunda irrigation scheme. *J. Indian Soc. Soil Sci*., 1977, **20**, 27.
38. Singh, B. and Singh, Y., Balanced fertilization for environmental quality – Punjab experience. *Fert. News*, 2004, **49**, 107–113.
39. Kumar, P., Food demand and supply projection for India, agricultural economics paper 98-01. Indian Agricultural Research Institute, New Delhi, 1998, p. 141.
40. Arora, R. P., Sachdev, M. S., Sud, Y. K. and Subbiah, B. V., Fate of fertilizer nitrogen in a multiple cropping system. In *Soil Nitrogen as Fertilizer or Pollutant*, International Atomic Energy Commission, Vienna, 1980, p. 3.
41. Goswami, N. N., Prasad, R., Sarkar, M. C. and Singh, S., Studies on the effect of green manuring in nitrogen economy in a rice–wheat rotation using a ^{15}N technique. *J. Agric. Sci.*, 1988, **111**, 413–417.
42. Pathak, H., Singh, U. K., Patra, A. K. and Kalra, N., Fertilizer use efficiency to improve environmental quality. *Fert. News*, 2004, **49**, 95–105.
43. Report, World Bank, 2005.
44. Moomaw, W. R., Energy, industry and nitrogen: Strategies for decreasing reactive nitrogen emissions. *Ambio*, 2002, **31**, 184–189.
45. Galloway, J. N., Nitrogen mobilization in Asia. *Nutr. Cycl. Agroecosyst*., 2000, **57**, 1–12.
46. World Bank, World Population Projections 1992–93 edition: Estimates and projections with related demographic statistics (eds Edward Bos, My T. Vu, Ann Levin and Rodolfo A. Bulatao), World Bank, Washington DC, 1995.
47. Mashelkar, R. A. *et al.*, Report of the expert committee on auto fuel policy, Ministry of Petroleum and Natural Gas, Government of India, New Delhi, 2002.
48. Garg, A., Shukla, P. R., Ghosh, D., Kapshe, M. and Nair, R., Future GHG and local emissions for India: Policy links and disjoints. *J. Mitigat. Adapt. Strategies Global Change*, 2003, **8**, 71–92.
49. Guha, M. K., The US utility perspective on technology transfer through the CDM. Presented in the Workshop on Development and Financing of Climate Change Partnership Projects. Indian Institute of Management, Ahmedabad, 9–10 December 1999.
50. Hutchinson, G. E., The biochemistry of terrestrial atmosphere. In *The Earth as a Planet* (ed. Kupier, G. P.), University of Chicago Press, Chicago, 1954, pp. 371–433.
51. Delwiche, C. C., The nitrogen cycle. *Sci. Am*., 1970, **223**, 136–147.
52. Soderlund, R. and Svensson, B. The global nitrogen cycle. In *Nitrogen, Phosphorus and Sulfur* (eds Svensson, B. and Soderlund, R.), Global Cycles, SCOPE 7, *Ecol. Bull.*, 1976, vol. 22, pp. 23–73.
53. Burns, D. A., Retention of NO_3^- in an upland stream environment: A mass balance approach. *Biogeochemistry*, 1998, **40**, 73–96.
54. Goulding, K., Pathways and losses of fertilizer nitrogen at different scales. In *Agriculture and the Nitrogen Cycle* (eds Mosier, A. R., Syers, J. K. and Freney, J. R.), Island Press, Washington, 2004, pp. 209–219.
55. ESA, Global air pollution map produced by Envisat's SCIAMACHY, 2004; http://www.esa.int/esaCP/SEM340NKPZD_index_1.html
56. Wood, S. W. *et al.*, Validation of version 5.20 ILAS HNO_3, CH_4, N_2O, O_3, and NO_2 using ground-based measurements at Arrival Heights and Kiruna. *J. Geophys. Res. D*, 2002, **107**, 8208.
57. Kanzawa, H. *et al.*, Validation and data characteristics of nitrous oxide and methane profiles observed by the Improved Limb Atmospheric Spectrometer (ILAS) and processed with the Version 5.20 algorithm. *J. Geophys. Res. D*, 2003, **108**, 8003.
58. Choi, Y., Wang, Y., Zeng, T., Martin, R. V., Kurosu, T. P. and Chance, K., Evidence of lightning NO_x and convective transport of pollutants in satellite observations over North America. *Geophys. Res. Lett*., 2005, **32**.
59. Boegh, E., Soegaard, H., Broge, N., Hasager, C. B., Jensen, N. O., Schelde, K. and Thomsen, A., Airborne multispectral data for quantifying leaf area index, nitrogen concentration and photosynthetic efficiency in agriculture. *Remote Sensing Environ*., 2002, **81**, 179–182.
60. Coles, V. J., Wilson, C. and Hood, R. R., Remote sensing of new production fuelled by nitrogen fixation. *Geophys. Res. Lett.*, 2004, **31**, L06301.
61. Reiners, W. A., Liu, S., Gerow, K. G., Keller, M. and Schimel, D. S., Historical and future land use effects on N_2O and NO emissions using an ensemble modeling approach: Costa Rica's Caribbean lowlands as an example. *Global Biogeochem. Cycles*, 2002, **16**, 1068.
62. Robertson, G. P. and Rosswall, T., Nitrogen in West Africa: The regional cycle. *Ecol. Monogr.*, 1986, **56**, 43–72.
63. Myers, R. J. K., Palm, C. A., Cuevas, E., Gunatilleke, I. U. N. and Brossard, M., The synchronization of nutrient mineralization and plant nutrient demand. In *The Biological Management of Tropical Soil Fertility* (eds Woomer, P. L. and Swift, M. J.), John Wiley, Chichester, UK, 1994, pp. 81–116.
64. Webb, J., Henderson, D. and Anthony, S. G., Optimizing livestock manure applications to reduce nitrate and ammonia pollution: Scenario analysis using the MANNER model. *Soil Use Manage*., 2001, **17**, 188–194.
65. Grübler, A., Trends in global emissions: Carbon, sulfur, and nitrogen. In *Encyclopedia of Global Environmental Change, Causes and Consequences of Global Environmental Change* (ed. Douglas, I.), John Wiley, N.J., 2002, vol. 3, pp. 35–53.
66. Schimel, D. S., Kittel, T. G. F. and Parton, W. J., Terrestrial biogeochemical cycles: Global interactions with atmosphere and hydrology. *Tellus AB*, 1991, **43**, 188–203.
67. Verchot, L. V., Davidson, E. A., Cattanio, J. H., Ackerman, I. L., Erickson, H. E. and Keller, M., Land use change and biogeochemical controls of nitrogen oxide emissions from soils in eastern Amazonia. *Global Biogeochem. Cycles*, 1999, **13**, 31–46.

68. Krug, E. C. and Winstanley, D., The need for comprehensive and consistent treatment of the nitrogen cycle in nitrogen cycling and mass balance studies: 1. Terrestrial nitrogen cycle. *Sci. Total Environ*., 2002, **293**, 1–29.
69. Vlek, P. L. G., Fillery, I. R. P. and Burford, J. R., Accession, transformation, and loss of nitrogen in soils of the arid region. *Plant Soil*, 1981, **58**, 133–175.
70. Clarke, J. F., Edgerton, E. S. and Martin, B. E., Dry deposition calculations for the Clean Air Status and Trends Network. *Atmos. Environ*., 1997, **31**, 3667–3678.
71. Schimel, D. S., Terrestrial biogeochemical cycle: Global estimates with remote sensing. *Remote Sensing Environ.*, 1995, **51**, 49–56.
72. Singh, R. and Nye, R. H., A model of ammonia volatilization from applied urea. 1. Development of the model. *J. Soil Sci.*, 1986, **37**, 9–20.
73. Jayaweera, G. R. and Mikkelsen, D. S., Ammonia volatilization from flooded soil systems: A computer model. I. Theoretical aspects. *Soil Sci. Soc. Am. J*., 1990, **54**, 1447–1455.
74. Potter, C., Krauter, C. and Klooster, S., Statewide inventory estimates of ammonia emissions from native soils and chemical fertilizers in California. Report prepared for the California Air Resource Board, Emission Inventory Branch, June 2001, pp. 18–25.
75. Potter, C. S., Matson, P. A., Vitousek, P. M. and Davidson, E., Process modeling of controls on nitrogen trace gas emissions from soils worldwide. *J. Geophys. Res*., 1996, **101**, 1361–1377.
76. Parton W. J. *et al*., Generalized model for NO_x and N_2O emissions from soils. *J. Geophys. Res*., 2001, **106**, 17403–17419.
77. Li, C., Aber, J., Stange, F., Butterbach-Bahl, K. and Papen, H., A process-oriented model of N_2O and NO emissions from forest soils: 1. Model development. *J. Geophys. Res*., 2000, **105**, 4369–4384.