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REVIEWS

Nitrogen Cycle Sustainability and Sustainable Technologies for Nitrogen Fertilizer and Energy Management

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Abstract | Nitrogen (N) is necessary for all forms of life and a crucial component in the increased production of food to feed the continuously increasing human and animal populations. In many ecosystems on land and sea, the supply of nitrogen controls the nature and diversity of plant life, the population dynamics of both grazing animals and their predators, and vital ecological processes such as plant productivity and the cycling of carbon and soil minerals. Since the beginning of the last century, mankind has injected increasing amounts of reactive nitrogen into the environment, intentionally as fertilizer and unintentionally as a by-product of combusting fossil fuels. As a result, nitrogen cycle is being altered causing possible grave impacts on biodiversity, global warming, water quality, human health, and even the rate of population growth in several parts of the world. The key N management technology for sustainable and profitable crop production is the synchronization of N supply with crop demand. Aiming at improving N-use efficiency in high-input cropping systems, the focus should be on higher yield with less fertilizer N. In low-input systems, additional use of N fertilizer may be required to increase yield level and yield stability. Realigning the time and rate of N application with help of modern tools, like SPAD meter, LCC, Green seeker, Simulation modeling, GIS and remote sensing as per spatial-indigenous nutrient supply capacity and temporal variability of soil enhances the synchronization between N supply and plant demand. Site specific N application with balanced fertilization and integration of locally available organic manures further improves the N use efficiencies in cropping system. Sustainable strategies for N management in energy sector are the development of technologies that either increases efficiency of fuel combustion or removes N oxides from the exhaust stream. The complete solutions, however, are closely linked to the development of non-polluting alternative energy sources. Research and development efforts needs to be strengthened to find out more effective technological solutions and try to balance them against cost and efficiency.

1 Introduction

Mineral elements play an important role in the growth and development of plants, on which we all depend, directly or indirectly, for food, feed and fibre. There are seventeen essential elements of which six are required in large quantities, including

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the predominant N, P and K, used in fertilizers for crop production. Nitrogen (N) occupies a unique position among these mineral elements, since it forms an important component of nucleotides (including the energy-carrying ATP), nucleic acids (DNA, RNA), proteins, vitamins and hormones in all living cells. In many ecosystems on land and sea, the biogeochemical cycle of N controls the nature and diversity of plant life, the population dynamics of both grazing animals and their predators, and vital ecological processes such as plant productivity and the cycling of carbon and soil minerals. In agriculture, the application of N influences the yield and quality of crops, whereas nitrogenous pollutants from agriculture, sewage, and fossil fuel burning could have adverse effects on human and animal health, environment and climate change. Thus, the sustainable management of the N cycle is of great relevance for our food security, health, ecology, environment, economy and development.

We live in a world surrounded by N gas but more than 99% of this N is not available to more than 99% of living organisms, and needs to be converted into more "reactive" forms (Nr). The natural processes of the generation of Nr, such as lightning, N_2-fixation by free-living and symbiotic bacteria in non-legumes and legumes are very limited. But it is the anthopogenic addition of Nr through fertilizer losses, pulses production, sewage, industrial and automobile exhausts etc., that far exceeds the natural processes of changing Nr into less reactive N_2, leading to concerns of accumulation, especially in the last half of this century.[1] The need to limit the anthropogenic perturbation of the natural N cycle and its sustainable management is now attracting increased attention from scientists, environmentalists, government and industry as well as international bodies. The accumulation of Nr can be limited by the more judicious and efficient application of N fertilizer in agriculture, limiting emissions from fossil fuel burning and by better management of wetland ecosystems that return N to the atmosphere in its nearly inert or unreactive form, N_2. In fact, it is the duty of the scientific community to provide policy makers with reliable estimates of reactive N transfers between different ecosystems and economic sectors, and to describe balanced, cost-effective and feasible strategies and policies for the sustainable management of the N cycle for food security, health, environment and development.

2 Nitrogen Economy in a Terrestrial System

Nitrogen in the soil comes from the atmosphere and is in the form of a strongly bonded gaseous molecule (N_2) which is about 79.08% by volume. The cycling of P and sulphur is also very closely associated with chemical N transformation. The soil get N through the fixation of molecular N_2 by microorganisms and from the return of ammonia and nitrate in rainwater. The exit of N from the soil is through crop removal, leaching and volatilization. The transformation of molecular form of N to combined forms occurs through biological N. Organic forms of N, in turn, are converted to NH_3 and nitrate by a process called mineralization. The conversion to NH_3 is termed ammonification and the oxidation of this compound to NO_3 is termed nitrification. The entrapping of NH_3 and nitrate by plants and organisms constitutes assimilation and immobilization, respectively. Animals receive the N they need for metabolism, growth, and reproduction by the consumption of living or dead organic matter containing molecules composed partially of N. The combined N is ultimately returned to the atmosphere as molecular N_2 through biological denitrification, thereby completing the cycle. The N cycle represents one of the most important nutrient cycles found in terrestrial ecosystems. Using data from different sources, Velmurugan et al.[2] attempted to quantify the different N fluxes involved in the N cycle in agroecosystems in India. The data shown in Figure 1 were worked out for the 1995–96 reference period. In the absence of reliable quantitative studies, large uncertainties were associated with many estimates shown in Figure 1, but these seem to be very good estimates to begin with. As more recent, robust and comprehensive indigenous data become available, a better quantification of the different processes of the Indian N cycle and a more precise understanding of its cascade effects will become possible in the years to come.

3 Biologically Versus Synthetically Fixed Reactive Nitrogen in Agroecosystems

Before the advent of N fertilizers, farmers used to maintain 25 to 50% of their farm under legume crops, which regenerated soil fertility through the 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. Some legume crop rotations have shown low N use efficiency similar to cereals that take up 50% or less of the N applied as N fertilizers.[3] This can be attributed to the mismatch between the timing of the nutrient supply and demand in annual cropping systems.

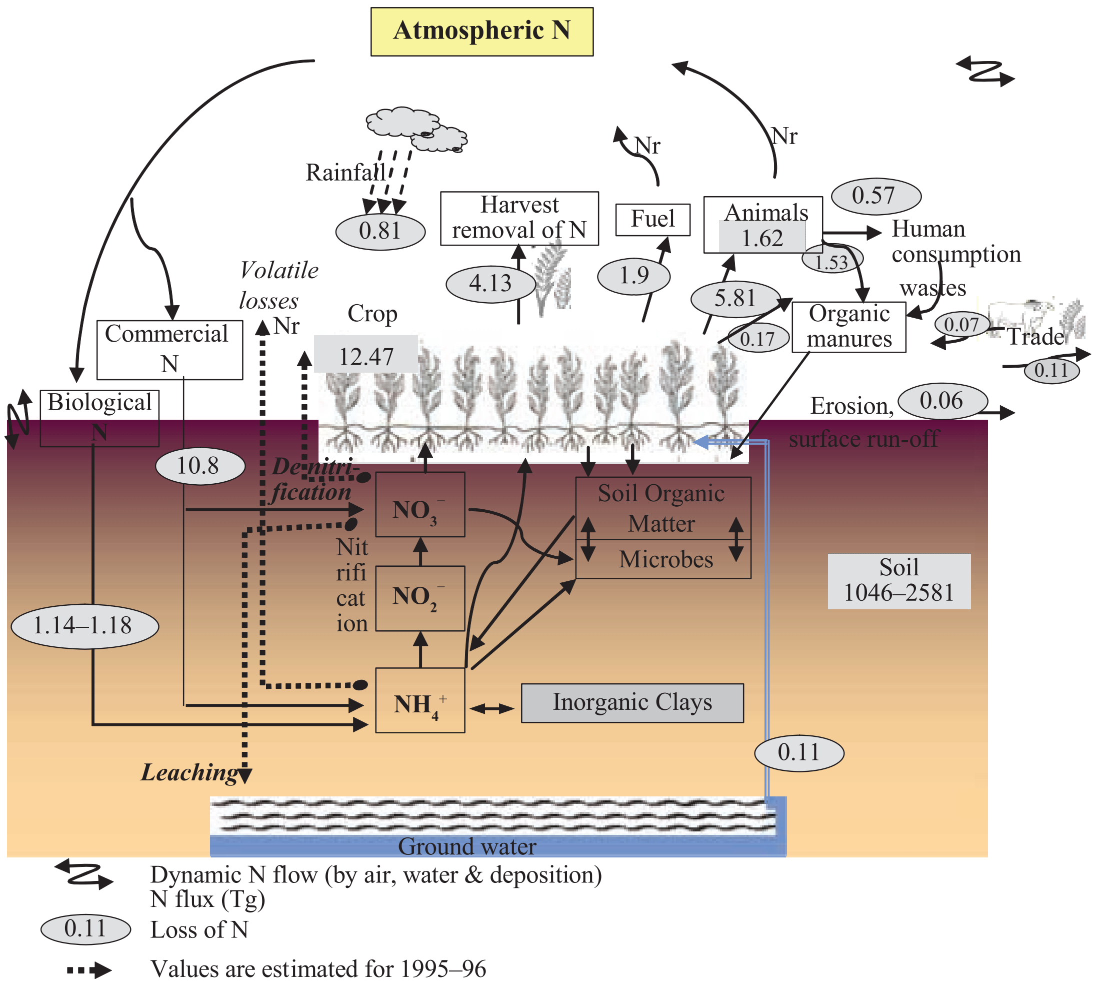

Figure 1: Nitrogen cycle in the agroecosystem.

It is generally argued that legume-based agroecosystems can maintain higher levels of synchrony between N supply and crop uptake than single or dual applications of N fertilizers,[4] but the data are not conclusive. 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.[5] Crews and Peoples[6] concluded that the ecological integrity of legume-based agroecosystems is marginally greater than that of fertilizer-based systems. Thus, there is no marked difference in N use efficiency between the two systems. N-budgeting from biological and synthetic N sources (Table 1) shows that out of 14.6 Tg of N as input from different sources, inorganic N fertilizers constituted the major percentage while fodder and feed accounted for the major percentage of total outputs.

Sufficient data does not exist to state conclusively that legume-N is less susceptible to ammonia volatilization than fertilizer N.[6] Nitrate leaching has been found to occur in both fertilized and

Table 1: Soil surface-N balance (Tg) for agricultural land of India.

India (1995 production level)	N source Tg N
Input	
Inorganic N fertilizier	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	**14.56–14.60**
Out puts	
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**

Source: Velmurugan et al. (2008).

legume-based cropping systems.[3] However, when leguminous crops are allowed to grow throughout the fallow season, these not only fix N, but also scavenge soil available N. Although there are relatively few studies that have directly compared nitrate leaching in legume and fertilizer-based systems, yet limited evidence suggests that, in some cases, nitrate leaching may be reduced when N is supplied by legumes rather than N fertilizers.[6] 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.[7] Little difference between legume and fertilizer-based agricultures has been reported for N_2O emissions. In a literature review of N_2O emissions from 87 different agricultural soils, Bouwman[8] reported fluxes ranging between 0 and 4 kg N ha^{-1} $year^{-1}$ for unfertilized control plots. Fields planted with legumes were found to maintain N_2O fluxes as low as 0–0.07 kg N per ha per year.[9]

4 Nitrogen Losses from Agricultural Fields

The pattern of global fertilizer consumption has also changed markedly over the past 30–40 years. In 1960, developing countries accounted for 12% of total fertilizer consumption and this has now increased to 60%. Asia accounts for 50% of world fertilizer consumption and 86% amongst consumption of the developing countries. Fertilizer application rates vary widely among the major world regions, from a low of 10 kg ha^{-1} in Sub-Saharan Africa to a high of about 216 kg ha^{-1} in East Asia.[10] The global N fertilizer demand is projected to expand at an annual rate of 1.7% reaching 94.6 Mt in 2008.[11] Consequently, N losses have also increased. The low recovery of N in annual crops is associated with its loss by volatilization, leaching, surface runoff and denitrification which not only lead to high costs of production but also to environment pollution (Fig. 2).

4.1 *Leaching*

The leaching of N in the form of NO_3^- beyond the soil profile is one of the major mechanisms of N lost in rice-wheat systems, especially in light-textured soils. The magnitude of the N loss depends upon soil characteristics, management practices, agro-climatic conditions and the type and method of N use. The time taken by NO_3^- to move from the root zone to the water-table, therefore, varies considerably. In sandy soils characterized by high percolation rates and shallow water tables with high rates of N application, NO_3^- may reach the water table in a matter of days with irrigation or rainwater. Conversely, in heavy soils with deep water tables, low rainfall conditions and low rates of N application create conditions whereby NO_3^- may take more time to reach the groundwater. In lowland rice fields with fine-textured soils, the leaching losses of N are low because of restricted percolation, whereas the losses from coarse-textured permeable soils can be substantial. In lowland rice-upland cropping systems (rice-wheat cropping system, RWCS), N loss can be high.

The drying of soil that normally occurs in paddy fields as the crop approaches maturity and also in upland crops such as wheat, favours nitrification. Nitrate-N which remains in the soil after the harvesting of paddy, and its accumulation

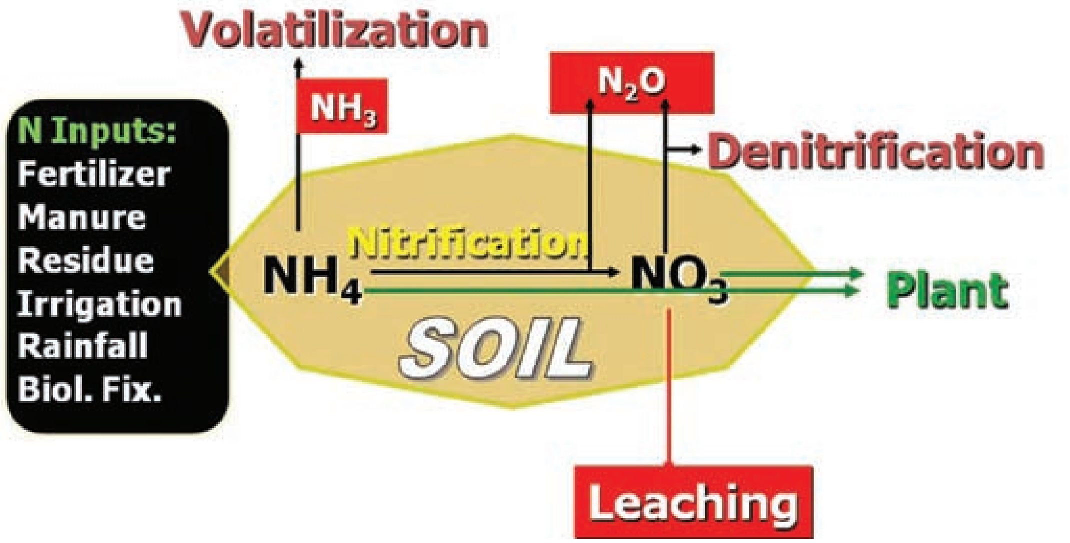

Figure 2: Nitrogen losses in environment.

during the subsequent fallow period is prone to losses by denitrification and leaching when the soil is again flooded.[12] Considerable attention has been paid the world over, particularly in developed countries on the leaching of nitrate. In developing countries of south Asia, however, its importance has been felt recently because of sporadic reports of NO_3^- enrichment in groundwater in a few agriculturally intensive rice-wheat areas.[13] However, such sporadic incidents of high NO_3-N contamination in groundwater may be related more to a sewage-sewerage, dumping of organic wastes rather than agricultural N fertilization barring a few sites where the soil is highly coarse textured and hence, permeable. The leaching loss of nitrate can be minimized by increasing the efficiency of water use by crop plants, particularly rice. The use of slow-release fertilizers and nitrification inhibitors and the puddling of rice fields are other alternatives of reducing leaching losses.[14]

4.2 *Ammonia volatilization*

Urea is the most widely used N fertilizer in the rice-wheat cropping system. Once urea is applied to the moist soil, it rapidly hydrolyses under subtropical conditions and most of the hydrolysis is completed within 2–4 days. The factors affecting ammonia volatilization are pH, the NH_4^+ content of soil and the temperature of the floodwater, algal and aquatic weed growth, crop growth, and soil properties.[15] Different forms of urea have been reported to release ammonia when applied to the soil. Sudhakara and Prasad[16] reported that the cumulative ammonia volatilization loss over a week after the application of 120 kg N ha^{-1} was 8.4% with prilled urea, 3.3% with urea super granules (USG), 2.9% with neem-coated USG and 2.6% with dicyandiamide (DCD) coated USG.

About 85% of the world's rice-cropped area is under wetland culture. Ammonia volatilization losses occur mostly in flooded rice soils which are moderately to slightly acidic in nature, although losses are higher in alkaline soils.[17] Volatilization losses in the flooded soils range from negligible to almost 60% of the applied N.[18] However, some losses were also reported from upland culture. Sarkar et al.[19] reported a loss of 15–20% of applied fertilizer N to wheat due to ammonia volatilization. Banerjee et al.[20] reported a volatilization loss ranging from 1 to 69 kg N ha^{-1} from the RWCS of North India depending upon fertilizer management practices, while Pathak et al.[21] observed that volatilization accounted for 5–31 kg N ha^{-1} in the RWCS in different transects of the (IGP). Once ammonia is emitted from agricultural systems, it may be transported and deposited in gaseous or dissolved forms to downwind terrestrial and aquatic ecosystems thus causing eutrophication.[22] Eutrophication (over-enrichment in nutrients) brings many undesirable changes which are harmful for aquatic flora and fauna. The volatilization loss can be minimized in the soil-water system by the application of soluble salts of calcium, potassium and magnesium; the use of urease and algal inhibitors; the deep placement of N fertilizers; and the use of modified forms of urea and slow-release fertilizers.

4.3 *Denitrification*

Denitrification occurs when NO_3^- is present under anaerobic conditions in the soil. This may occur where oxygen diffusion is impeded by water at the centres of soil aggregates or in water-saturated regions or wherever the local oxygen demand is exceptionally high. The formation of a thick reducing zone within the flooded soils of rice fields favours denitrification. Although the basic processes underlying denitrification have been studied extensively and are well understood, its quantification in the field remains a major problem. Direct measurement is logistically difficult and such data are, therefore, scarce. On an average, a loss of about 25 kg N ha^{-1} with the application of 120 kg N ha^{-1} is generally reported. Aulakh et al.[23] estimated that 23–33% of the N applied through fertilizer is lost *via* denitrification during rice cultivation. Denitrification loss is the highest under alternate flooding and drying, a condition under which most irrigated rice in north India is grown.[12] In addition to the loss processes mentioned above some fertilizer N can be lost due to runoff, especially in the *kharif* season when heavy monsoon rains occur in hilly regions, such as Himachal Pradesh and Uttrakhand in India.

The major problems due to the denitrification process are that a considerable amount of nitric and nitrous oxides are emitted into the atmosphere. Nitric oxide contributes to the formation of tropospheric ozone, a major atmospheric pollutant that affects human health, agricultural crops, and natural ecosystems while nitrous oxide is 300 times more potent than CO_2 in causing global warming.[24] Denitrification losses can be reduced by using nitrification inhibitors like DCD, iron pyrite, nitrapyrin, phenylacetylene, encapsulated calcium carbide, terrazole, etc.

5 Nitrogen Loss from Fossil Fuels in Industry, Transport and Energy Production

Fossil fuel combustion is a major source of NO_x inputs to the atmosphere. There are two broad categories of sources for these emissions. Thermal NO_x is generated by the oxidation of diatomic N as a by-product of combustion. In the second category, fuel NO_x is formed when the N contained in the organic compounds that comprise fossil fuels is released to the atmosphere. While thermal NO_x is dominant for fuels with low N content such as natural gas and petroleum distillates, fuel NO_x which accounts for 50–90% of emissions, is associated with heavier fuels such as residual oil and coal containing between 0.3 and 3.0% N by weight.[25] Estimations of NO_x emissions are often not subject to direct measurement but are instead inferred from data on the fuel use. The consumption of different energy carriers such as hard coal, lignite, gasoline, residual fuel oil, natural gas, is multiplied by average emission coefficients derived from field observations and/or laboratory studies.[26] This approach is useful in generating order-of-magnitude emission estimates, but is unable to account for the role of specific technologies in mediating the relationship between fuel use and NO_x emissions. This method, however, is often the best that can be used to estimate NO_x emissions in developing countries, where disaggregated data on the disposition of fuel consumption by end use or process are often of low quality or are entirely lacking.[27]

Garg et al.[28] attempted to provide aggregated energy consumption of major fuel categories in India during 1985–2005. These data, as listed in Table 2 along with default emission factors for different source categories,[29] were used by Garg et al.[28] as the basis for working out NO_x emissions from the energy sector. Wherever possible, India-specific emission factors were used. The NO_x emissions from mobile vehicles are related to the air–fuel mix, combustion temperatures and the pollution control devices installed in the vehicle. Diesel vehicles emit more NO_x as compared to petrol-driven vehicles. NO_x emissions from heavy-duty vehicles is significantly higher than those for cars and light commercial vehicles. Other than these fossil fuel combustion source categories for NO_x emissions, the production of nitric acid is the main non-energy source of NO_x emissions.[28] Nitric acid is produced from the catalytic oxidation of ammonia, and N oxides are released in the process. The emissions are estimated from the amount of nitric acid produced.

Data pertaining to the NO_x emissions in India as listed in Table 3 reveal that around 2.11 Tg NO_x were emitted in 1985 and these increased at a rate of about 4.5% per annum between 1985–2005.[28] Coal (mainly in the power generation sector) and oil combustion have almost equal shares in the total NO_x emissions. The road transport sector is the predominant source of NO_x emissions and contributed 34% to Indian emissions in 2005. Emissions from diesel combustion in the transport sector have more than doubled during 1985–2000. Power generation and industry are the next largest contributors. An analysis of changing sectoral NO_x emission shares during 1985–2005 indicates an increase in the power sector share from 18 to 30% and road transport from 25 to 33%.[28] On theother hand, the emission share of biomass burning has declined from 28 to 15%, other industries from 10 to 6% and railways from 6 to 3%. It must be noted here that absolute emissions from all these sources have increased during this period. Differential growth rates result in changing emission shares.

6 Livestock- and Human-Excreted Nitrogen and its Ammonia Volatilization

Nitrogen in Asia was transferred to the atmosphere by NH_3 volatilization at a rate of ~4.6 Tg N year^{-1} in 1961 and this increased to ~13.8 Tg N

Table 2: Energy consumption during 1985–2005 in India (Garg et al., 2006).

Fuel type	Units	1985	1990	1995	2000	2005
Bituminous coal	Tg	116.7	165.8	231.2	289	347
Lignite	Tg	8.1	13.8	21.8	22.7	31
Coking coal	Tg	36.5	47.7	51.9	51.6	56.2
Natural gas	BCM$_a$	4.2	10.9	19.1	23.3	31
Oil products	Tg	43.3	58.6	78.8	108.8	132
Motor gasoline	Tg	2.3	3.5	4.7	6.6	9
Diesel	Tg	15.9	23.6	34.9	42.0	43
Kerosene	Tg	6.2	8.4	9.9	11.3	12.6
Heavy fuel oil	Tg	9.6	10.8	12.9	16.2	18.6

Source: Synthesized and compiled from CMIE (2000, 2005), OCC (1998), INC (2004) Enerdata database; IEA (2003); BCM (Billion Cubic Meter).

Table 3: NOx emissions from different sectors in India (Tg–NOx).

Source categories	1985	1990	1995	2000	2005	CAGR % (1985–2005)
Power	0.377	0.620	0.964	1.283	1.547	7.3
Road	0.520	0.670	0.985	1.380	1.696	6.1
Rail	0.120	0.101	0.100	0.110	0.132	0.5
Navigation	0.010	0.012	0.014	0.018	0.023	4.3
Aviation	0.018	0.024	0.033	0.042	0.051	5.4
Cement	0.040	0.060	0.085	0.116	0.148	6.7
Steel	0.123	0.152	0.181	0.206	0.231	3.2
Brick	0.078	0.094	0.109	0.133	0.165	3.8
Other industries	0.204	0.229	0.263	0.287	0.315	2.2
Biomass burning	0.586	0.633	0.670	0.670	0.630	0.5
Nitric acid production	0.002	0.004	0.006	0.011	0.013	9.8
Other sectors	0.030	0.040	0.046	0.049	0.051	2.7
All India (Tg NOx)	2.11	2.64	3.46	4.31	5.02	4.4

Source: Garg et al. (2006).

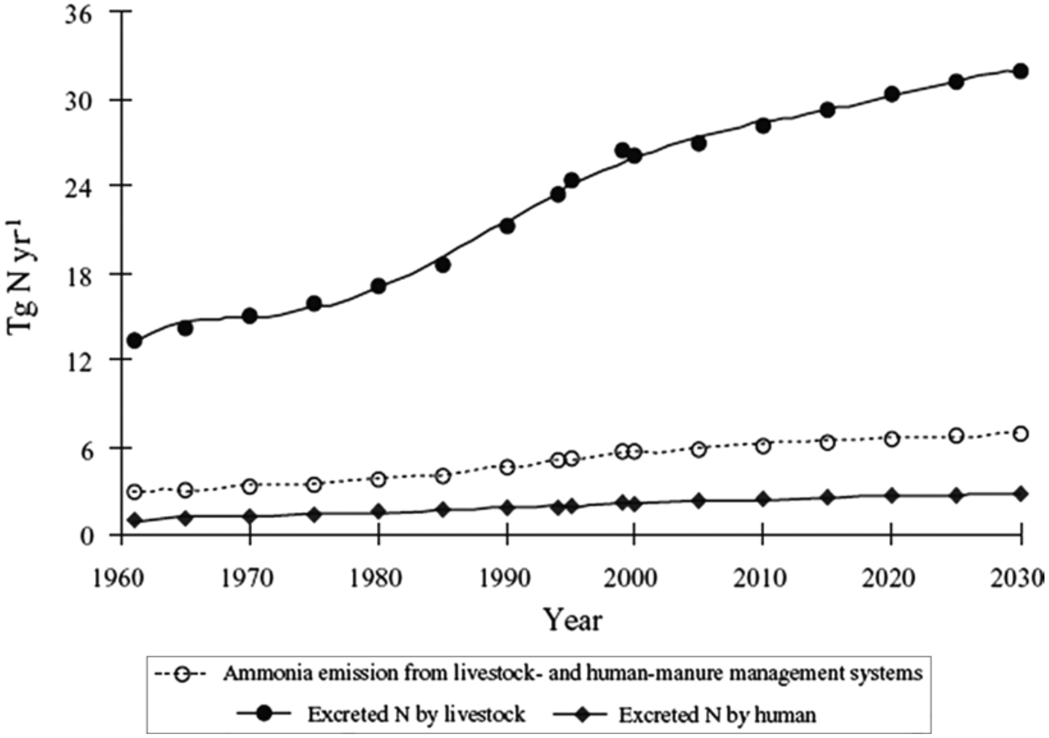

Figure 3: Livestock- and human-excreted nitrogen and its ammonia volatilization in Asia (*Source:* Zheng et al. 2002).

year^{-1} in 2000.[30] It is expected to reach ~18.9 Tg N year^{-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 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 to downwind terrestrial lands at a rate ranging from 3.8 Tg N year^{-1} in 1961 to 15.7 Tg N year^{-1} in 2030, while the deposition to coastal waters stands at a rate of 0.8–3.4 Tg N year^{-1} over 1961–2030.

According to estimates given by Zheng et al.[30] for human-excreted N, the temporal variation in livestock-excreted N is an indicator of the growth of animal husbandry in Asia. As Figure 3 shows, livestock production developed very rapidly in the

Table 4: Ammonia and nitrous oxide emmission from livestock waste—a comparison between different studies under Indian perspective (Aneja et al., 2010).

		Aneja et al. (2010)	Yamaji et al. (2004)	Oliver et al. (1998)[c]	Zhao & Wang (1994)[c]	
Pollutant	Category	2003	2000	1990	1990	EDGAR[c] 1995
NH_3	Livestock waste	1392	1300			
	Application[a]	1700[a]	–	3756	4100	–
N_2O	Livestock waste	136	143			
	Application[b]	83[b]	–	185	–	200

[a] Ammonia emissions from application of wastes to agricultural lands (Yan *et al.*, 2003).
[b] Nitrous oxide emissions from application of wastes to agricultural lands (Yan *et al.*, 2003).
[c] Emissions from all stage of animal wastes treatment. These values are equal to the sum of waste and application (http://www.rivm.nl/bibliotheek/rapporten/773301001.pdf).
IPCC emissions estimates for agricultural sources in India in 2000.
Ammonia: 3,450 Gg NH3/yr (or 2,840 Gg NH3-N/yr).
Nitrous oxide: 465 Gg N2O/yr (or 296 Gg N2O-N/yr).
Based on IPCC, 2009, RCP Database, version 2.0.5. http://www.iiasa.ac.at/web-apps/tnt/RcpD.

1980s–1990s. But its development rate in the coming decades is expected to be slower and almost equal to that of the 1960s–1970s. The total amount of ammonia as well as N_2O lost from livestock has been estimated to be 1392 Gg NH_3-N and 136 Gg N_2O-N per year under Indian conditions keeping the base year 2003.[31] Table 4 presents N_2O and NH_3-N emmissions from livestock excreta used as manure by various groups of workers at different time intervals.

7 Strategies for Sustainable Nitrogen Use in Indian Agriculture

7.1 *N-efficient genotypes for N management*

The selection of genotypes with a more efficient mechanism of N uptake and metabolism is a strategy aimed at increasing the N utilization efficiency of the crop. Experiments for the efficient use of N under conditions of low N availability have been carried out with wheat [32] and maize.[33] In order to characterize and select genotypes for the efficient use of N, several authors have used physiological and biochemical parameters. To provide a scientific basis to management technologies aimed at maximizing NUE, a series of investigations were conducted by Abrol and his group on the main shoot of field-grown wheat (*Triticum aestivum* L.) to determine the relationship between the supply of N fertilizer in the sequentially formed laminae and the demand (potential) for its utilization/assimilation. It was observed that earlier formed laminae had close to maximal assimilatory activity as determined by the in *vivo* method. There was a gradual decline in its activity with the lowest in the flag lamina.[34] The placement of laminae in 15 mM NO_3^- in Hoagland's solution after cutting it at the basal end, revealed an enhancement in the assimilatory activity primarily of the upper laminae. Further, this observation confirmed that at later stages of growth, it is the availability of nitrate and/or its uptake which is the constraint[35] (Fig. 4). Abrol[36] also calculated the total potential of each lamina to assimilate nitrate by taking into consideration the size (area) and its duration in days. Despite low nitrate assimilation and the possibly poor availability of nitrate at later stages of growth, the upper laminae reduced most of the nitrate. It was confirmed on the basis of subsequent experiments that nitrate is taken up at the early stages of growth, and stored in the stem, leaf sheath and petioles. It is subsequently assimilated by the upper laminae.

By the split application of N fertilizers or use of the slow release fertilizers, the NUE in terms of N accumulation can be improved. Abrol[36] screened a large number of wheat genotypes for nitrate assimilatory activity and observed a 2–3 fold variation. Further, it was shown that high nitrate reductase (HNR) activity was reflected in enhanced NR activity in all the sequentially formed laminae (which account for approximately 65% of total nitrate assimilated as calculated by the integration of the *in vivo* method).[37] There was a higher potential for the total nitrate reduced in the HNR cultivars such as HD 2177 and HD 2204 compared to low nitrate reductase (LNR) ones such as Pusa Lerma and UP 301.[38] High NR activity was associated with either enhanced accumulation for total N which may or may not be associated with an increase in biomass and/or yield.[36] The availability

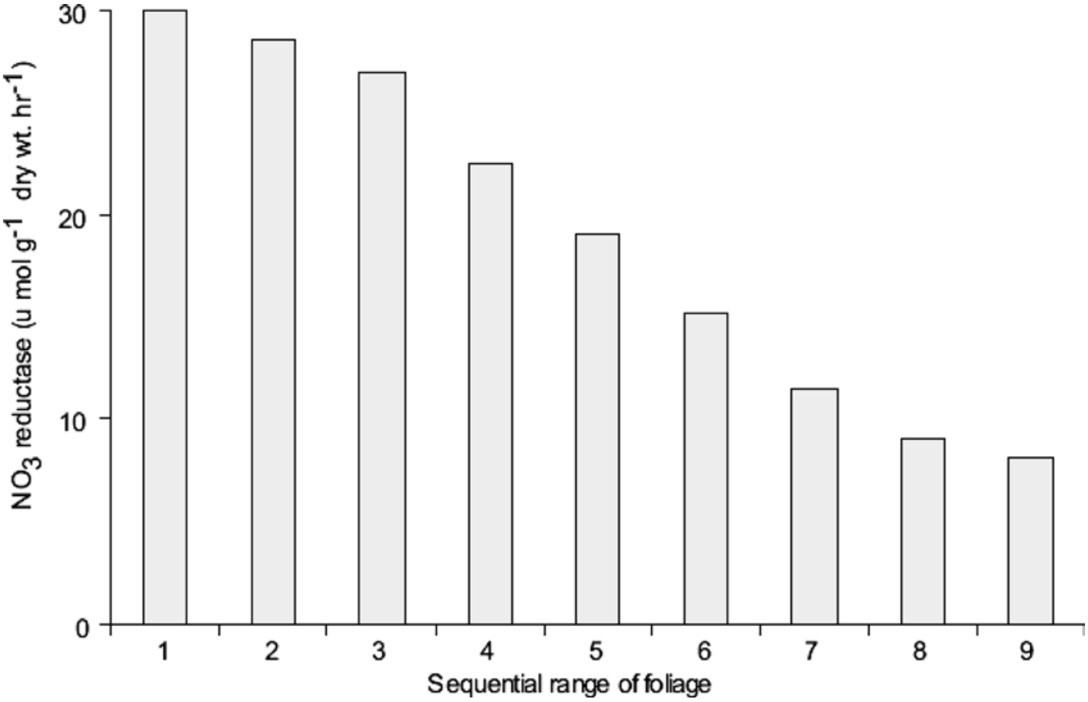

Figure 4: Mean in vivo NR activity of the laminae on the main shoot. Each value is a mean of 3 values at full expansion (Abrol, 1990).

of N at later stages of growth coupled with HNR types was more beneficial than its association with LNR types.[36,39] In the laminae, HNR was associated with lower nitrate content. This observation had relevance to a selection of genotypes with low nitrate content in leafy vegetables, fodder crops and so on.[40] The HNR genotypes were associated, in contrast to transgenics with the over-expression of NR, with the co-ordinated expression of all enzymes of the nitrate assimilatory pathway.[41]

N-efficient and N-inefficient wheat genotypes were identified on the basis of the differential response of wheat genotypes with low (1 mM) and high (25 mM) N (N) supply.[32] Growth performance, measured in terms of fresh weight, dry weight and length of root and shoot, was higher in N-efficient than N-inefficient wheat genotypes at low N levels. Interestingly, although the growth of N-efficient genotypes did not show any change with an increasing level of N supply, there was a marked increase in the growth of N-inefficient genotypes with an increase in the N level. Thus, the development of a wheat genotype that can make the best use of N in low N soils is essential for the sustainability of agriculture.[42,43]

7.2 *Biofertlizers for efficient nitrogen use in sustainable agriculture*

Certain micro-organisms like bacteria and blue-green algae have the ability to use atmospheric N and taxi this nutrient to the crop plants. Some of these 'N fixers' like rhizobia are obligate symbionts in leguminous plants, while others colonize the root zones and fix N to a loose association with the plants. A very important bacterium of the latter category is *Azospirillum*, which was discovered by a Brazilian scientist and which made headlines in the mid 1970s. The crops which respond to *Azospirillum* inoculation in India are maize, barley, oats, sorghum, pearlmillet and forage and other crops. *Azospirillum* applications increase the grain productivity of cereals by 5–20%, millets by 30% and fodder by over 50%. The third group includes free-living N fixers such as blue-green algae and *Azotobacter*. Mycorrhizal fungi and plant growth promoting rhizobacteria have also been shown to have agronomical implications.[44,45]

The most widely used biofertiliser for pulse crops is *Rhizobium* which colonizes the roots of specific legumes to form tumor-like growths called root nodules. The *Rhizobium*-legume association can fix upto 100–200 kg N per hectare in one crop season and, in certain situations, can leave behind substantial N for the following crop. Adequate information on seed inoculation procedures and crop responses is available.[46] Stem-nodulating legumes such as *Sesbania rostrata*, *Aeschynomene* sp. and *Neptunia oleracea* have become popular in improving soil fertility. The N–fixing bacteria associated with such stem nodulating legumes belong to *Azorhizobium* and the fast growing species of *Rhizobium*. The N-accumulating potential of stem nodulating legumes under flooded conditions ranges from 41–200 kg N/ha.[47] Besides flood tolerance, other features, including the susceptibility of the N-fixing potential of stem-nodules to adverse soil conditions, made them ideal candidates for use as green manure in flooded rice soils. Legumes are known to leave a considerable amount of residual N in the soil which benefits the subsequent cereal crop. These benefits however, depend on the purpose for which the legume crop is taken i.e. grain, fodder or green manure.

The beneficial effects of free-living N-fixers, *Azotobacter*, on cereals, millets, vegetables, cotton and sugarcane under both irrigated and rainfed field conditions, have been well substantiated and documented. The application of this biofertiliser has been found to increase the yield of wheat, maize, cotton and mustard upto 30% over controls. Apart from N, this organism is also capable of producing antibacterial and antifungal compounds, hormones and siderophores.[48]

The utilization of blue-green algae as a biofertiliser for rice is very promising. A judicious use of these algae could provide to the country's entire rice acreage as much N as obtained from 15–17 lakh tones of urea. Methods have been developed for the mass production of algal biofertiliser and it is becoming popular among the rice growers in many parts of India.[49] Recent researchers have shown that algae also help to reduce soil alkalinity and this opens up possibilities for the bioreclamation of such inhospitable environments. This area is of particular relevance, because seven million hectares of arable land in India are salt affected.

A small floating water fern, *Azolla,* is commonly seen in low-land rice fields and in shallow freshwater bodies. This fern harbours a blue-green alga, *Anabaena azollae*. The *Azolla-Anabaena* association is a live floating N factory using energy from photosynthesis to fix the atmospheric N amount to 100–150 kg per hectare per year from about 40–60 tonnes of biomass.[50] Reports of its current use as a biofertiliser for rice in China, Vietnam, Indonesia, Thailand and other East and South Asian countries are available. An integrated system of rice-*Azolla*-Fish has been developed in China.

7.3 *Green manuring crops for efficient nitrogen supply*

A green manuring (GM) crop can be defined as a crop grown for the purpose of being ploughed into the soil while still green, or soon after maturity, for soil improvement. These crops are also referred to as fertility building crops which include many types of algae and azolla, legumes and non-legume crops, loppings of perennial woody trees and certain weeds. Among these, legumes are superior GM crops because they fix atmospheric N. Non-legumes as GMs are relatively of less importance in India. There are several hundred species of tropical legumes, but only a fraction of these have been studied for their potential as GMs. GM crops should have some important characteristics in order to be agronomically attractive and economically viable. These characteristics include rapid growth, production of sufficient biomass and fixing of adequate N. They require very few and require minimum cultural practices during the growth period so that they are relatively economical to produce. A legume with leafy growth and succulent foliage which is able to suppress weeds and nodulate profusely would be the best choice for a GM.[51] Other important agronomic and physiological attributes of GM plants are: early establishment and high seedling vigour, early onset of BNF and its efficient sustenance, photoperiod-insensitiveness, high-N content, tolerance to water stress (excess or deficit), pests and diseases and adverse soil conditions, ease of incorporation and good yield of highly viable seeds. Commonly used GM crops in India with their potential to supply total N are listed in Table 5.

The most commonly used tropical GM legumes belong to the genera *Crotalaria* (sun hemp), *Glycine* (soybean), *Indigofera* (indigo), *Mucuna* (velvetbean), *Vigna* (cowpea and mungbean), *Cajanus* (pigeonpea), *Cyamposis* (clusterbean) and *Sesbania* (root nodulating and stem nodulating). Sesbania can add 15–25 t biomass ha^{-1} in 50–60 days.

Table 5: Biomass and N-accumulation of GMs in India (Singh et al., 2010).

Green-manure crop	Age (days)	Dry matter (t ha^{-1})	N accumulated (Kg ha^{-1})
S. aculeata	60	[a]4.6	133
Sun hemp	60	[a]6.1	134
Sun hemp	42	4.4	99
	56	6.6	140
Sun hemp	49	3.4	74
Sun hemp	56	[a]3.3	120
S. aculeata	56	[a]2.9	76
Sun hemp	50	2.0	98
S. aculeata	50	[a]3.8	81
Sun hemp	60	4.6	78
S. aculeata	60	2.9	57
S. aculeata	42	3.2	80

(*Continued*)

Table 5: (Continued).

Green-manure crop	Age (days)	Dry matter (t ha^{-1})	N accumulated (Kg ha^{-1})
	49	3.9	96
S. aculeata	49	3.9	84
S. cannabina	45	3.1	98
	55	5.3	147
	65	7.3	163
S. aculeata	52	3.5	99
	57	5.1	106
S. aculeata	45	2.5	53
S. aculeata	50	3.8	112
S. aculeata	45	4.7	116
S. aculeata	56	3.7	98
Sun hemp	58	4.8	149
Sun hemp	60	5.4	110
S. aculeata	50	4.7	85
	60	5.9	131
Sun hemp	50	3.4	68
	60	5.3	110
S. aculeate	53	2.9	57
Sun hemp	53	4.6	78
S. aculeata	50	4.2	89
Sun hemp	45	3.5	77
	60	6.2	121
Sun hemp	60	[a]3.4	159
S. aculeata	60	[a]5.3	185
S. aculeata	55	4.8	131
S. aculeata	50	4.7	85
	60	5.9	131
Sun hemp	50	3.4	68
	600	5.3	110
S. rostrata	50	5.0	96
	60	6.1	145
S. rostrata	60	[a]5.0	219
Mungbean	49	1.9	42
Clusterbean	49	1.3	25
Cowpea	56	[a]2.0	38
I. tinctoria	56	1.7	54
P. mungo	50	[a]2.8	68
P. radiata	50	[a]2.7	60
Cowpea	49	4.4	99
Clusterbena	49	3.2	91
Cowpea	60	[a]4.6	74
Pillipesara	60	[a]5.0	102
Cowpea	60	6.9	113
T. purpurea	60	[a]3.4	115
P. trilobus	60	[a]3.5	126
Cowpea	60–70	3.3	45
Mungbean	60–65	2.8	47

[a] Dry matter us calculated as 20% of the fresh biomass.

Sun hemp is less tolerant to salinity, acidity and excess water than sesbania but it performs better in low rainfall and limited soil moisture areas. In South India, *Tephrosia purpurea* under drought conditions and Pillipesara (*Phaseolobus trilobus*) in erosion-prone areas have been found promising.[52] Another drought-tolerant GM suitable for rainfed rice is *Indigofera tinctoria,* which can contribute 62–122 kg N ha^{-1} to the succeeding rice crop, depending on soil, climate, and cropping conditions.[53] There is great scope for using this legume in traditional rice—wheat cropping system areas. The exploitation of fast growing stem-nodulating aquatic legumes like *S. rostrata* and *Aeschynomene afraspera* have opened up new ways of using GM legumes in rice. Within 45 days, *S. rostrata* can accumulate 110 kg N ha^{-1} and *A. afraspera* 90 kg N ha^{-1}.[54] Although *S. rostrata* has performed better in South India, it did not do well in northern India and failed to nodulate on the stem during the hot months of May and June.[55] These aquatic legumes can grow in flooded conditions and because of their stem nodules, the plants can continue to fix N_2 under submerged conditions. Their N_2-fixation is tolerant to applied fertilizer N.

A supply of N from GM crops is the commonly observed and the most economical benefit in crop production. The N-supplying potential of organic matter compared to that of inorganic fertilizers, and referred to as mineral fertilizer equivalent (MFE) or fertilizer N equivalent (FNE) has been regarded as the most useful index of organic material N efficiency. The FNE values of different GMs in wetland rice from various studies in India ranges from 34 to 148 kg ha^{-1}, but more typically are between 75 to 100 kg N ha^{-1} for 45–60 day old GM crops. Table 6 shows the FNE of various GM crops in rice cultivation. On an equal N basis, in many studies the efficiency of N from GM was equal to or more than that of fertilizer N.[56]

In order to realize the maximum benefits from green manuring, it is essential that GM crops be incorporated into the soil at a young age to ensure the adequate mineralization of N. The incorporation of 45–50 day old GMs has been found to be optimal to maintain soil fertility. The objective of GM management is to achieve the maximum biomass and N yields within the shortest period. The cultivation of a sole GM crop involves thorough land preparation, irrigation, and considerable labour.

7.4 Biological nitrification inhibition—identifying efficient crop cultivars for reducing nitrification loss

Ammonical fertilizer applied to soil is converted to nitrate *via* nitrite by biological oxidation which

Table 6: Fertilizer N equivalence of green manure in rice (Singh et al., 2010).

Green-manure crop	Age (days)	GM N (kg ha^{-1})	FNE (kg ha^{-1})
S. aculeata	–	23	34
S. aculeata	67	–	80
S. aculeata	50	–	80
S. aculeata	50	57	50
Sun hemp	50	78	75
S. cannabina	45–65	98–147	100–120
Mungbean/cowpea	40–45	74–86	80
S. rostrata	50	–	70
S. aculeata	45	109	123
S. aculeate/sun hemp	(a)	–	40–60
S. aculeata	56	98	45
Sun hemp	56	149	60
S. aculeate/sun hemp/cowpea	60	108–113	120
S.cannabina/cowpea/sun hemp	60	–	50–105
S. cannabina	48	–	80
S. rostrata	–	70	70
S. aculeate	60	–	90
S. aculeate	–	45–75	72
S. aculeate	–	97–150	136
Sun hemp	–	41–70	72
Sun hemp	–	121	148
Cowpea	–	55–80	98

is termed "nitrification". This process is carried out by two groups of chemo-lithotrophic bacteria, *Nitrosomonas* spp. and *Nitrobacter* spp. The loss of N during and following nitrification reduces the effectiveness of N fertilization and at the same time causes serious N pollution problems. Certain plant species possess the ability to release molecules/compounds from their roots that have a targeted suppressive effect on soil nitrifying bacteria,[57–60] thus inhibiting the nitrification process. This is called 'biological nitrification inhibition' (BNI). The BNI function can improve N uptake due to its inhibitory effects on nitrification, which in some situations could enhance agronomic NUE in production systems.[57] Several tropical forage grasses, cereal and legume crops have shown a wide range in the BNI-capacity.[61] Among the grasses, the highest BNI capacity was found in *Brachiaria* spp with a substantial genotypic variation in the BNI capacity of *Brachiaria humidicola*. Among the cultivated crop species, *P. maximum*, which is adapted to high N availability environments showed the least BNI capacity.[61] However, among the cereal crops, only sorghum showed a significant BNI capacity while other cereal crops including rice, maize, wheat and barley did not possess sufficient BNI capacity.[61,62]

It was observed that plants exhibited BNI only under low N availability; thus N-stress was found to be a major factor inducing BNI.[57,63] It was found that legumes do not show appreciable BNI capacity. In the case of legumes, it is likely that the BNI attribute would have little or no adaptive value due to their ability to fix N symbiotically. Conserving N may not offer as much of a comparative advantage for legumes as it might attract competition from non-legumes. The active principle or the compound identified as the nitrification inhibitor released from *Sorghum bicolor* is phenylpropanoid, methyl 3-(4-hydroxyphenyl) propionate (MHPP)[62] while *B. humidicola* exuded a cyclic diterpene termed a 'brachialactone'.[59]

From the field studies conducted at the Centro Internacional de Agricultura Tropical (CIAT), Palmira, Colombia, it was shown that in *B. humidicola* plots, there was a 90% decrease in ammonium oxidation rates within 3 years of establishment. This was due to the very low populations of nitrifier bacteria.[59] A comparison was made between legume (soybean) and forage grasses *Panicum maximum*, *B. humidicola* cv. Mulato in terms of the inhibition of N_2O emission. It was found that N_2O emission who suppressed to the extent of >90% in field plots of *B. humidicola*, compared to that from the field planted to soybean (Fig. 5). A negative relationship between the BNI capacity of the roots and N_2O emissions was found based on field monitoring of N_2O emissions over a three-year period in tropical pasture grasses that have a wide range in the BNI capacity in their roots (Fig. 6). Studies on BNI activity in wheat revealed that cultivated wheat lacks a BNI capacity, while the roots of a wild-wheat, *L. racemosus*, possess a high-BNI capacity[58,64] (Fig. 7). Inhibitors released from the roots of wild-wheat effectively suppressed soil nitrification for more than 60 d. Crossing between *L. racemosus* and cultivated wheat showed that the genes conferring a high-BNI capacity were located in chromosome Lr#n and could be successfully introduced into and expressed in cultivated wheat.[64,65] Thus, it may be possible to develop the next-generation of wheat cultivars with sufficient BNI-capacity in the roots to suppress soil nitrification in production systems based on wheat.[64]

7.5 *Controlled-release nitrogen fertilizers, nitrification inhibitors and urease inhibitors*

When the price of N fertilizer may increases due to the removal of subsidies and/or increased production costs, these fertilizers will remain an important source of plant N. Slow release N fertilizers viz. urea super-granules, coated urea like polymer, sulphur and lac-coated urea have great promise in providing improved synchrony. Several urease and nitrification inhibitors (N-serve, DCD, AM etc.) have been tested for their efficacy in arresting N losses from the soil.

Some natural products (Neem, Karanj) with coated urea are found to be effective besides being eco-friendly.[66,67] Most recently, the nitrification and urea hydrolysis inhibitory properties of some natural essential by-products have been evaluated.[66–68] This technology has two pronged benefits viz. promoting the cultivation of essential oil-bearing plants like *Mentha arvensis*, *Mentha spicata* etc. for domestic and export purposes, and utilizing the by-product (after extraction of

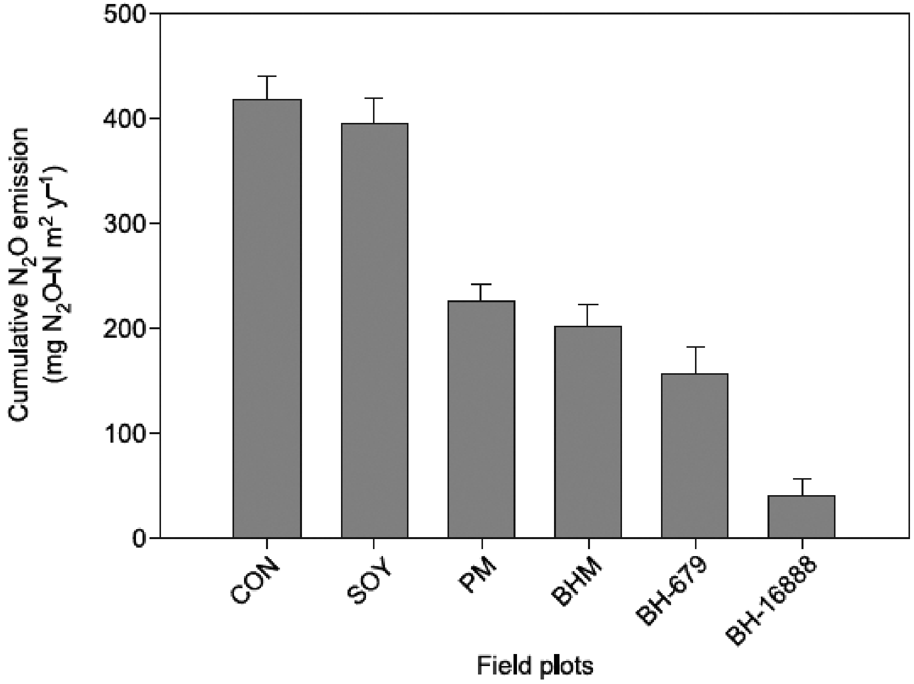

Figure 5: Soil ammonium oxidation rates (mg NO_2–N per kg of soil per day) in field plots planted with tropical pasture grasses (differing in BNI capacity) and soybean (lacking BNI capacity in roots) over 3 years from establishment of pastures (for soybean, during planting seasons every year, and after six seasons of cultivation) CON, control; SOY, soybean; PM, *Panicum maximum*; BHM, *B. humidicola* cv. Mulato; BH, genotypes of *B. humidicola* (Subbarao *et al.*, 2009a).

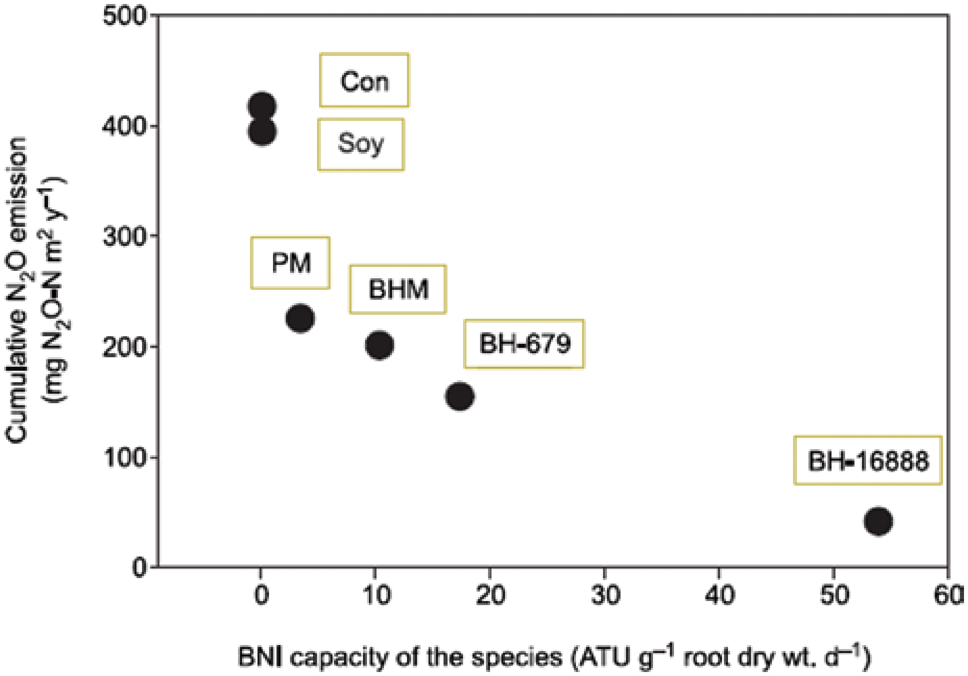

Figure 6: The relationship between the BNI capacity of plant species to the N_2O emissions from field plots. The N_2O emissions were monitored over a period of three years, Sept. 2004 to Nov. 2007 (Subbarao *et al.*, 2009).

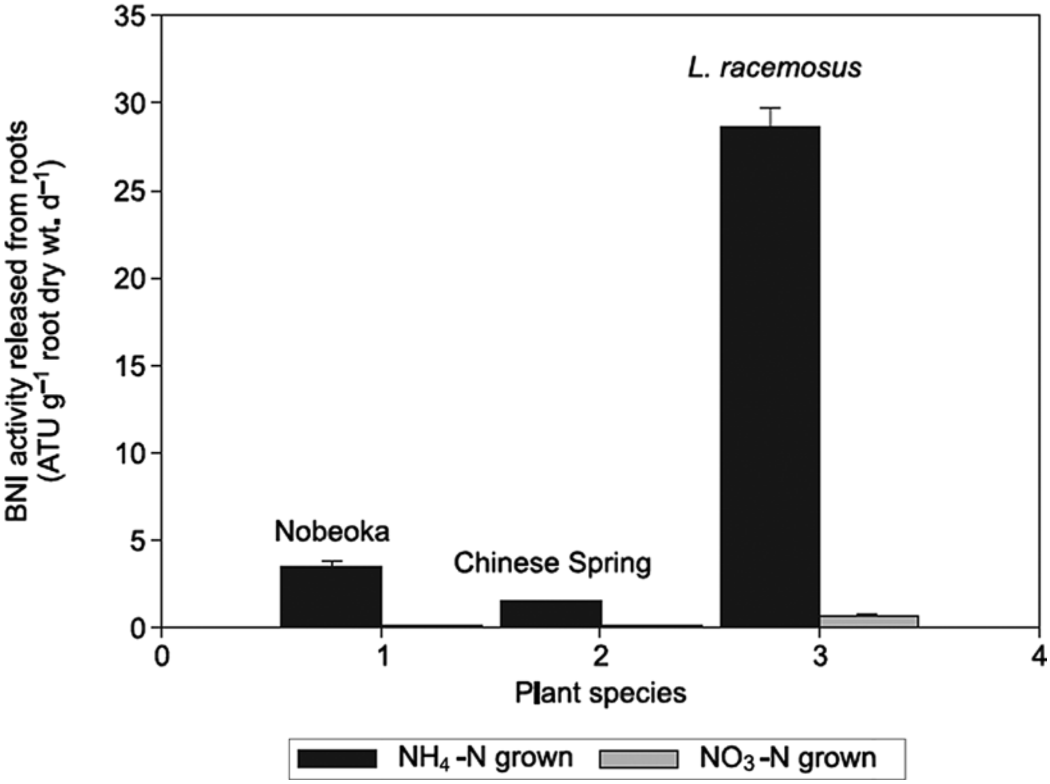

Figure 7: BNIs (biological nitrification inhibitors) released from roots (i.e. root exudates) of two cultivars of wheat and their wild relative *L. racemosus*; plants were grown with either NH_4^+ or NO_3^- as the nitrogen source. (Subbarao *et al.*, 2007c).

principal active ingredients) as potent urease and nitrification inhibitors. Under waterlogged paddy conditions in the Gangetic alluvial soils of UP, DMO (Dementholated mint oil) coated urea exhibited 25–30% higher N use efficiency as compared to plain urea applied @ 100 kg h^{-1}.[66]

7.6 *Split application of nitrogenous fertilizer*

The application of the same amount of N in more than two splits under field conditions increases the N availability at later stages of growth so that the suboptimal activity of the upper laminae can be exploited. It was observed that there was a significant improvement in the nitrate assimilatory activity of the upper laminae[69] and enhancement in the total N harvest and grain protein content. The magnitude of enhancement was higher in the high NR cv. compared to the low NR ones. The application of additional N at later stages of growth was also useful, as has been demonstrated by a number of studies. It needs to be mentioned that a high NR cultivar show a better response than a low NR cultivar at low soil N levels as well.[70]

7.7 *Need-based and location specific nitrogen management strategies*

For the optimization of an N dose to ensure higher N use efficiency and to achieve target productivity, several measures have been initiated; however, it needs elaborate study, both at on-station and on-farm locations.

Using 'Plant-based Tools' for 'Real-Time N management (RTNM)' and Site-Specific N management (SSNM) such as a chlorophyll/SPAD meter and a Leaf colour chart (LCC) could ensure N use efficiency by reducing N losses appreciably. The SPAD (soil-plant-analysis-development) meter is a simple portable instrument that measures the relative amount of leaf chlorophyll content. **SPAD-guided N management** can improve the congruence of N supply and crop demand simultaneously, resulting in a high grain yield and greater N use efficiency.[71] Moreover, by using SPAD, breeders and biotechnologists can choose N efficient lines and identify the genes responsible for high N use efficiency.[72] Despite having all these advantages, some of its demerits restrict widely its use and this needs further study. Whether the same SPAD threshold value can be used for a wide range of varieties and growing conditions needs to be studied further. Although SPAD-based N management enables the plant to become less susceptible to pre-mature lodging and more resistant to pest incidence, more experimental evidence authenticating this observation is needed.[71] *In lieu* of a high cost SPAD meter, a less costly ($1 per unit) tool, LCC has been developed by IRRI to measure the greenness of the leaf and relate it to plant N status. This is an ideal tool for need-based, location specific N management optimizing N use in rice. However, it also has a drawback; the inability to indicate the smaller variations in leaf greenness. Hence, the standardization of LCC with the SPAD meter is needed for their efficient use.

'Soil test crop response' based 'Target yield equation' is also an improved methodology for estimating the appropriate amount of N to be applied. This methodology can prescribe the appropriate N dose to achieve a yield depending on the initial N status of the soil; however, to be widely adopted and succesful. The farmers' accessibility for testing soils needs to be ascertained. Simultaneously, technical guidance should be provided to follow this methodology.

Improved crop management is believed to ensure better N utilization. Concurrently, environmental security following improved management practices deserves emphasis. The adverse consequences on the environment and human health due to excessive N use have already been stated. The major focus could be on water management as it relates substantially to N utilization. The rainfed rice ecosystem suffers from moisture stress, less moisture in uplands and excess moisture in lowland situations. N volatilization is the problem inupland situations, while leaching and runoff loss is the problem in lowland situations. Therefore, studies need to develop appropriate conditions under these situations so that these losses can be avoided or minimized. The moisture retentivity of upland soil needs to be improved either by surface bunding or by increasing soil organic matter content. On the other hand, studies on organic and inorganic N management ensuring better N sustainability under lowland situation can be conducted as an insurance against unforeseen eventualities due to excess water accumulation encountering N loss. Contrary to the studies required for creating an environment for proper N utilization in rainfed rice, saving N from undesirable loss may be a research issue in irrigated rice. When a proper utilization pattern poses a constraint to N use efficiency in rainfed rice, the draining of applied N is the problem in irrigated rice. This phenomenon not only escalates the application of high doses of N but also pollutes both the surface water bodies consisting of flora and fauna and ground water sources of drinking water. To resolve this problem, studies on controlled water management are warranted. Technology constituting aerobic rice cultivation, irrigation based on 'crop water stress index' needs to be developed.

Optical sensor-based N application is a site-specific fertilizer application system that uses the optical reflectance measurements of growing plants to estimate N fertilizer requirements. The advantage of this system is that it does not require the mapping of soils, soil testing or yield monitors. However, some basic steps are required to develop an optical sensor-based N application system. A sufficient amount of N to meet the growth requirement of the crop throughout the growing season is applied to a narrow strip of the field prior to planting. This is referred to as an 'N rich strip' (NRS). The planting of the crop in the fertilized NRS has to be done and once the crop is well established, optical reflectance readings are taken from the NRS area of the field. These measurements provide information that enable a comparison of N uptake from plants growing in the area of the field where N is not yield limiting to plants growing elsewhere in the field. The system possesses a self-propelled boom sprayer equipped with optical reflectance sensors, computers, and a global positioning device that is used to assist with steering the sprayer to prevent repeated applications on individual grids throughout the field. An algorithm programmed into the system's computers uses the sensor information from the NRS and sensor information from each grid of the field to determine the N treatment levels.[73] The intent of the algorithm is to determine the quantity of N to apply to each individual grid to achieve the plateau yield.[74] As the applicator moves across the field, the machine optically senses, computes the level of N, and treats individual grids with 28% liquid N solution on the go.

Given the substantial investment needed to further develop the system, and the potential environmental benefits from lower N applications, estimates of its relative economic value are considered necessary to understand what is needed for the system to be adopted. However, this technology is in the early developmental stage. The algorithm used to estimate N requirements should also consider economics. Fine-tuning the N fertilizer optimization algorithm in a way that incorporates the prices of N and crop produce may improve N recommendations, which could translate into additional net benefits to the farm operation. Field data for two years was shown to be sufficient to reliably establish yield potential prediction equations for winter wheat. Raun et al.[75] have successfully showed that using an optical sensor based algorithm that employs yield prediction and N responsiveness by location (0.4 m^2 resolution) can increase yields and decrease environmental contamination due to excessive N fertilization. Data based on mid-season N fertilizer rates on predicted yield potential and a response index can increase NUE by over 15% in winter wheat when compared to conventional methods.

8 Future Strategy

Efforts to improve energy efficiency, measured in terms of the services obtained per unit of fuel consumption, will be a major focus of environmental policy in India because the anthropogenic emissions of NOx are dominated by fossil fuel combustion. Changes in the N cycle through emissions of NOx in India as linked to the use of fossil fuel energy are likely to increase dramatically over the next several decades, unless there is a concerted effort to control fossil fuel consumption. Technological changes that either increase the efficiency of fuel combustion or remove N oxides from the exhaust stream should be able to reduce the total amount of N emitted, but complete solutions are closely linked to the development of non-polluting alternative energy sources.

For fertilizer N mangement, a three-fold option can be used for future strategy.

- **Need based** N management optimizing the N dose and increasing N use efficiency to reduce N applications in crop production.
- **Improve crop management** along with N management maintaining environmental security to conserve bio-diversity and to protect from health hazards.
- **Developing an N-efficient crop**, which can grow and yield well at low N levels.

9 Conclusion

Improving NUE in major food crops requires collaboration among farmers, agronomists, soil scientists, agricultural economists, ecologists, and policymakers. Agriculture can contribute significantly to reducing the global reactive N load with increases in PFP_N through enhancing both the indigenous N supply and recovery efficiency of N (RE_N), which, in turn, will require innovative crop and soil management practices. Many approaches have been suggested for increasing NUE, as for example, optimal time, rate, and methods of application for matching N supply with crop demand,the use of specially formulated forms of fertilizer, including those with urease and nitrification inhibitors, the integrated use of fertilizer, manures, and/or crop residues, and optimizing irrigation management. In addition, some modern tools such as precision farming technologies, simulation modeling, decision support systems, and resource-conserving technologies also help to improve NUE. Implementing global or regional policies on N use in agriculture, however, is difficult because of varied agricultural priorities and resource availability in different countries. Moreover, farmers also have different economic capabilities. While rich farmers may be able to adopt the advanced technologies for increasing NUE, poor farmers may not be able to because of the non-availability of resources and infrastructure. The nature of the relationships among N use, yield and NUE at the farm level is markedly different. Therefore, policies at a national level across the board would not be acceptable to all farmers because of their different socio-economic backgrounds. Hence, greater NUE can be achieved if policies and investments in research and extension target increases in NUE are at the field scale rather than at regional and national scales.

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 in the accurate modeling of the N cycle. In addition to this, in India, climatic conditions (air and soil temperature, precipitation, wind and relative humidity) vary with the seasons and strongly influence fluxes of N_2O emissions and NH_3 volatilization. Accurate estimates can be obtained by means of model simulations in conjunction with observations at large scales and the linking of point measurements to spatial data sets.

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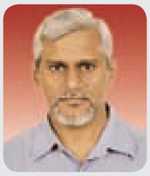

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