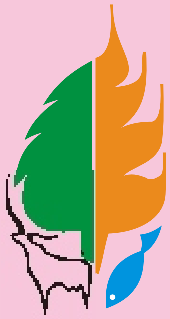
POLICY
PAPER
33

Policy Options for Efficient Nitrogen Use



NAAS

NATIONAL ACADEMY OF AGRICULTURAL SCIENCES, NEW DELHI
DECEMBER 2005

Convenor	:	Prof. Y. P. Abrol, INSA Senior Scientist and Editor, NAAS
Co-Convenor	:	Dr. S. M. Virmani, Foreign Secretary, NAAS
Editors	:	Prof. Y. P. Abrol
	:	Prof. B. N. Johri
Co-ordinator (Publications)	:	Prof. V. P. Gupta
Citation	:	NAAS.2005. Policy Options for Efficient Nitrogen Use. Policy Paper No. 33, National Academy of Agricultural Sciences, New Delhi. pp 12.

Published by M. Vijaya Kumar, Executive Secretary I/c
National Academy of Agricultural Sciences
NASC Complex, Dev Prakash Shastry Marg, Pusa Campus, New Delhi 110012
Tel: (011) 25846051-52, 25841253; Fax: (011) 25846054
Email: naas@vsnl.com; Web site: http://www.naas-india.org

Printed by : Jagdamba Printers, Mobile : 9810326639

NATIONAL ACADEMY OF AGRICULTURAL SCIENCES, NEW DELHI

EXECUTIVE COUNCIL 2005

PRESIDENT
Prof. M. S. Swaminathan
(Chennai /Delhi)

IMMEDIATE PAST-PRESIDENT
Prof. V. L. Chopra
(Delhi/Palampur)

VICE-PRESIDENTS
Prof. Panjab Singh
(Varanasi)

Dr. C. R. Bhatia
(Navi Mumbai)

SECRETARIES
Dr. S. Ayyappan
(Delhi)

Dr. R. K. Singh
(Delhi)

FOREIGN SECRETARY
Dr. S. M. Virmani
(Hyderabad)

EDITORS
Dr. Y. P. Abrol
(Delhi)

Dr. B. N. Johri
(Bhopal)

TREASURER
Dr. M. L. Lodha
(Delhi)

MEMBERS
Dr. S. S. Acharya
(Jaipur)

Dr. T. K. Adhya
(Cuttack)

Dr. Anwar Alam
(Srinagar)

Dr. B. V. David
(Chennai)

Dr. B. S. Dhillon
(Ludhiana)

Dr. S. P. Ghosh
(Kolkata)

Dr. S. L. Intodia
(Udaipur)

Dr. S. S. Kadam
(Pune)

Dr. M. Udaya Kumar
(Bangalore)

Dr. I. C. Mahapatra
(Bhubaneswar)

Dr. B. N. Mathur
(Amritsar)

Dr. S. Nagarajan
(Delhi)

Dr. Rita Sharma, FA, ICAR
ICAR Nominee (Delhi)

NAAS Documents on Policy Issues*

1	Agricultural Scientist's Perceptions on National Water Policy	-1995
2	Fertilizer Policy Issues (2000-2025)	-1997
3	Harnessing and Management of Water Resources for Enhancing Agricultural Production in the Eastern Region	-1998
4	Conservation, Management and use of Agro-biodiversity	-1998
5	Sustainable Agricultural Export	-1999
6	Reorienting Land Grant System of Agricultural Education in India	-1999
7	Diversification of Agriculture for Human Nutrition	-2001
8	Sustainable Fisheries and Aquaculture for Nutritional Security	-2001
9	Strategies for Agricultural Research in the North-East	-2001
10	Globalization of Agriculture: R & D in India	-2001
11	Empowerment of Women in Agriculture	-2001
12	Sanitary and Phytosanitary Agreement of the World Trade Organization Advantage India	-2001
13	Hi-Tech Horticulture in India	-2001
14	Conservation and Management of Genetic Resources of Livestock	- 2001
15	Prioritization of Agricultural Research	- 2001
16	Agriculture-Industry Interface: Value Added Farm Products	-2002
17	Scientists' Views on Good Governance of An Agricultural Research Organization	-2002
18	Agricultural Policy: Redesigning R & D to Achieve It's Objectives	-2002
19	Intellectual Property Rights in Agriculture	-2003
20	Dichotomy Between Grain Surplus and Widespread Endemic Hunger	-2003
21	Priorities of Research and Human Resource Development in Fisheries Biotechnology	-2003
22	Seaweed Cultivation and Utilization	-2003
23	Export Potential of Dairy Products	-2003
24	Biosafety of Transgenic Rice	-2003
25	Stakeholders' Perceptions On Employment Oriented Agricultural Education	-2004
26	Peri-Urban Vegetable Cultivation in the NCR Delhi	-2004
27	Disaster Management in Agriculture	-2004
28	Impact of Inter River Basin Linkages on Fisheries	-2004
29	Transgenic Crops and Biosafety Issues Related to Their Commercialization In India	-2004
30	Organic Farming: Approaches and Possibilities in the Context of Indian Agriculture	-2005
31	Redefining Agricultural Education and Extension System in Changed Scenario	-2005
32	Emerging Issues in Water Management - The Question of Ownership	-2005

---

* *For details visit web site: http://www.naas-india.org*

NATIONAL ACADEMY OF AGRICULTURAL SCIENCES, NEW DELHI

POLICY OPTIONS FOR EFFICIENT NITROGEN USE

PREAMBLE

Nitrogen (N) is necessary for all forms of life and is a crucial component for increasing production of food to feed the continuously increasing human population. However, barring N_2, which cannot be directly used in agriculture, all reactive forms of nitrogen (urea, ammonia, nitrate and their derivates) used to produce food can threaten the environment. Reactive N species (NOx) are also formed from fossil fuel consumption by industries and vehicles, with attendant environmental implications. Therefore, the challenge now facing Indian agriculture is to further enhance the productivity of agricultural system without adversely impacting environment and ecology. This is the basic dilemma for N management policies. The increase in food production has been a hallmark of the green revolution achieved through the combination of better seeds with responsiveness to water and fertilizer, particularly nitrogenous fertilizers. N based fertilizers constitute a major fraction, nearly 70 per cent, of the total fertilizer material. The increase in fertilizer N use in the last three to four decades has resulted in unprecedented increase in agricultural production in the northwestern India leading to food security of the country. From the beginning of green revolution, N-fertilizer use has been a success story for Indian crop production. With 6 million tonnes N-fertilizer in 1989-90 to 10.4 million tonnes in 1998-99, every million tonnes N-fertilizer used resulted in 10 million tonnes of cereal production. The per hectare use of nutrients from fertilizers increased from less than a kilogram in the 1950s to more than 100 kg per hectare of gross cropped area by 2000. Accordingly, the all India annual consumption of fertilizers increased from 70,000 tonnes in 1950-51 to nearly 18 million tonnes at present. India is currently the third largest producer and consumer of fertilizers (after China and USA) and fertilizer usage is bound to increase with further intensification of agriculture. While interest in organic manures and biofertilizers is increasing (and rightly so), these can at best meet the total demand for fertilizers, at least in the near foreseeable future.

Expansion of fertilizer use has, however, not been uniform. While the soils in most parts of the country continue to be deficient in N, the fertilizer N use may be as high as

300 kg ha-1 yr-1 in the intensively cropped regions of northwestern India. This has led to a peculiar situation in which demands for expansion of fertilizer N use in some areas coexist with the concerns over the environmental hazards of excessive and inefficient N fertilizers use in other areas. This, coupled with N contributions from industrial effluents/exhausts, animal wastes and geo-deposits have led to soil acidification, widespread pollution of groundwater and eutrophication of surface waters, posing a public health problem and the ecosystem imbalance. The ozone depletion and greenhouse effects of NOx gases from various farm and non-farm sources may pose new concerns for N-C balance, especially for environment and sustainable agriculture.

There have also been genuine concerns over fertilizer use efficiency, in general, and N use efficiency (NUE) in particular, for economic as well as environmental reasons. Worldwide, NUE for cereal production (wheat, rice, maize, barley, sorghum, millet, oat and rye) is as low as 33 %. The unaccounted 67 % represents an annual loss of N fertilizer worth upto Rs. 72,000 crores. The manufacture of nitrogenous fertilizers involves huge amounts of foreign exchange and consumes large quantities of non-renewable energy resources such as naphtha, natural gas, coal etc. Poor utilization of fertilizer N by plants also adds to the pressure on these finite resources. Low NUE for crops implies higher costs to producers and consumers and, therefore, reduced competitiveness. Loss of N from soil plant system results from gaseous plant emission, nitrification, denitrification, surface runoff, volatilization and leaching beyond rooting zones of crops. Many ^{15}N recovery experiments conducted in the country on different crops have reported unaccounted losses of fertilizer N from 20 to 50 % depending on the local conditions. These losses of fertilizer N, or in general, the leakages of the reactive N from the agricultural systems into the environment are a cause of serious concern. Nitrogen on its own rarely increases yield much and for long; other nutrients, water, crop variety, weed and pest control must all be in proper proportion and available before fertilizer N can do its best. Harvesting high yields by applying only N is at best a short-lived phenomenon, as was shown in the early years of the green revolution. Clearly "N-driven systems" are not sustainable, as N becomes a 'shovel' to mine the soil of other nutrients, with the result that soils initially well supplied in other nutrients become deficient in them and productivity declines. Researchers have shown that the production practices that have resulted in increased N use efficiency relative to conventional or standard practices are those that will counter conditions or environments that contribute to N loss from soil-plant systems. The challenge is to make such modern farming systems accessible and affordable to the farmers, who are constantly under pressure to cut input costs.

Another aspect of N management is its global implications. Whereas the global C cycle is being perturbed by less than 10 % due to anthropogenic activities, the global reactive N cycle is being perturbed by over 90 %. Increasing agricultural N use to meet the perpetual demand for food production, combined with the increasing release of N from dairies and industrial exhausts/effluents makes it inevitable that perturbation of N cycle will continue to be much faster than that of carbon. Although eutrophication of aquatic ecosystems and health hazards due to nitrate/nitrite contamination are critical local concerns, gaseous emissions may eventually prove to be the most serious on a global scale. The accumulation of NOx gases have global consequences that cannot be constrained by political boundaries or explained away by local policies. Hence, regulatory approaches must strive to balance the need for uniform standards with the diverse local realities and the costs of compliance, and maximize the economic benefits that result from adoption of improved food-production practices that help meet environmental quality standards. Narrow profit margins do not allow farmers to absorb the additional costs of regulation.

Thus, the challenge now facing India is to find ways to further our agricultural and industrial development in a sustainable manner without adversely impacting, the environment and ecology, with respect to nitrogen. In order to prepare ourselves for this challenge, we need a precise understanding of the scale of the nitrogen use/misuse/release through various agricultural, industrial, vehicular and other activities and their contribution to the pollution of waters and air with special reference to various point and non-point sources and the biogeochemical N cycle. While well coordinated nation-wide surveys on N in our environment are lacking, the overall indications from the few sample studies by agricultural and environmental scientists, pollution control boards and others point to the alarmingly high levels of nitrates in some areas of the country, especially in ground/surface waters. The rise of NOx levels in the polluted airs of our cities often makes eye-catching graphics in the media. We need to clearly integrate the information from various separate studies, account for their methodological differences and identify the underlying issues/sources of concern as well as areas that need further study. Considering that N is an essential part of our agricultural and industrial developmental paradigm, the options for mitigation of N pollution will have to be addressed at various levels, such as establishing/ updating national N information systems, improvements in fertilizer formulations, promotion of biological N fixation, enhancement of the N use efficiency of our crops and farming systems, reduced dependence on non-renewable energy sources, improvements in fossil fuel quality, fuel-use efficiency and reduction of fossil fuel use/abuse, reduction in NOx emissions from farming, industrial and vehicular sources, minimizing anthrophogenic (including agri-industrial) N load in naturally overloaded areas (eg. geodeposits) and fragile ecosystems.

The above perspective led the **Society for Conservation of Nature** to hold a brain storming session sponsored by the **National Academy of Agricultural Sciences on** "Policy options for efficient N use" on October 4-5, 2005 at NAAS, New Delhi with Prof. Y.P. Abrol, INSA Senior Scientist and Editor, NAAS as convenor and Dr. S.M. Virmani, Foreign Secretary, NAAS as Co-convenor. A background paper on N in agriculture and environment was circulated in advance to over 80 scientists and specialists from agricultural, environmental and industrial sectors, based on which over 50 papers on specific aspects were received. These were integrated into a few position papers that were presented and discussed during the brainstorming session attended by more than 35 participants. Their recommendations formed the basis for this policy paper. One of the most important realizations that emerged from this exercise is that the problems related to N in agriculture, industry and environment are multidimensional. **The sheer diversity of research areas / expertise / approaches it encompasses and the various levels at which the problems need to be identified / tackled, calls for an integrated network approach to harness our intellectual, financial and infra-structural resources effectively**.

The session deliberated on the important issues in the total gamut of nitrogen use in crop production related to:

Low recovery of costly fertilizer N input implies higher costs to producers and consumers and, therefore, reduced competitiveness.

Manufacture of nitrogenous fertilizers consumes large quantities of non-renewable energy resources -- naphtha, natural gas and coal adding to the pressure on these finite resources.

Nitrogen, not recovered by crops contributes to environmental problems including those of pollution of groundwater, eutrophication of surface water, green house gaseous emissions of nitrous-oxides, ammonia etc

THE DELIBERATIONS LED TO THE FOLLOWING RECOMMENDATIONS:

1. The rice-wheat cropping system with its high demand for fertilizer nitrogen has been the mainstay of the food security during the last three decades. Main attributes favaourable for this system are the availability of good quality high yielding seeds of rice and wheat, well researched production technology which the farmers could adopt easily and also abundant water, may be at the cost of over exploitation, coupled with procurement of rice and wheat by government agencies and market stability. Research on N use in this system can contribute to curtailing the leakages of N to the environment and at the same time make fertilizer N application more cost effective while keeping pace with the increasing demand for food. The N use by crops can be enhanced by maintaining synchrony in water and plant growth so that leakages can be checked using farmer friendly tools such as Leaf Color Charts (LCC) for rapid diagnosis of N deficiency in plants. Because little additional arable land is available, site-specific precision agriculture approaches that minimize fertilizer use must be employed wherever feasible to produce optimum yields. This is especially necessary for high-nutrient-consuming crops including the major cereal grains - rice, wheat and maize. Quantifying the pathways of N loss is of immense utility in the development of strategies for reducing N losses and to enhance N use by plants. Another important area is the development of N management recommendation compatible with new emerging resource conservation for rice-wheat system such as zero or minimum tillage, direct seeding and bed planting. A good comprehensive study at 4 - 5 locations, considering all the aspects of N pathway in soil-plant system, which can be further enlarged using simulation modeling to develop technologies for various rice-rice agro-eco regions is a need of the time.

2. Use of urea super granules (USG) and nitrification inhibitors based on neem products improves N use efficiency but these still have not gained popularity with farmers. Advantage of deep-placed USG in transplanted rice over split application of prilled urea was recognized long ago. Its lack of popularity at the farmers' level can be attributed to its commercial non-availability, need of suitable machinery for placing granules into the soil and lack of fiscal support by the Government of India. There is, however, a successful case study by IFDC in neighbouring, Bangladesh.

3. Fertilizer use in maize and cotton and other crops in the dryland areas is low and needs to be looked into to optimize with water availability. The basic constraint in dryland areas is water conservation technology. The evaluation of optimum fertilizer doses considering the soil moisture status and rainfall pattern, and their application in a staggered manner in suitable split doses depending on the crop nutrient requirement at critical physiological stages needs to be worked out. Also the diagnosis of limiting nutrients in soil-plant system pertaining to local situations is necessary for improving the fertilizer N use and its efficiency in dry land regions.

4. The subsidies on fertilizer should be rationalized so that there is parity in nutrient pricing to promote balanced fertilizer use. There should be a research cess on fertilizers which then should go to funding research for developing efficient use of nitrogenous fertilizers. Farmers must be able to make profit in their ventures to continue farming. Because maximization of profits is generally not congruent with minimizing losses of reactive N from agriculture, optimization of systems to meet these objectives (and others) will be required. Optimization can best be achieved if the external costs of N losses from agriculture are internalized. This means that consumers must pay more for their food. Costs that should be included in the price of food are the costs for production and the farmer's profit, but also the environmental costs associated with fertilizer production and transport, transport of resources and products, and waste processing. Policies designed to promote greater N-use efficiency in agriculture should emphasize incentives to farmers rather than punitive regulations, so as to avoid export of crop and livestock production to areas with less stringent environmental guidelines.

5. Agricultural practices and nitrate in environment are very closely interlinked. Globalization of agriculture demands consideration of the costs of input and output. There is no way of leaving N from crop production scenario of the country where without N fertilization grain production would have been 80 million tonnes which now stands at 220 million tonnes with N fertilizer. It is essential to conduct yield maximization trials with N responsive high yielding crop varieties with quantification of the extent of nitrate pollution and watershed contamination. However, till date there has been no concerted effort in the country to look into the fertilizer N use and build-up in nitrate levels in the environment. Also the reports about increased levels of nitrate in some pockets,

whether due to fertilizer N, animal production systems or are of geogenic sources, have not been authenticated. There is need to address these issues in detail to formulate a comprehensive fertilizer N policy for enhanced agricultural production and safe environment. This calls for the nitrate monitoring in ground waters in different agro-eco regions in a systematized manner to identify the sources contributing to the built-up of nitrates in ground waters under given crop, input and farming systems so that a comprehensive data base can be established for development of proper policy vis-à-vis fertilizer N use. Since it is impossible to have too many field studies, simulation models must be modified and/ or developed through intensive detailed field investigations and validated for diverse set of conditions. It will need extrapolating the results to other locations. At present, there is lack of both, authentic data and validated models, under Indian conditions. The information on N cycling at field, sub-regional, regional or national level is lacking and needs to be developed as well as collated from the available data. It is pertinent to mention that anthropogenic fluxes largely control the natural as well as the anthropogenic N cycles. Using remote sensing and GIS, it is possible to spatially describe dominant controlling factors for N cycle, such as land use, vegetation type, farming systems, soil and water characteristics and need to link the information through networking for optimization of policy on N use in different agro-eco systems.

6. Animal manures constitute 5-10% of N input in Indian agriculture, but can be a significant source of nitrate pollution in some areas due to leakages during storage and handling. Efficient use of animal manure in Indian agriculture should cover minimization of the collection loss, proper composting, reducing loss during storage, integrated nutrient management (INM), optimizing application method, and gobar gas technology be studied and package of practices need to be developed. Information required for this includes, nutrient content dynamics and, for technique and precision, nutrient loss, techno-managerial issues of implementation, policy issues of incentive and punishment for adopting the efficient methods. Policy issues should include integration of crop and livestock production system, promotion of gobar gas plants and improving their efficiency, training of women and incentive for better manure management, research for improved compost preparation and socio-economic evaluation of manure use.

7. Nitrate toxicity and health hazards has been much talked about but studies are available as far as the nitrate toxicity on human being is concerned except reports

documenting methaemoglobinemia in infants due to high nitrate ingestion. Reports indicate nitrate ingestion is a cause of methaemoglobinemia for all ages, recurrent diarrhea, RRTI (recurrent respiratory tract infection) up to 8 years of age and recurrent stomatitis. An observation that a sudden rise in the occurrence of these diseases when the nitrate concentration is more then 26 ppm, suggests a need for downward revision of permissible limits of nitrate in drinking water. Apart from methaemoglobinemia, a few studies indicated nitrate as a cause of malignancy (liver and gastric cancer), but these are controversial studies and no firm conclusion have been drawn so far. Removal of nitrate from drinking water is difficult and costly. It is recommended that a simple policy change may be urgently introduced in government campaign in areas having high nitrates in potable waters. As the treatment options are not much, there is need to formulate guidelines for preventing nitrate toxicities specifically in infants, children and pregnant women in areas having high levels of nitrate in potable waters.

8. Tropical agriculture contributes significantly to green house gases (GHGs), especially emission of methane (CH4) and nitrogen oxide (N_2O). To meet the future food grain production targets, the fertilizer consumption is expected to sustain production levels. The unique nature of rice production (flooded soil and high N input) makes it a significant contributor of CH4 and N_2O to the environment. Emission of N_2O from rice fields is directly related to N-fertilizer application. Crop residue and green manure gives as much N_2O as chemical N-fertilizer alone, but nitrate leaching is restricted. Improvements in NUE should diminish N_2O emission. This can be done even while increasing the use of fertilizers if their use efficiencies are tightly managed. Future research should focus on quantification of the fertilizer impact on GHG emission from different agro-climatic zones on an annualized basis, quantification of sink potentials for GHGs, reduce uncertainties in GHG and N deposition and develop simulation models for estimation and extrapolation of GHG emission. A strong database on N_2O emission from agriculture is essential for which intensive research is needed combining simulation models and GIS for determining the impact of N-inputs on N_2O fluxes. Development and use of environmentally compatible mitigation options for controlling N_2O emission from agriculture is urgently needed. Since mitigation of N_2O emission is closely linked to food production and the progress of national economics, it is important to continuously review and monitor the sources and sinks of N_2O in agriculture. Unlike N_2O, NH4 is highly reactive and

returns to the earth through deposition. **We don't have any data on N deposition in India**. Data from Europe and elsewhere indicate that N deposition is significant and need to be collected in Indian conditions to remove uncertainties.

9. There is need to develop crop rotations involving legumes to tap the benefits of biological nitrogen fixation (BNF). Nitrogen use efficiency for cereals following legumes is greater than that for cereals following cereals or fallow. The role of legumes in N economy is well researched but the problem is how to increase N input and the options are increased system efficiency or increase in the area under the system. N derived from BNF in legumes varies from 40-80% and residual effect on succeeding crops is variable and depends on several factors. The more intensive systems (growing more crops in a given period of time) require greater fertilizer N inputs but are economically advantageous to farming community. More intensive dry land cropping systems involving legumes in rotation lead to increased water use efficiency and also better maintain soil quality. The research has shown a positive impact of BNF on nitrogen economy of cropping systems but the vast potential of BNF has remained unrealized at the farmers' level due to many reasons and needs to be looked into from the holistic approach on nitrogen use in agricultural production systems. Some aspects which need immediate attention are: increasing public investment in microbiology for teaching, research and training, encouraging private investment in manufacture of biofertilizers, constitution of nodal agency for registration of manufacturers, establishment of quality control laboratories and act as a watch dog and promoting products through DAVP and media. The private sector needs to play a crucial role and set an example by employing qualified microbiologists for production, assuring quality through creation of brand equity, ensuring *niche* marketing through entrepreneurship ventures and providing dealers' involvement as advisor and friend on product and proper application.

   There is an urgent need to improve the inputs of organics and BNF and to increase the production of quality inoculants and popularize their use in Indian agriculture rapidly. Development of effective and competitive strains tolerant to high temperature, drought, acidity and other abiotic stresses are of high priority. Newer formulations of mixed biofertilizers, improvement of inoculant quality and devising effective delivery systems are crucial for making further progress in taking the BNF technology to farmers' fields.

10. Breeding and selecting crop cultivars that make more efficient use of soil and fertilizer N (including higher N fixation and N partition) while maintaining productivity and crop quality has been a long-term goal of production agriculture. Development of nitrogen-efficient cultivars could help decrease fertilizer N inputs and resulting reactive N losses to air and ground water. These nitrogen-efficient cultivars could also be useful in regions where limited-resource farmers are unable to afford synthetic N fertilizers. Selection of N efficient genotypes that is the varieties which can extract more N from soil at lower availability will enhance the production in these regions. Molecular and biotechnological approaches for searching for regulatory targets for manipulation of N use efficiency be strengthened. Unravelling the details of N signal transduction to provide additional clues to improve N uptake and assimilation efficiency.

11. Our first duty, as scientists working on N, must be to get our science as right as we can. But we also have a duty to society to provide the best advice we can, presented as clearly as we can, on how to use nitrogen efficiently and how to keep it from getting into places where it is not wanted. Improving N-use efficiency in major food crops will not be easy. It will require collaboration among ecologists, agronomists, soil scientists, agricultural economists, and politicians. Great needs exist for accurate measurements of actual fertilizer N-use efficiency, N losses, and loss pathways in major cropping systems. Only in this way we can: a) identify opportunities for increased N-use efficiency by improved crop and soil management; b) quantify N-loss pathways in major food crops; and c) improve human understanding of local, regional, and global N balances and N losses from major cropping systems. The starting point for any improvement has to be a clear understanding of the fluxes and balances of nitrogen at the farm level. Direct on-farm measurements are necessary because estimates from small plots on research stations overestimate field-scale fertilizer N-use efficiency. Focus new initiatives in research on options that will reuse or remove reactive N before it cascades through the environment. Especially promising target areas include: a) decreasing NOx emissions from fossil fuel combustion in power plants and industry by pre-combustion removal of organic nitrogen, b) converting NOx in flue gas streams into saleable fertilizer products, c) increasing N-use efficiency by crop and animal production systems, d) decreasing reactive N losses from animal wastes, and e) recycling reactive N back on the land from which feed grains and

forages are produced. Fostering multi-disciplinary innovations in the management of reactive N such as, i) research by agricultural economists on possibilities for internalization of environmental costs in crop and animal agriculture production systems, ii) research by agronomists and agricultural engineers on means by which to integrate farm wastes such as crop residues and animal manures more effectively into crop nutrient management plans, and iii) on possible innovations in the manufacture of reactive N fertilizer materials that could result in their more efficient use in cropping systems. We need to find the answer of the "N legacy question" by determining the extent to which reactive N accumulated in various ecosystem reservoirs in recent decades is retained and how these accumulations will affect the future productivity, stability, and resiliency of crops, forests, and natural ecosystems. We also need to 1) develop multi-pollutant multi-effect strategies to optimally combat environmental effects resulting from human activities; 2) develop technological road maps for future infrastructures where fossil fuels can be replaced by renewable energy sources, e.g. through exploration of hydrogen-based rather than fossil-fuel-based energy production systems; 3) establish an institutional framework that supports exchange of information between researchers on the effects of reactive N in its various aspects, e.g. food production, use of fossil fuels, and the environment; and identify mechanisms, such as the World Bank / IMF/ ADB to fund researchers in the developing world to investigate specific regional impacts and solutions; 4) develop better ways to assess the uncertainty of current and future reactive N loading to water bodies.

TOP PRIORITIES FOR INNOVATIONS IN REACTIVE N RESEARCH AND POLICY

Developing economically sound applicable policies and measures

Developing incentives for improving N-use efficiency through integrated nutrient management practices

Integration of plant and animal production systems

Conversion of agriculture from total reliance on synthetic reactive N fertilizers to a significant input from BNF

Development of modified N fertilizers - controlled release fertilizers, urea supergranules, neem coated urea etc. for lowland rice and other areas prone to reactive nitrogen leakages

Novel molecular techniques to develop plants with higher N-use efficiency

Accurate and site-specific test for estimating soil-mineralizable N and developing site-specific N management for different crops

GENERAL REMARKS:

The need to develop N budgeting guidelines at field and farm levels and further expanded to watershed scale requires urgent attention so that the effect of fertilizer N use in particular and overall N use in totality can be worked out for efficient management of N input in agricultural systems. With this objective in view we need a systems approach across the various agricultural disciplines in a network mode to tackle the issue of N use and develop strategies for increased production with minimal environmental consequences and at the same time a sustainable system which is also economically viable for the farming community.

It is recommended that a **Nitrogen Research Centre** be established to address all facets of the problem in totality. It will be a step in the forward direction in coming decades, keeping in view the food requirements in future and the quality of environment vis-à-vis enhanced fertilizer N use to achieve the future targets with least human health problems. **This issue needs to be addressed urgently at national level**.