Reactive nitrogen in Indian agriculture: Inputs, use efficiency and leakages

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The flows of reactive N in terrestrial, aquatic and atmospheric ecosystems in India are being increasingly regulated by inputs, use efficiency and leakages of reactive N from agriculture. In the last three decades, use of reactive N in the form of chemical fertilizers has kept pace with the production of foodgrains, although the consumption is concentrated in certain areas with intensive farming. As for cereal-based agriculture, recovery of N by rice and wheat at on-farm locations in India rarely exceeds the 50% mark. Agricultural activities in India account for more than 80% of the total N_2O emissions, including 60% from the use of N fertilizers and 12% from burning of agricultural residues. In Asia, reactive N transfers to the atmosphere by NH_3 volatilization are expected to reach 19 Tg N yr^{-1} in the next three decades; 29% being India's contribution. Of the total anthropogenic emissions of NO_x and N_2O from Asian agriculture, about 68% is due to the combined contributions of India and China. Additionally, riverine discharge of dissolved inorganic N derived from N in river basins and leaching of nitrate-N to the surface and ground water bodies also contributes to the application of reactive N in agriculture. Integrated management of organic amendments and fertilizer N can improve efficiency of reactive N use by crop plants, while achieving targets of productivity and quality. The greatest challenge in improving N use efficiency lies in developing precision management of reactive N in time and space. Approaches to maximize synchrony between crop-N demand and the supply of mineral N from soil resources along with reactive N inputs in high-yielding agricultural systems are critical towards this end. Among a host of upcoming technologies aimed at improving N management strategies, leaf colour charts, chlorophyll meters and optical sensors, which allow in-season estimation of N requirement of crops, are the most promising.

Keywords: Indian agriculture, inputs, leakages, reactive nitrogen, use efficiency.

AGRICULTURE is the mainstay of the Indian economy, contributing about 22% of the gross domestic product and providing livelihood to two-thirds of the population. In India livestock rearing is complementary to agriculture, with an expected livestock population of over 480 million[1]. In terms of land use, the total area under cultivation is 169.7 mha, with an additional area of 0.4 mha under plantation crops[2]. Limited prospects for expanding irrigation and converting marginal lands into productive arable lands pose a formidable challenge towards achieving agricultural self-sufficiency; considering the projected increase in demand from 215 to 300 mt by 2020. While genetically engineered alternatives are yet to address the issue of demand and supply owing to low acceptability and increased costs, future increases in production of rice, wheat and other cereals would continue to depend heavily on increased use of nutrients, particularly N.

Forms of N (NO_3^- and NH_4^+) which are taken up by plants can be made available for crop production through chemical fertilizers, natural and anthropogenic biological N fixation and through recycling of plant and animal wastes. These can be then converted into several other forms (NH_3, NO_x, N_2O), which can move readily among terrestrial, aquatic and atmospheric realms. Galloway *et al.*[3] labelled this diverse pool of N forms as 'reactive N' and defined the term to include all biologically, radiatively and/or photochemically active forms of N. The fate of reactive N in agroecosystems in India assumes great importance since reactive N fixed biologically or applied as fertilizer not only leads to increased crop production, but can also leak from agroecosystems in the form of N_2O, NH_3 and NO_x gases, depending on how efficiently plants use it.

Industrial fixation of N for use as fertilizer represents by far the largest human contribution of new reactive N to the N-cycle[4], with fertilizer use in India during the last 11 years (1995–2005) equalling the total quantity used up to 1994 (ref. 5). From 1960 to 1990, genetic improvements led to the development of highly fertilizer-responsive rice and wheat varieties with improved management strategies, resulting in a dramatic rise in productivity and production of rice and wheat in India. This has witnessed a linear increase since then and at present contributes to more than 75% of the total foodgrains produced in the country[5], with nitrogen fertilizers contributing largely to this remarkable increase (Figure 1).

In the years to come, Indian agriculture will have to strike a delicate balance between inputs and outputs of reactive N. Substantial reactive N inputs will have to be linked to minimal leakage of reactive N. This article attempts to provide an overview of the information available from India to achieve the required input–output balance of re-

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active N through appropriate technological and policy interventions. Extent of losses of reactive N forms from agroecosystems and possibility of reducing leakage of N by enhancing N use efficiency through the adoption of precision technologies has also been explored.

Reactive N inputs in Indian agriculture

Using the approach followed by Parris and Rielle[6] for some of the OECD (Organisation for Economic Cooperation and Development) countries, Prasad *et al.*[7] computed soil-surface N balance for agricultural land of India for the period 2000–01. Fertilizer N input was calculated by summing the area-weighted portion of fertilizer sold in each state and multiplying by the N content of the fertilizer. Livestock manure N production from different states was calculated as the number of live animals distinguished in terms of general species (sheep, goat, cattle, buffalo, horse, mule, donkey, camel, pig, poultry, yak)[8] multiplied by the respective N excretion coefficients for the Asian region, as given by the Intergovernmental Panel on Climate Change[9]. Table 1 presents a complete picture of reactive N inputs to agricultural land in India. Interestingly, fertilizer N and biological

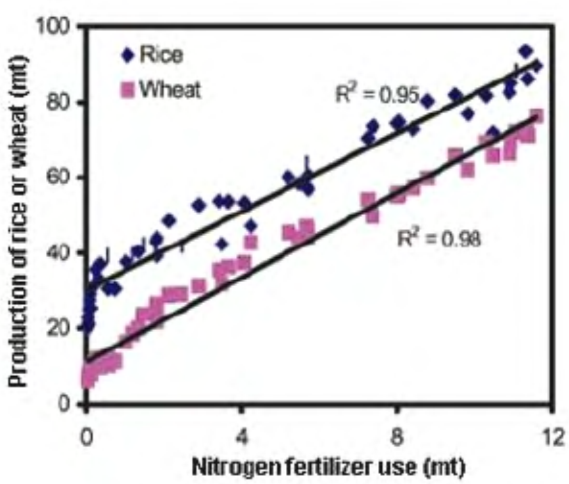

Figure 1. Production of rice or wheat in relation to fertilizer N use in India during 1951–2004 (source: FAI[5]).

Table 1. Inputs of reactive N to surface soil of agricultural land of India during 2000–01

Input	Total N		
	Tg	Percentage contribution	kg N ha^{-1}
Inorganic fertilizers	11.50	32.48	57.76
Livestock manure	15.60	44.06	130.17
Nitrogen fixation	4.10	11.58	17.10
Atmospheric deposition	4.20	11.86	31.81

Source: Prasad *et al.*[7].

N fixation – the sources of new reactive N – constituted only 44% of the total additions.

The consumption of fertilizers varies significantly from state to state. The all-India per-hectare consumption of fertilizer [10]N was 59.2 kg in 2003–04. While the north zone had a consumption of more than 100 kg N ha^{-1}, in the east and west zones the consumption was lower than 50 kg ha^{-1} (Table 2). Among the major states, the per-hectare consumption of fertilizer N was more than 100 kg in Punjab and Haryana. In Assam, Chhattisgarh, Himachal Pradesh, Jammu and Kashmir, Kerala, Madhya Pradesh, Maharashtra, Orissa and Rajasthan, N consumption per hectare was lower than the all-India average of 59.2 kg ha^{-1}. Rice occupied an area of 44.7 mha and accounted for 31.8% (5.34 mt) of total fertilizer consumption in India during 2003–04 (Table 3). Fertilizer N use on irrigated rice (103 kg ha^{-1}) is almost double that on rainfed rice (56 kg ha^{-1}). Wheat, grown largely under irrigated conditions, accounts for 20.5% (3.44 mt) of total fertilizer consumption in India. Fertilizer use per hectare in 2003–04 was 137 kg (100 kg ha^{-1} N, 30 kg ha^{-1} P_2O_5 and 7 kg ha^{-1} K_2O). Fertilizer use on irrigated wheat (144.9 kg ha^{-1}) was almost double that on rainfed wheat and the trend is similar for all the nutrients. Table 4 reveals that from 1999–2000 to 2003–04, 93.7–100% of fertilizer N applied to agricultural land was produced in India.

Nitrogen inputs from biological N fixation (field bean, soybean, clover, alfalfa, pasture), as reported in Table 1, were obtained from dry biomass production multiplied by the fraction of N in nitrogen-fixing crops[7]. Area under green manuring[10] was about 7 mha. Biological N fixation was found to be high in Andhra Pradesh (71.2 kg N ha^{-1}) followed by Madhya Pradesh (38.7 kg N ha^{-1}), Maharashtra (36.5 kg N ha^{-1}) and Orissa (34.4 kg N ha^{-1}). The use of biofertilizers is of relatively recent origin. Biofertilizers consist of N fixers (*Rhizobium, Azotobacter*, blue-green algae, *Azolla*) and fungi (mycorrhizae). A contribution of 20–30 kg N ha^{-1} has been reported from the use of biofertilizers under Indian conditions[10].

The use of organic manure is the oldest and most widely prevalent practice of nutrient replenishment in India. Prior to the 1950s, organic manure was almost the only source of reactive N other than atmospheric N deposition. Organic manures make a significant contribution to the supply of plant nutrients and soil fertility. Since livestock population dictates the production of manure, distribution and density across states and regions of the livestock population are important to study N balances. It is noteworthy that a substantial proportion of cattle excreta is used for purposes other than supplying nutrients. Thus estimates of total N inputs to agricultural soils as calculated in Table 1 by Prasad *et al.*[7], seem to be on a higher side. According to Balaraman[11], 2 bt of cattle manure containing 3.44 mt of N is generated annually in India. At the present production level, the estimated annual production of crop residues is about 300 mt. As two-thirds of all crop

Table 2. Consumption of fertilizer (kg ha^{-1}) in four zones of India during 2003–04

Zone	Fertilizer N	Fertilizer N + P_2O_5 + K_2O
East (Assam, Bihar, Jharkhand, Orissa, West Bengal)	49.0	75.8
North (Haryana, Himachal Pradesh, Jammu and Kashmir, Punjab, Uttar Pradesh, Uttaranchal)	102.9	140.1
South (Andhra Pradesh, Karnataka, Kerala, Tamil Nadu)	60.0	105.4
West (Chhattisgarh, Gujarat, Madhya Pradesh, Maharashtra, Rajasthan)	38.0	59.4
All-India	59.2	89.8

Source: FAO[10].

Table 3. Fertilizer use in rice and wheat during 2003–04 in India

Crop	Gross cropped area (mha)	Share in fertilizer consumption (%)	Fertilizer consumption (kg ha^{-1})			
			N	P_2O_5	K_2O	Total
Rice – irrigated	24.0	22.2	103.4	32.8	18.8	155.0
Rice – rainfed	20.7	9.6	56.6	14.5	6.5	77.6
Wheat – irrigated	22.8	19.7	105.6	32.1	7.3	144.9
Wheat – rainfed	2.9	1.3	55.7	15.9	4.3	75.9

Source: FAO[10].

Table 4. Production, import and consumption of fertilizer N in India (000' t)

	1999–2000	2000–01	2001–02	2002–03	2003–04
Production	10,873	10,943	10,690	10,508	10,575
Import	856	164	283	135	205
Consumption	11,593	10,920	11,310	10,474	11,076

Source: FAO[10].

residues are used as animal feed, only one-third is available for direct recycling[10]. The production of urban compost[1] had been 180.8 mt during 1996–97. Unlike fertilizers, the use of organic material has not increased much in the last two to three decades. In addition to improving soil physico-chemical properties, the supplementary and complementary use of organic manure also improves the efficiency of mineral fertilizer use.

Nitrogen use efficiency of agricultural crops

During the last half-decade while fertilizer N consumption in India has been touching new heights, production of both rice and wheat is plateauing (Figure 2). In fact, fertilizer N efficiency in foodgrain production expressed as partial factor productivity of N (PFP_N) has been decreasing exponentially since 1965 (Figure 3). PFP_N is an aggregate efficiency index that includes contributions to crop yield derived from uptake of indigenous soil N, fertilizer N-uptake efficiency, and the efficiency with which N acquired by the plant is converted to grain yield. An initial decline in PFP_N is an expected consequence of the adoption of N fertilizers by farmers and not necessarily bad within a systems context. While fertilizer use increased exponentially during the course of the green revolution, resulting in a steep decrease in PFP_N; the decrease in PFP_N during the last decade has been due to low fertilizer N-uptake efficiency. This is of particular concern for the reactive N budget as fertilizer N use in India is continuously increasing (Figure 2).

Nitrogen use efficiency can mean different things to different people and is easily misunderstood and misrepresented. For example, Table 5 shows data from an experiment on irrigated wheat in Punjab. Recovery of 43% N in the above-ground biomass of applied N is low and suggests that N may pose an environmental risk. Total N uptake by wheat was 107 kg N ha^{-1}; 52 from the fertilizer and 55 from the soil. Total N removed in harvested grains worked out to be 70% of the total fertilizer N applied. Nitrogen contributions from the soil in a given year/season and on a long-term basis can greatly alter apparent recovery efficiency of applied N (RE_N), because there occurs large fertilizer N substitution of soil N. Although both indigenous soil resources and applied fertilizer N contribute to the plant available N pool consisting of NO_3 and NH_4 ions, this pool represents a small fraction of total soil-N. For example, a typical irrigated soil under rice–wheat cropping system in the Indo-Gangetic Plain contains about

2000 kg N ha^{-1} in the top 30 cm of soil from where roots derive majority of N supply. The amount of N derived from indigenous resources during a single cropping cycle typically ranges from 30 to 100 kg N ha^{-1} which represents only 1.5–5% of total soil N. Although small in size, the indigenous N supply has a high N-fertilizer substitution value because of the relatively low RE_N from applied N fertilizer. Further, as the C/N ratio of soil organic matter is relatively constant, changes in soil C balance introduced by management practices, including fertilizer use, affect the soil N balance. The overall fertilizer N use efficiency can thus be increased by achieving greater RE_N, by reducing the amount of N lost from soil organic or inorganic pools, or both. When soil-N content is increasing, the amount of sequestered N contributes to higher N use efficiency and the amount of sequestered N derived from applied N contributes to a higher RE_N. Conversely, any decrease in soil N stocks reduces overall N use efficiency and RE_N.

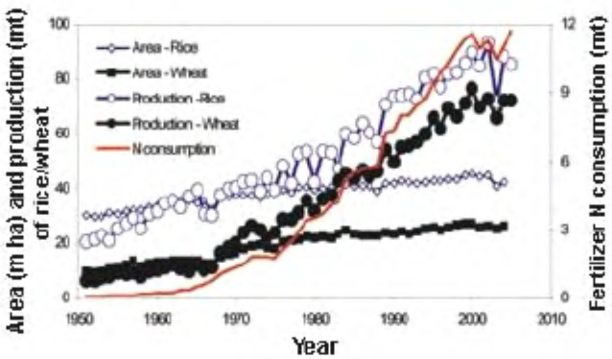

Figure 2. Time trends of fertilizer N consumption vis-à-vis area and production of rice and wheat in India (source: FAI[5]).

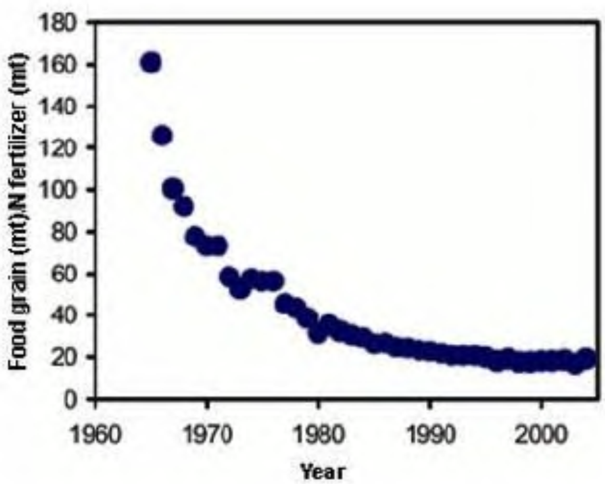

Figure 3. Fertilizer N efficiency of foodgrain production (annual foodgrain production divided by annual fertilizer N application) during 1965–2004 in India (source: FAI[5]).

A recent review[13] on N use efficiency reported average single-year fertilizer N recovery efficiencies as 57% for wheat and 46% for rice in experimental plots. Nitrogen recovery in crops grown by farmers, however, is often much lower. A review of the best available information suggests that the average N recovery efficiency for fields managed by farmers' ranges from 20 to 30% under rain-fed conditions and 30 to 40% under irrigated conditions. Nitrogen use efficiency exceeding 40% is expected to occur in response to improved N management practices. Cassman *et al.*[12] found that N recovery from on-farm locations averaged 31% for irrigated rice in Asia and 40% for rice under field-specific management. For wheat grown in India, the recovery averaged 18% under poor weather conditions, but 49% when grown under good weather conditions (Table 6). Ladha *et al.*[13] compiled data on ^{15}N recovery by cereal crops and found that average RE_N-^{15}N was 44% in the first growing season and total recovery of ^{15}N fertilizer in the first and five subsequent crops was only around 50%. Assuming that the amount of ^{15}N in the roots becomes negligible in the sixth growing season, the remaining 50% of the ^{15}N fertilizer would have either become part of the soil organic matter pool or was lost from the cropping system[14].

Fertilizer N use efficiency is controlled by crop demand for N, supply of N from the soil, fertilizer and manure, and loss of N from the soil–plant system[15]. Crop N demand is the most important factor influencing fertilizer N use efficiency. It is determined by biomass yield and physiological requirement of tissue N. Solar radiation, temperature and moisture regimes determine the genetic yield ceiling, but actual crop yields are far below this threshold, because it is neither possible nor economical to remove all limitations to growth. Hence, the interaction of climate and management causes tremendous year-to-year variation in the on-farm yield and crop N requirement. Physiological N efficiency – the change in grain yield per unit change in N accumulation in aboveground biomass, is controlled by the mode of photosynthesis (C_3 or C_4 photosynthetic pathway) and grain N concentration that is also influenced by N supply[12]. Both rice and wheat are C_3 plants, but due to lower grain N concentration rice has higher physiological efficiency than wheat in terms of yield.

Table 5. Fertilizer N use efficiency in a typical experiment on irrigated wheat in Punjab to which recommended fertilizer N level of 120 kg N ha^{-1} was applied

Fertilizer N level (kg ha^{-1})	120
Fertilizer N recovered in the crop (kg ha^{-1})	52
Total N taken up by the crop	107
N removed in the harvested grain	84
N removed in crop residues	23
Crop recovery efficiency (RE_N; 52 kg N recovered/120 kg N applied; %)	43

Source: Bijay-Singh *et al.*[65].

Table 6. Nitrogen fertilizer recovery by rice and wheat from on-farm measurements

Crop	Region	Number of farms	Average N levels, kg N ha^{-1} (± SD)	RE_N (%) (± SD)
Rice	Asia – farmers' practice	179	117 ± 39	31 ± 18
	Asia – field-specific management	179	112 ± 28	40 ± 18
Wheat	India – unfavourable weather	23	145 ± 31	18 ± 11
	India – favourable weather	21	123 ± 20	49 ± 10

Source: Cassman *et al.*[12].

Nitrogen needs of crop plants are met with by applying fertilizer N and net N mineralization from soil organic matter and organic manure. Fertilizer N is applied in forms readily available to plants, but mineralization of N is controlled by soil, water, temperature and aeration. Once these factors become optimum, the amount of N that is mineralized depends upon the quality and quantity of organic matter in the soil. High rates of net N mineralization can result in dilution of fertilizer N. But if crop demand for N and the amount of fertilizer N remain constant, an increase in net N mineralization will lead to a decrease in observed N use efficiency. Loss of N via denitrification, ammonia volatilization and leaching may lead to low N use efficiency, particularly when conditions for plant growth are favourable and plant-N demand cannot be met because of large N losses. Relative magnitude of different N loss mechanisms will depend upon soil type, weather, fertilizer-use and crop management, with climate exerting the strongest influence on the amount and pathways of N losses.

Loss of reactive N from agroecosystems

Reactive N leaves the agroecosystems through leaching as nitrate or dissolved forms of organic N, or through gaseous emissions to the atmosphere in the form of NH_3, NO, N_2O or N_2. All of these avenues of loss, with the important exception of N_2, are linked to one or more local, regional or global environmental hazards. Essentially, all emitted NH_3 is returned to the surface by deposition[16], one of the causes of soil acidification since the early 1980s. Atmospheric N deposition may lead to eutrophication of natural ecosystems and loss of biodiversity[17]. Nitrous oxide is one of the greenhouse gases, contributing 6% of the anthropogenic greenhouse effect. It also contributes to the depletion of stratospheric ozone[18]. Reactive N in the form of NO_3^- is an important pollutant of groundwater and surface water.

According to estimates made by Zheng *et al.*[19] in Asia, reactive N was transferred to the atmosphere by NH_3 volatilization at a rate of ~4.6 Tg N yr^{-1} in 1961 and it increased to ~13.8 Tg N yr^{-1} in 2000. It is expected to reach ~18.9 Tg N yr^{-1} in the next three decades. China's contribution increased from ~25% in 1961 to ~39% in 2000, while India's contribution decreased from ~41% in 1961

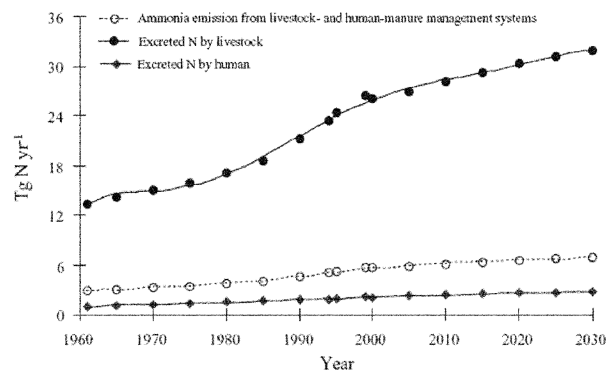

Figure 4. Livestock and human-excreted nitrogen and its ammonia volatilization in Asia (source: Zheng *et al.*[19]).

to ~29% in 2000. In the next three decades, however, the contribution of China is expected to decrease to ~35% and that of India is anticipated to remain at ~29%. The NH_3 released to the atmosphere is redeposited in downwind terrestrial lands at a rate ranging from 3.8 Tg N yr^{-1} in 1961 to 15.7 Tg N yr^{-1} in 2030, while the deposition to coastal waters stands at a rate of 0.8–3.4 Tg N yr^{-1} over 1961–2030. The temporal variation in livestock-excreted N is an indicator of the growth of animal husbandry in Asia. Estimates made by Zheng *et al.*[19] reveal that NH_3 volatilization rate from animal and human excreta stored in manure management systems in Asia was ~2.8 Tg N yr^{-1} in 1961, gradually increased to ~5.5 Tg N yr^{-1} in 2000 and has been projected to reach ~6.9 Tg N yr^{-1} by 2030 (Figure 4).

Ammonia volatilization losses of reactive N fixed by legumes or applied through N fertilizers can be substantial, especially in regions that are irrigated and/or have alkaline soils[20]. Ferm[21] observed that about half of the ammonia that is volatilized is deposited in downwind ecosystems within a 50 km radius, while the other half is deposited over a much broader region. Losses of amm nia following fertilizer applications to upland and lowland cropping systems can range from ~0 to >50%, while losses from flooded rice[22] can reach as high as 80%. Fertilizer placement, timing of application, soil temperature and fertilizer type determine loss rates[22]. Ammonia volatilization from legume residues may be high when these are left on the soil surface, but the losses do not appear to

Table 7. Extent of gaseous N losses computed using ^{15}N-balance approach from flooded rice soils in India

N application rate (kg ha^{-1}) and source	Method and time of N application	Gaseous N loss (% of applied N)	Reference
180, urea	Basal	34–50	66
180, urea	Three splits	17–28	66
58–116, urea, $(NH_4)_2SO_4$	Basal	46–50	67
100, urea	Basal	58	68

Table 8. N_2O emissions from various source categories in India (Gg–N_2O)

Source category	1985	1990	1995	2000	2005	Compounded annual growth rate (%)
Synthetic fertilizer use	80	94	109	129	151	3.2
Field burning of agricultural residues	15	18	21	21	20	1.4
Indirect soil emissions	17	19	21	25	30	2.9
Manure management	4	5	6	6	8	3.9
Fossil-fuel combustion	7	9	12	15	19	4.9
Industrial processes	6	7	9	12	16	5.0
Waste	5	6	7	8	9	2.8
Total N_2O	134	158	185	217	253	3.2

Source: Garg *et al.*[29].

match those measured in some fertilized systems. Loss of N via ammonia volatilization can be substantial when urea is top-dressed in both rice and wheat grown under Indian conditions. To wheat, urea is generally applied after the irrigation event to minimize leaching and denitrification losses. However, placement of urea on the wet surface of alkaline porous soils promotes ammonia volatilization. For example, in a field study with wheat, Katyal *et al.*[23] demonstrated that the timing of fertilization and irrigation influenced the losses of applied reactive N via ammonia volatilization. If applied on the wet soil surface following irrigation, as much as 42% of the applied ^{15}N was lost due to volatilization. Deep placement of urea due to its application before irrigation and resultant reduction in losses of applied ^{15}N from 42 to 15% are well demonstrated from the work of Katyal *et al.*[23].

Water management in rice and wheat fields influences the extent of N losses due to nitrification–denitrification and ammonia volatilization. Up to 50% of the applied N can be lost through denitrification when alternating aerobic–anaerobic conditions prevail in the rice fields. A vast majority of soils, particularly in the Indo-Gangetic Plains, are relatively coarse-textured and experience frequent alternating wetting and drying cycles. Quantification of denitrification losses in flooded rice fields has been hindered by the lack of viable methodology for direct measurement. Table 7 provides a general idea of gaseous losses of N occurring in flooded soils. Since these data have been generated from ^{15}N balances, it indicates losses via ammonia volatilization as well as nitrification–denitrification.

Nitric oxide (NO) and nitrous oxide (N_2O) are trace gases that are commonly formed during the microbial processes of nitrification and denitrification. Very little quantitative information is available about NO fluxes. Bouwman[24] compiled data on N_2O emissions from 87 different agricultural soils and reported fluxes ranging between 0 and 30 kg N_2O–N ha^{-1} yr^{-1}. More than a third of all nitrous-oxide emissions on a global basis is anthropogenic and primarily due to agriculture[25]. Zheng *et al.*[19] estimated NO emission from Asian cultivated soils (excluding the burning of crop residues) in the 1980s and 1990s at 0.8–1.2 Tg N yr^{-1}, which accounts for 16–24% of the global total[26,27] ranging from 1.6 to 8.4 Tg N yr^{-1}. The estimate of N_2O emission from agricultural soils and manure management in Asia for the 1990s ranged from 1.1 to 1.4 Tg N yr^{-1}, accounting for 17–32% of the latest global estimates[18] of 3.9–6.3 Tg N yr^{-1}. Of the total anthropogenic emissions of NO_x and N_2O from Asian agriculture, about 68% is due to the combined contributions of India and China.

Following IPCC methodologies[9,28], Garg *et al.*[29] estimated direct N_2O emissions from different sources (Table 8). Taking 178 Gg-N_2O emission for 1994 as the benchmark, there has been a noticeable lowering in direct N_2O emission estimates from the soils, including from the use of synthetic fertilizers. This is mainly due to the use of India-specific emission factors that are lower by almost 30% than the IPCC default values. The previous emission factors were 0.93 kg ha^{-1} N_2O–N for all types of crop regimes. The revised emission factors used for rice–wheat systems are 0.76 kg ha^{-1} N_2O–N for rice and 0.66 for wheat with urea application without any inhibitors[30]. Agriculture sector activities account for more than 80% of the total N_2O emission, including 60% from the use of synthetic fertilizers, about 12% each from agriculture residue burning and indirect soil emission and about 3% from manure management[29]. Using the geographical information system (GIS)-interfaced Asia-Pacific Integrated Model (AIM/Enduse), which employs technology share projections for estimating future N_2O emissions, Garg *et al.*[31] analysed reference scenarios and concluded that agriculture sector activities account for more than 90% of the total N_2O emissions in India presently, including 66% from the use of synthetic fertilizers, about 10% each from field burning of agriculture residues and indirect soil emission, and about 5% from livestock excretion. Synthetic fertilizers are the single largest source of N_2O emissions presently, and are projected to retain this prominence in future.

When nitrate-N gets accumulated in the soil either from mineralization of organic matter or fertilizer applications, and water supplied via precipitation or irrigation exceeds crop demands, nitrate anions readily combine with base cations and leach through the soil profile. High soil nitrate N levels and sufficient downward movement of water to move nitrate N below the rooting depth are often encountered in soils of the humid and subhumid zones, to a lesser extent in the soils of the semi-arid zone and quite infrequently, if at all, in arid-zone soils[32]. Substantial leaching losses occur if rainfall is received when soils are at, or approaching field capacity. Both intensity and amount of rainfall or irrigation are important in determining the rate and extent of leaching. When high fertilizer rates are combined with heavy irrigation regimes on coarse-textured soils, leaching losses of nitrate N can be substantial[33]. Where summer fallow is followed by monsoon-type heavy rainfall, leaching losses of N can be serious. An appraisal of the extent of nitrate leaching to groundwater bodies in different parts of India has been made by Agrawal *et al.*[34], by considering together fertilizer N use per unit area and extent of groundwater development for irrigation purposes. Using the data generated by reconnaissance of nitrate content in shallow groundwaters by the Central Ground Water Board[35], Agrawal *et al.*[34] categorized different states with respect to potential hazard of nitrate pollution of groundwaters, which also reflects the extent of nitrate-N leaching beyond the root zone of crops. With the highest groundwater development, average nitrate content in groundwater and average fertilizer N use, the losses of nitrate-N via leaching in the agricultural systems in Punjab and Haryana are the largest among different regions in the country. According to Agrawal *et al.*[34], irrigation without artificial drainage in the poorly drained flat plains of Punjab and Haryana, comprising a thick pile of unconsolidated and permeable Late Quaternary–Holocene alluvial sediments[36], increases the leaching of nitrate-N compared to in the freely drained regions of the northern and northeastern states and peninsular plateau in the southern part of the country. Agriculture is not intensive in the northern and northeastern states as reflected in the meagre consumption of N fertilizers and negligible groundwater use. The situation in the peninsular states lies between the two extremes.

In the Asian N-cycle case study conducted by Zheng *et al.*[19], the riverine discharge of dissolved inorganic N derived from anthropogenic reactive N in Asia into the Pacific and Indian Oceans was estimated at ~2.6 Tg N yr^{-1} in 1961, ~6.8 Tg N yr^{-1} in 2000 and ~9.6 Tg N yr^{-1} in 2030. The discharge rates around 2000 accounted for approximately 34% of the global total[37] of ~20 Tg N yr^{-1}. The estimated rate of this study for the mid 1990s (~6.4 Tg N yr^{-1}) is lower than that (~9 Tg N yr^{-1}) presented by Seitzinger and Kroeze[37]. National-level analysis showed that ~66% of the Asian total dissolved inorganic N discharge by rivers occurs in China and India. According to Caraco and Cole[38], reactive N is being exported in the form of nitrates out of the watershed of the Ganges, Yangtze, Huanghe and Mekong at a rate of 601, 495, 276 and 144 kg N yr^{-1} km^{-2} respectively.

Biologically vs synthetically fixed reactive nitrogen

Before the advent of N fertilizers, farmers maintained 25–50% of their land under legume crops, which regenerated soil fertility through biological fixation of atmospheric dinitrogen (N_2) by legume–rhizobial symbiosis. Although the harvested seed of some pulse (edible legume) crops contained much of the N_2 fixed by the legume plants, the residues of such pulse crops still constituted a net N input to subsequent crops. Legume-based rotations are still common in several parts of India, particularly with a large number of resource-poor farmers. As is typical for cereal crops to take up 50% or less of the N applied as N fertilizers, some legume rotations have also shown similar low N use efficiency[39-41]. Sometimes it can be attributed to mismatch between the timing of nutrient supply and demand in annual cropping systems, although it is generally argued that legume-based agroecosystems can maintain higher levels of synchrony between N supply and crop uptake, when compared to single or dual applications of N fertilizers[42,43]. However, the data are inconclusive. Some studies showed relatively greater N synchrony in legume-based systems[44], but others suggest that fertilizer-based systems are superior[45,46]. The potential advantage of N fertilized systems is that crops can receive multiple top-dressings during the growing season to better match N supply with crop N demand[12]. Crews and Peoples[20] concluded that the ecological integrity of legume-based agroecosystems is marginally greater than that of fertilizer-based systems.

Sufficient data do not exist[20] to state conclusively that legume-N is less susceptible to ammonia volatilization than fertilizer N. Ammonia volatilization from legume residues may be high when these are left on the soil surface, but the losses do not appear to match those measured in some fertilized systems. Venkatakrishnan[47] measured ammonia losses of 23% from a sesbania (*Sesbania rostrata*) green-manured plot after 63 days. However, incorporating legume residues may reduce N losses through ammonia volatilization[22] at the expense of increasing potential of denitrification losses of N. As fertilizer-based systems exhibit nitrate accumulation in the soil following fertilizer applications during the growing season, legume-based systems are also vulnerable to nitrate accumulation, particularly when soils are not cropped[41]. Nitrate leaching has been found to occur in both fertilized and legume-based cropping systems[41,48]. However, when leguminous crops are allowed to grow throughout the fallow season, these not only fix N, but also scavenge available N from the soil. Thus green manure has been shown to substantially reduce the risk of nitrate leaching experienced in various cropping systems[49]. Although there are relatively few studies that have directly compared nitrate leaching in legume and fertilizer-based systems, limited evidence suggests that in some cases, nitrate leaching may be reduced when N is supplied by legumes compared to N fertilizers[20]. While a few studies have carefully compared N_2O fluxes between legume-based and fertilizer-based farming systems, no direct comparisons have been made of NO fluxes[26]. Little difference between legume and fertilizer-based agriculture has been reported for N_2O emissions. In a literature review of N_2O emissions from 87 different agricultural soils, Bouwman[24] reported fluxes ranging between 0 and 4 kg N ha^{-1} yr^{-1} for unfertilized control plots. Fields planted with legumes were found[50] to maintain N_2O fluxes as low as 0–0.07 kg N ha^{-1} yr^{-1}. Evidence also exists that N_2O can be produced by *Rhizobium*[51], but it is difficult to appreciate the significance of this observation under field situations.

Integrated management of reactive N contained in organic manure and chemical fertilizers

In the coming decades, one of the major issues in designing sustainable agricultural systems will be the management of soil organic matter and the rational use of organic inputs such as animal manure, crop residue, green manure, sewage sludge and food industry waste. In India, the contribution of nutrients by organic amendments has traditionally been considered to be significant. However, despite the fact that organic manure contain almost all the essential plant nutrients and produces several other non-nutrient benefits, its value was principally assessed in terms of N only[52]. Nevertheless, these studies have revealed that: (1) N contribution of organic amendments was highly variable, unstable and typically low, and (2) organic manure/amendments should supplement and not supplant nutrient supplies through fertilizers[53]. As a result, combined use of chemical fertilizers and organic manure, referred to as integrated nutrient management, has emerged as an important component of the soil fertility management research programme in India. Investigations lasting from one to two seasons to several years, conducted with or without irrigation, across diverse environments have provided useful information on the N equivalence of organic manure (Table 9). In general, N release from organic amendments is slow and is considered to be better synchronized with removal of N by crop plants[54]. Efficient integrated nitrogen-management systems thus ensure that fertilizer N is applied only when adequate amount of N is not being mineralized from organic components. Fertilizer N equivalence of organic materials is thus also influenced by the manner in which fertilizer N was integrated with organic components of the system. Bijay-Singh *et al.*[55] showed that poultry manure-N was almost as efficient as urea-N in increasing yield and N uptake of rice. On the other hand, rice yield from combined application of 12 t of farmyard manure (FYM) ha^{-1} and 80 kg N ha^{-1} was equal to an application of 120 kg N ha^{-1} as fertilizer[56]. Efficiency of N added from FYM compared with urea, ranged from 42 to 53% in rice[57]. In 1970, systematic long-term fertilizer experiments were initiated at 11 diverse locations in India[58], in which a treatment on topping the recommended application rate of NPK through chemical fertilizers with FYM at 15 t ha^{-1} yr^{-1} was used to highlight the value of the combined use of fertilizers and manure on sustainable crop production[59]. Data for the last three decacdes indicate that with regular application of recommended doses of NPK, productivity stagnated or declined after initially increasing for 5–6 years, but the combined application of fertilizers and FYM unfailingly sustained productivity at all the locations.

What can be done with increasing N use in Indian agriculture?

While fertilizer N consumption in developing countries is continuously increasing, it has been decreasing in developed countries since the late eighties and is stabilizing around levels observed in the mid-seventies. According to FAOSTAT[60], consumption of reactive N in 1970 in the form of nitrogenous fertilizers was 8.8 mt in developing countries and 22.9 mt in developed countries. Consumption in the developing world surpassed that in developed world in 1990; it was only 29.0 mt in the developed countries vis-à-vis 55.7 mt in the developing countries during 2002. Since effects of excessive reactive N in the environment are not confined to political boundaries, developing countries like India and China, which need to support their huge populations by producing enough food by applying higher doses of nitrogenous fertilizers, will

Table 9. Fertilizer N equivalent of different organic manure applied to lowland rice in combination with fertilizer N

Organic manure	Total organic manure – N (kg N ha^{-1})	C : N ratio	Soil	Fertilizer N equivalent (kg N ha^{-1})
Cattle manure	60	26	Typic ustipsamment	40
Poultry manure	75	12	Typic ustipsamment	75
Pig manure	80	–	Typic ustipsamment	50
Green gram straw	100	16	Typic ustipsamment	60
Rice straw	27	77	Oxisol	0
Wheat straw	25	80	Typic ustipsamment	0
Green manure†	104	20	Typic ustochrept	120
Green manure†	–	–	Typic ustochrept	60
Green manure†	97–149	–	Oxisol	60
Azolla	24	8	Oxisol	30

†*Sesbania aculeate*; Source: Katyal[69].

remain in the eyes of the world until and unless higher N doses are used efficiently with least pollution of the environment. With a population of around 1.1 billion, a growth rate of 1.4% and an ineffective population control policy, it appears difficult to reduce the population of India in the 21st century. Following the linear relation[19] between accumulation of N in the environment derived from anthropogenic reactive N in Asia in the past four decades (Y, Tg N yr^{-1}) with a total population (X, billion) as $Y = 22.798 \times X - 34.383$ ($R^2 = 0.98$, $P < 0.001$), it does not seem possible to mitigate N-enrichment to any great extent because Indian agriculture will have to produce food for its burgeoning population by increasingly relying on reactive N. Galloway *et al.*[61] list three specific needs for agriculture if it has to continue to produce enough food for the masses and at the same time protect the environment from reactive-N related problems: (1) reduced use of chemical fertilizers, (2) increased efficiency of reactive N use in food production, including recycling of agricultural wastes, and (3) increased denitrification of reactive N that cannot be recycled. The first leads to reduced production of reactive N, the second keeps reactive N in the agroecosystem and also helps achieve the first and the third eliminates reactive N before it can leak to the environment. Under Indian conditions, maximum emphasis needs to be given on increasing N use efficiency in agroecosystems, particularly in rice and wheat-based cropping systems, as most of the reactive N is applied to these crops.

Recent literature on improving N use efficiency has emphasized on achieving greater synchrony between crop N demand and N supply from all sources throughout the growing season[12]. This approach explicitly recognizes the need to efficiently utilize both indigenous and applied N because losses of N via different mechanisms increase in proportion to the amount of available N present in the soil at any given time. Decisions regarding improvements in fertilizer-N use efficiency would have to commence at the field scale, where farmers need to deal with the variability in soils, climate and cropping patterns. As there exists a large fertilizer-N substitution value of soil N, it is important to ascertain the amount and temporal variations of indigenous N supply during crop growth to determine the optimal timing and amount of fertilizer N application. Since indigenous N supply is highly variable in the same field over time as well as in different fields within a given agroecological region[12], accurate predictions are not easy. This high degree of variability and small size of the indigenously available N relative to much larger background of total soil N, makes the prediction of indigenous soil N supply as one the key challenges for enhancing fertilizer N-use efficiency. Optimum moisture and temperature, insect and weed management, adequate supply of nutrients other than N and use of best cultivars all contribute to efficient uptake of available N and greater conversion of plant N to grain yield. In other words, only a well-managed crop can lead to optimum N use efficiency and profit from applied N along with least possible N losses to the environment by maintaining plant-available N pool at the minimum size required to meet crop N requirement at each stage of growth. Many ecological variables interact to determine the incidence of environmental hazards associated with N losses, but the extent to which nitrate is allowed to accumulate in soils under any cropping system seems to be most important. If crop demands for N are closely synchronized with processes that regulate N availability in the soil, then little nitrate is allowed to accumulate, which in turn minimizes soil acidification, nitrates in groundwater and production of N trace gases[20].

Most of the fertilizer-N is lost during the year of application. Consequently, N and crop management must be fine-tuned in the cropping season in which N is applied. Two broad categories of concepts and tools have been developed to increase N use efficiency. Those in the first category include genetic improvements and management factors that remove restrictions on crop growth and enhance crop N demand and uptake. Management options that influence the availability of soil and fertilizer-N for plant uptake come in the second category. These include site-specific N application rates to account for differences in within-field variation in soil N supply capacity (in large fields), field-specific N application rates in small fields, remote sensing or canopy N status sensors to quantify real-time crop N status, better capabilities to predict soil N supply capacity, controlled release fertilizers and fertigation. Ladha *et al.*[13] compared different strategies to improve N use efficiency on the basis of benefit–cost ratio and limitations. With high benefit–cost ratio and with no limitation, use of simple and inexpensive leaf colour chart assists farmers in applying N when the plant needs it. As the use of leaf colour chart can adequately take care of N supply from all indigenous sources, it ensures significant increase in RE_N and reduced fertilizer N use. This tool is particularly useful for small-to-medium size farms in developing countries. Similarly, precision farming technologies based on gadgets like optical sensors have demonstrated that variable rate N-fertilizer application has the potential to significantly enhance N use efficiency by crops like rice and wheat. Efforts are already underway to make these technologies available to farmers, but it will take time before these will become farmer-friendly under Indian farming conditions.

Modern N management concepts usually involve a combination of anticipatory (before planting) and responsive (during the growing season) decisions. Improved synchrony, for example, can be achieved by more accurate N prescriptions based on the projected crop N demand and the levels of mineral and organic soil N, and also through improved rules for splitting of N applications according to phenological stages, using decision aids to diagnose soil and plant N status during the growing season (models, sensors), or using controlled-release fertilizers or inhibitors. Important prerequisites for the adoption of advanced N-management technologies are that they must be simple, provide consistent and large enough gains in fertilizer N use efficiency, involve little extra labour and be cost-effective.

Applying an ecosystem framework to agriculture can expand the scope of current agronomic framework to include biogeochemical processes for improving fertilizer N use efficiency. Ecosystem-based approach helps optimize organic and mineral N reservoirs with longer mean residence times that can be accessed through microbial and plant-mediated processes. Recoupling N and C cycles is central to increasing internal N cycling capacity and it is an important component of this agroecosystem framework[62]. Increasing the capacity of the soil to supply N can lead to reduction in the amount of fertilizer N to be applied and thus improved N use efficiency[12]. Diversifying organic N sources can also lead to improved N use efficiency through build-up of various soil organic matter pools which impact plant and microbial-mediated processes regulating C and N cycling. Reliance on diverse organic N sources through the use of recycled organic residues such as crop residues, is an important means of maintaining various pools of soil organic matter[62]. More focused research efforts in this area are needed in India, because this approach provides a unifying framework that is particularly suited to characterizing interrelationships among the environmental conditions (abiotic components), management practices and biogeochemical processes that control yield, N use efficiency, C storage and N losses.

In the absence of known crop production functions, Roy *et al.*[63] estimated future fertilizer application rates and nutrient-use efficiencies by first quantifying the relationship between crop production and total fertilizer application rates[64] that existed during 1995–97. Assuming nutrient-use efficiency improvements in each country to be a function of the current fertilizer productivity, fertilizer response coefficient and the projected rate of change in crop yield, Roy *et al.*[63] worked out N productivity and yield relationships (Figure 5) for rice in selected countries. N productivity, as measured by kg yield (kg per N)$^{-1}$, shows considerable variation across countries. This is due to differences in resource base, production practices, management skills, and economic incentives. However, given this variability, the scope for higher levels of N productivity is substantial in all the countries, including India.

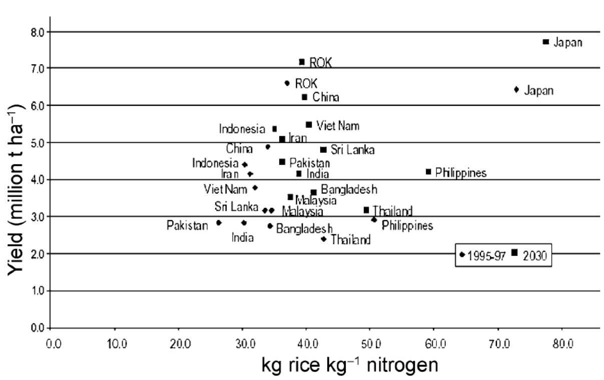

Figure 5. Nitrogen productivity and rice yield scenarios in 1995–97 and 2030 (source: Roy *et al.*[63]).

Conclusion

Use of increasing amounts of reactive N in the form of fertilizers in Indian agriculture and proper management of fertilizer N will remain at the forefront of issues to improve the global reactive N balance over both the short and long term. To achieve the tripartite goal of food security, agricultural profitability and environmental quality in a country like India, improving N use efficiency in agriculture will have to be the top priority. Efficiency with which reactive N is utilized by crop plants is governed by N requirement of crops, N supply from soil, and fertilizer and N losses from the soil–water–plant system. While optimum moisture, temperature, supply of adequate amount of nutrients other than N, and pest and weed management define crop N requirement, large field-to-field variability of soil N supply restricts efficient use of N fertilizers when broad-based blanket recommendations are used in rice and wheat. Integrated management of organic and inorganic N sources can help achieve high N use efficiency. Innovative fertilizer management has to integrate both preventive and field-specific corrective N-management strategies to increase profitability in irrigated rice and wheat systems, and to ensure that there exists synchrony between crop N demand and supply of mineral N from soil reserves and fertilizer inputs. This will lead to maintenance of plant-available N pool at the minimum size required to meet crop N requirements at each growth stage, with little vulnerability to loss of N to the environment. There is significant potential to increase N use efficiency at the farm level, because concepts and tools needed to achieve it are already available. However, new technologies need to be cost-effective and user-friendly, so that these become attractive to farmers. Collaborative effort of agronomists, soil scientists, agricultural economists, sociologists, ecologists and politicians can help agriculture make substantial contribution to reduce the global reactive N load.

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