Optimizing Nitrogen Management in Food and Energy Production and Environmental Protection

Report from the Second International Nitrogen Conference

Held at the Bolger Center in Potomac, Maryland, USA

14-18 October 2001

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in cooperation with other Conference participants

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Preface

In March 1998, the government of the Netherlands sponsored the First International Nitrogen Conference – "Nitrogen, the Confer-N-s." The Conference was organized under the general auspices of the Convention on Long-Range Transboundary Air Pollution (CLRTAP) of the United Nations Economic Commission for Europe (UNECE). It was held in Noordwijkerhout in the Netherlands on 23-27 March 1998.

Three significant conclusions emerged from the First Conference:

- Increased circulation of nitrogen in the atmosphere and biosphere is occurring in all parts of the globe;
- Nitrogen has a range of well-understood beneficial and detrimental consequences for people and the environment;
- Scientists and decision makers must work together to develop integrated approaches to solve nitrogen-related problems.

These insights led to the recommendation that a Second International Nitrogen Conference be held in the United States during the autumn of 2001. While the primary focus of the First Conference was on Europe, with a secondary emphasis on North America, the Second Conference concentrated primarily on North America and Europe with a secondary focus on Asia – the most rapidly developing part of the world.

The participants in the Second Conference represented many stakeholder groups concerned with reactive nitrogen production, uses, and consequences once it begins to cycle in the environment. They included leaders in international, federal, state, and provincial government agencies; environmental and public interest groups; business leaders in crop and animal agriculture, energy production, transportation, and communications; and professional societies and trade associations.

Cutting-edge nitrogen science and policy issues were explored through several approaches before, during, and after the Second Conference (full references for Conference products are in Section VI):

1. A 2.5-day Workshop among authors of plenary papers four months before the Conference;
2. Seventeen plenary paper presentations during the Conference;
3. Nineteen oral and poster sessions featuring 285 presentations;
4. Three lively and well-attended Roundtable Discussions;
5. 50 sessions of NitroGenius played during the Conference – an interactive computer simulation game in which participants assume the roles of different stakeholders in making decisions to optimize nitrogen management;
6. More than 500 answers from conference participants to a series of nine nitrogen science and policy questions (see Appendix A);
7. Statements developed by groups of conference participants to identify "common ground" on issues that stimulated debate during the Conference;
8. Suggestions by individual conference participants that will contribute to the ability of their home country, institution, or agency to optimize nitrogen management in their society;
9. Publication of peer-reviewed contributed papers in *TheScientificWorld* (Galloway et al., 2001; 2002a) and of plenary papers in a special issue of *AMBIO (31:59-199, 2002)*;
10. Preparation of a Summary Statement (Cowling et al., 2001) that contains distilled scientific findings and recommendations for decision makers that were derived from the Second Conference.

In contrast with the brief (16-page) Summary Statement, this Report from the Second International Conference contains substantially more detail, particularly from the first, sixth, seventh, eighth, and ninth approaches described above.

Executive Summary

The Second International Nitrogen Conference was held in Potomac, Maryland in the United States during the autumn of 2001. About 400 people from 30 different nations and six continents attended the conference. They were drawn from different scientific disciplines and many industrial, governmental, and non-governmental organizations in North America and abroad.

> The term **reactive nitrogen (Nr)** includes all **biologically active, photochemically reactive, and radiatively active nitrogen (N) compounds** in the atmosphere and biosphere of the Earth. Thus, Nr includes: a) inorganic reduced forms of N (e.g., NH_3, NH_4^+), b) inorganic oxidized forms of N (e.g., NO_x, HNO_3, N_2O, NO_3^-, NO_2^-), and c) organic compounds (e.g., urea, amino acids, amines, proteins, nucleic acids, etc.).

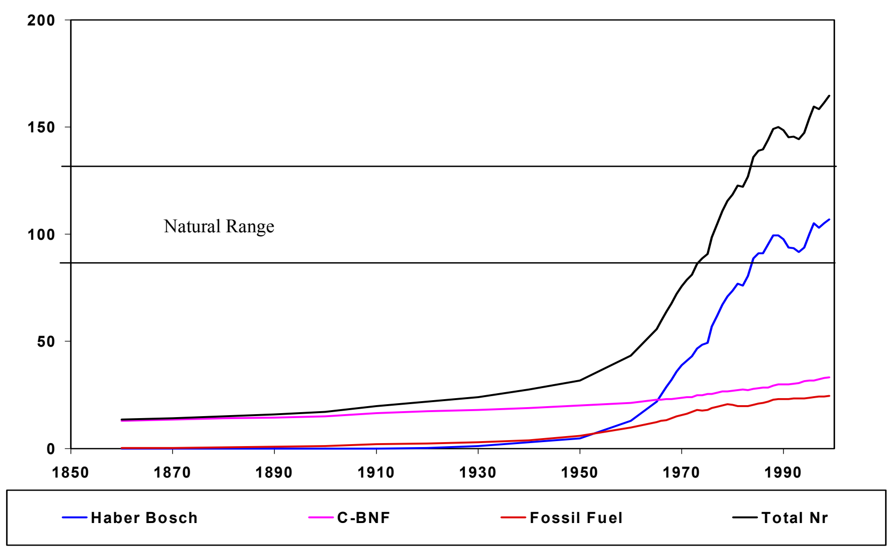
The primary objectives of the Second Conference were to:

- Increase scientific knowledge about sources of reactive nitrogen (Nr) and its effects,
- Stimulate communication among leaders involved in Nr production and consumption,
- Explore balanced strategies by which to increase food and energy production while decreasing environmental impacts.

The general theme of the Conference was "Optimizing Nitrogen Management in Food and Energy Production and Environmental Protection."

Scale and Scope of Reactive Nitrogen (Nr)

Nitrogen constitutes a major part of nucleic acids and proteins that are essential for all forms of life. Before gaseous N_2 can be used by organisms, the strong triple bonds of non-reactive N_2 molecules must be broken. Today, human-induced production and release of Nr into the environment is ~160 TgN/yr, about 10 times greater than in 1860, and is still growing. It dominates Nr creation on all continents. The largest global Nr sources are production of NH_3 (mostly for synthetic fertilizer) by the Haber-Bosch process (~ 100 TgN/year), biological fixation by nitrogen fixing legumes (~35 TgN/yr), and NO_x emission with the use of energy through combustion of fossil fuels (~25 TgN/yr). There are large regional differences in Nr creation rates on both absolute and per capita bases. The total amount of Nr created in Asia is larger than in any other region, but per capita Nr creation is largest in North America and Europe. Humans also redistribute large amounts of Nr from one country or region of the world to another through exports of fertilizers, feed grains, and fossil fuels.



'Haber-Bosch' is Nr creation via the Haber-Bosch process and includes production of NH_3 for non-fertilizer purposes. 'C-BNF' is Nr creation from cultivation of legumes, rice and sugar cane. 'Fossil Fuel' is Nr created from fossil fuel combustion. 'Total Nr' is the sum created by these three processes. 'Natural Range' refers to the approximate natural range of biological N fixation in the pre-human terrestrial environment.

Most forms of life are adapted to use Nr efficiently. Addition of Nr to most ecosystems leads to increased uptake, storage, and use and hence to increased productivity within ecosystems. Further additions of Nr beyond an optimal amount lead to imbalances in the N cycle and potential leakages in the form of emissions of different forms of Nr to other compartments, contributing to a cascade of sometimes beneficial and sometimes detrimental effects. These effects include providing wholesome food for growing populations, as well as acidification and eutrophication of terrestrial and aquatic ecosystems, climate change, damage to human health, and loss of biodiversity. A large portion of the Nr created every year by human activities accumulates in the environment. Thus, the concentration of Nr is increasing in many environmental reservoirs. "Hot spots" of Nr creation and emissions occur on every continent in industrial areas where fossil fuel combustion is intense and in agricultural areas where large amounts of fertilizer are used or confined animal feeding operations are concentrated.

The only way to remove Nr from circulation is storage in long-term reservoirs (e.g., soils, sediments, and standing biomass) or conversion back to non-reactive N_2 by denitrification. In some cases, it may be possible to capture and beneficially reuse Nr and deliver it to food or fiber production areas where there are nitrogen deficiencies. The population of the world is expected to peak at ~9 billion people at the end of the 21st century. At that time, if all humans have the same per capita Nr creation rate as they do today, the global Nr creation rate will be ~250 Tg N/yr compared to the current ~160 Tg N/yr. If all people have the same Nr creation rate as exists in North America today (~100 kg N/person/yr), then the global rate will be ~900 Tg N/yr.

Food Production and Nr

Food production heavily depends on the use of synthetic N fertilizers. Food production must increase substantially in the decades ahead to meet dietary needs and food preferences of a larger and wealthier global population. However, the area of land available for food production can no longer be increased without severe damage to ecosystems and biodiversity. In most of the world, livestock will increasingly contribute to the supply of N in human diets. Typical N-use efficiencies for production of human-digestible protein from feed grains and forages are ~50-60% for fish, ~ 40-50% for poultry and eggs, ~35-40% for dairy, ~30-40% for swine, and ~15-30% for beef. Therefore, significant improvements in N-use efficiency are essential to decrease losses of Nr to the environment.

Energy Production and Nr

Combustion of fossil fuels forms NO_x as a waste product from fuel-N (organic N) and atmospheric-N (N_2). The primary sources of NO_x emissions are the combustion of coal, oil, and natural gas for energy production and use (e.g., generation of electricity, transportation, industrial and construction processes, domestic space and water heating, etc.). Over the last 30 years, technological advances have achieved significant decreases in the rate of NO_x emissions per unit of fuel burned. Global energy consumption is projected to increase ~2-3% annually from 1999 to 2020 – for a total increase of ~60% over current rates. Most of this increase will occur in developing countries. Natural gas use is expected to more than double in many industrialized countries, but coal is expected to remain the major energy source in the future, most notably in China and India. While NO_x emission trends in North America and Europe are projected to decline in the future due to regulatory measures, global NO_x emissions will probably increase as developing countries increase their standard of living by consuming more electricity and driving more.

Recommendations for Nr Management, Research, and Education

1. Focus new initiatives in research on options that will reuse or remove Nr before it cascades through the environment. Determine the technological and economic feasibility, social acceptability, and environmental sustainability of innovative technologies, such as on-farm and centralized systems for converting animal manures and various other types of Nr-rich waste streams into value-added products. Alternative cropping and domestic animal rearing systems, including traditional practices, should be explored and improved.

2. Strengthen incentives for environmental stewardship. This could be achieved through bonuses for good practices or through eco-taxes on products that incorporate the environmental costs related to production, transport, and waste processing.
3. Develop multi-pollutant multi-effect strategies to optimally combat environmental effects resulting from human activities. In order to accomplish this, it is necessary to determine and prepare maps of critical Nr loads for the atmosphere and for terrestrial and aquatic ecosystems, below which no unwanted effects occur. Improved scientific understanding is needed of gaseous emissions of Nr compounds, atmospheric transport and transformation processes at all scales from local to global, and wet and dry deposition processes. Further develop integrated assessment models, such as NitroGenius, to explore different cost-effective options to diminish the cascading effects of Nr.
4. Make firm commitments to long-term monitoring programs, in order to evaluate the effectiveness of environmental policies and programs.
5. Increase scientific knowledge of the fate, flows, denitrification rates, and residence time of Nr in various parts of the nitrogen cascade through accumulation in soils, sediments, and standing biomass. Improve quantification of Nr flows between stages within the cascade.
6. Develop integrated research approaches that address Nr issues in the context of linkages with other nutrient cycles, especially carbon, sulfur, and phosphorus. Develop technological road maps for future infrastructures where fossil fuels can be replaced by renewable energy sources, for example through exploration of hydrogen-based rather than fossil-fuel-based energy production systems.
7. Establish a quasi-permanent international research and/or research and policy assessment program, such as an Intergovernmental Scientific Panel on Nitrogen (ISPN) through the United Nations or another international body.

All of these recommendations will require collaboration among ecologists, agronomists, soil scientists, agricultural economists, and politicians. Improved education will be required for farmers, foresters, other natural resource managers, as well as scientists and engineers in many other professions.

Additional information from the Second International Nitrogen Conference also can be obtained in the following products (full references can be found in Section VI of this Conference Report):

- Program and Abstracts from the Conference (ESA, 2001)
- Conference Summary Statement published by the Ecological Society of America (Cowling et al., 2001)
- Special issue of *AMBIO*, in which the plenary papers from the Conference are published (AMBIO, Vol. 31 No. 2, March 2002)
- Contributed Papers published in electronic form in *TheScientificWorldJOURNAL*, http://www.thescientificworld.com (Galloway et al., 2001).
- Contributed Papers published in hard copy by A.A. Balkema Publishers (Galloway et al., 2002a)
- N2001 Conference website, http://n2001.esa.org/

The Third International Nitrogen Conference will be held in Nanjing, Peoples Republic of China, in October 2004 under the sponsorship of the Chinese Academy of Sciences and the Soil Science Society of China.

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- Board on Environmental Studies and Toxicology of the (U.S.) National Research Council
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- American Society of Agronomy
- Crop Science Society of America
- Soil Science Society of America
- American Dairy Science Association
- American Society of Animal Science
- Poultry Science Association
- American Meat Science Society

The Conference was planned over a 2-year period. During that time, the 9 members of the Organizing Committee (Mary Barber, Rona Birnbaum, Jan Willem Erisman, Jonathan Garber, Richard Haeuber, Kaj Sanders, Sybil Seitzinger, Stan Smeulders, and Joe Wisniewski) and the 22 members of the Science and Policy Program Committee (Mary Barber, Ton Bresser, William Chameides, Robin Dennis, Jan Willem Erisman, Robert Howarth, Charles Lander, Jerry Melillo, William Moomaw, Arvin Mosier, Rosamond Naylor, Kaj Sanders, Kenichi Satake, David Schimel, Sybil Seitzinger, Stan Smeulders, Robert Socolow, Jeffrey Stoner, Peter Vitousek, Ford West, Robert Wright, and Zhaoliang Zhu) worked diligently with the Conference Co-Chairs (Jim Galloway and Ellis Cowling) to ensure that the conference would be successful.

We also appreciate the efforts of the publishers involved with the six major products from the Conference: Elisabeth Kessler of Ambio, Anne Allen and Tara Retzlaff of TheScientificWorld; Janjaap Blum of A.A. Balkema Publishers; Joe Wisniewski and Carol Jordan, who oversaw the peer review of all contributed papers.

Finally, this conference and its associated activities could not have been so successful without the hard work and creative planning of staff at Ecological Society of America (ESA), particularly Mary Barber, Rhonda Kranz, and Ellen Cardwell. The Headquarters Staff of ESA is a class act!

Optimizing Nitrogen Management in Food and Energy Production and Environmental Protection

Report from the Second International Nitrogen Conference

Human efforts to produce food and energy are changing the nitrogen cycle of the Earth. Many of these changes are highly beneficial for humans, while others are detrimental to people and the environment. These changes transcend scientific disciplines, geographical boundaries, and political structures. They challenge the creative minds of natural and social scientists, economists, engineers, business leaders, and decision makers. The Second International Nitrogen Conference was designed to facilitate communications among all stakeholders in the "nitrogen community" of the world. The Conference participants' goal in the years and decades ahead is to encourage every country to make better choices about nitrogen management in food production and consumption, energy production and use, and environmental protection.

I. Introduction

The Second International Nitrogen Conference: Optimizing Nitrogen Management in Food and Energy Production and Environmental Protection was held at the Bolger Conference Center in Potomac, Maryland on October 14-18, 2001.

The primary objectives of the Second Conference were to:

- Increase scientific knowledge about reactive nitrogen (Nr; see definition in the box on page 2) sources and effects on people and the environment;
- Stimulate communication among leaders involved in nitrogen production and consumption;
- Explore balanced strategies to increase food and energy production while decreasing impacts on people and the environment, thereby making progress toward the general theme of the Conference: "Optimizing Nitrogen Management in Food and Energy Production and Environmental Protection."

The Schedule for the Conference is detailed in Appendix B.

More than 400 scientists, engineers, resource managers, decision makers, and policy analysts attended the Conference (see list of participants in Appendix C). The participants came from 30 nations and six continents of the world. The disciplines represented included agronomy, animal nutrition, aquatic ecology, atmospheric chemistry and physics, atmospheric modeling and meteorology, biochemistry, biogeochemistry, crop science, environmental science, forestry, geography, geology, horticultural science, human nutrition, journalism, law, limnology, medical and environmental health sciences, oceanography, plant ecology, plant pathology, plant physiology, political science, poultry science, and soil science.

This Conference Report contains ideas and opinions from many participants in the Conference. The Conference was designed with a mix of general plenary presentations; lunchtime science and policy briefings; smaller concurrent sessions of more focused science- and policy-oriented oral and poster presentations; daily round table discussions of the topics presented; and many opportunities for informal discussion. In addition, input was solicited before the Conference in the form of nine questions to which many participants submitted answers.

II. Summary of Science

A. Definition, Scale, and Scope of Reactive Nitrogen

Nitrogen is essential for life. It is a fundamental component of the nucleic acids that determine the genetic character of all living things and the enzymes that drive the metabolic machinery of every living cell.

The term **reactive nitrogen (Nr)** is used in this Conference Report to include all **biologically active, photochemically reactive, and radiatively active nitrogen (N) compounds** in the atmosphere and biosphere of the Earth. Thus, Nr includes: a) inorganic reduced forms of N (e.g., NH_3, NH_4^+), b) inorganic oxidized forms of N (e.g., NO_x, HNO_3, N_2O, NO_3^-, NO_2^-), and c) organic compounds (e.g., urea, amino acids, amines, proteins, nucleic acids, etc.).

Before gaseous dinitrogen (N_2) molecules can be used by organisms, the triple bonds of non-reactive N_2 molecules must be broken down to single N atoms. These single atoms become reactive forms of nitrogen when they bond with other essential nutrient elements – oxygen, carbon, or hydrogen. Breaking the triple bonds between gaseous dinitrogen atoms is an energy-requiring reaction. Natural oxidation of dinitrogen occurs in such high-temperature natural processes as lightning strikes, volcanic eruptions, and wild fires.

Certain unique microorganisms have developed the special metabolic machinery to produce biologically active reduced forms of nitrogen. Biological nitrogen fixation (BNF) is accomplished by free-living bacteria or blue-green algae, or by bacteria that have developed symbiotic relationships with the roots of leguminous plants such soybeans, clover, and alder trees. Before 1860, BNF was the dominant Nr source for the terrestrial biosphere. The rate of Nr creation was less than the demand in many terrestrial and aquatic ecosystems. The remarkable diversity among plants, animals, insects, and microorganisms found in nature is partly the result of intense competition among life forms – many of which evolved under N-limited conditions.

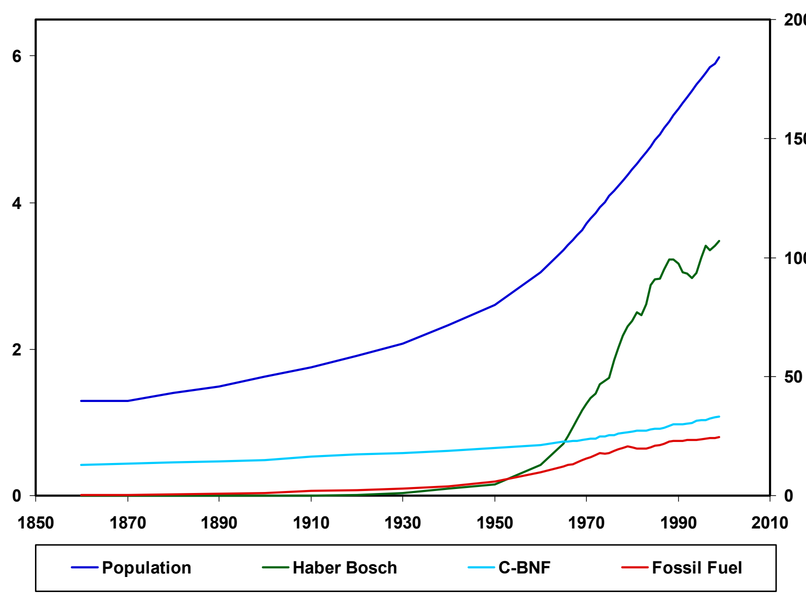

Figure 1. Global population trends from 1860 to 2000 (billions; left axis) and Nr creation (Tg N yr-1; right axis). 'Haber-Bosch' is Nr creation via the Haber-Bosch process and includes production of NH_3 for non-fertilizer purposes. 'C-BNF' is Nr creation from cultivation of legumes, rice, and sugar cane. 'Fossil Fuel' is Nr created from fossil fuel combustion.

Today, human-induced production and release of Nr into the environment is ~160 Teragrams (Tg) N/yr, about 10 times greater than the human contribution in 1860 and still growing. Much of this change has been quite recent. Only in the past two decades has the earth's nitrogen cycle been changed from one where the natural process of biological nitrogen fixation was the dominant source of N to one where human activity now is the major provider of Nr on the planet's land masses. The largest contemporary global Nr sources are production and use of NH_3 by the Haber-Bosch process (~100 Tg N/yr; mostly for synthetic N fertilizers), widespread planting of nitrogen-fixing legumes (~35 Tg N/yr), and production of energy through combustion of fossil fuels (~25 Tg N/yr) (Figure 1).

There are large regional disparities in Nr creation rates on both absolute and per capita bases. Total Nr creation in Asia is larger than in any other region. Per capita Nr creation is largest in North America and Europe. Humans also redistribute large amounts of Nr from one country or region of the world to another through exports of fertilizers, feed grains, and fossil fuels.

Most plants, animals, and microorganisms in the biosphere are adapted to efficiently use and retain small increments of additional Nr. Thus, addition of Nr to most ecosystems first leads to increased uptake, storage, and use and hence to increased food or fiber production. Further additions of Nr beyond an optimal amount, which is different for each ecosystem, lead to imbalances in the N cycle and potential leakages in the form of movement of different forms of Nr to other compartments (see discussion of the N cascade in section B).

A large, but as yet unknown, portion of the Nr created every year by human action accumulates in the environment. Thus, the concentration of Nr is increasing in many environmental reservoirs. “Hot spots” of Nr creation and emissions occur on almost every continent – in industrial areas, especially where fossil fuel combustion is intense, and in agricultural areas, especially where confined animal feeding operations are concentrated.

The only way to remove Nr from circulation is storage in a long-term reservoir (e.g., soils, sediments, and biomass) or conversion back to non-reactive N_2 by denitrification. In some cases, it may be possible to capture Nr and deliver it to food or fiber production areas where there are nitrogen deficiencies.

The population of the world is expected to peak at ~9 billion people at the end of the 21st century. At that time, if all humans have the same per capita Nr creation rate as they do today, the global Nr creation rate will be ~250 Tg N/yr compared to the current ~160 Tg N/yr. If all people have the same Nr creation rate as exists in North America today (~100 kg N/person/yr), then the global rate will be ~900 Tg N/yr.

B. Effects of Increased Reactive Nitrogen (Nr) in the Environment

Reactive nitrogen can have many effects on the natural resources of the Earth. Depending on the effect, the resource being affected, and the societal value system, the effect can be detrimental, beneficial, or both. For example, N is an essential nutrient for growth of all plants, humans, animals, microorganisms, and insects. Because of this, Nr emissions and deposition are not harmful to the environment unless the amounts deposited exceed an "optimum" loading which is different for each particular type of ecosystem (Figure 2). Until the optimum is reached, ecosystems generally benefit from additional Nr inputs, that is, the productivity of the

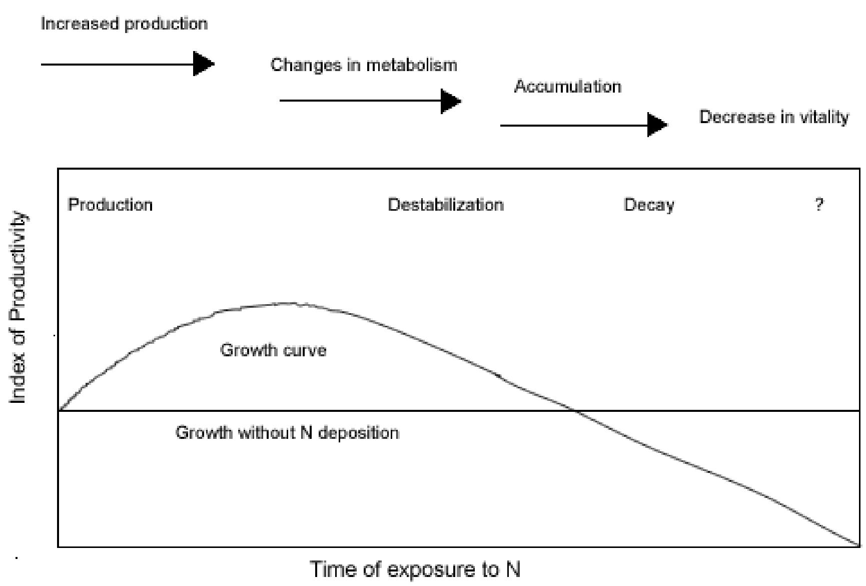

Figure 2. Hypothetical growth curve showing the productivity of terrestrial ecosystems receiving different loadings of biologically active nitrogen. Adapted from *Gunderson, 1992. Proceedings of a Workshop in Löckeberg, Sweden.*

system increases. When the optimum is exceeded, however, negative effects occur and the productivity of the system decreases. Of course, the "optimum" can be defined in terms of different measurements of productivity. Thus the "optimum" for highest economic yield may be different from the "optimum" for maximum biodiversity or for maximum growth. The following lists provide a general tabulation of the effects of Nr enrichment on public health, ecosystem productivity, and on the wealth and other societal values in various nations and regions of the world.

Direct effects of Nr on human health include:
• Increased yields and nutritional quality of foods needed to meet dietary requirements and food preferences for increasing human populations; • Respiratory and cardiac disease induced by exposure to high concentrations of ozone and fine particulate matter; • Concentrations of Nr (primarily as nitrate) in surface and groundwater can decrease drinking water quality by exceeding health standards for use by rural and even some urban populations.
Direct effects of Nr on ecosystems include:
• Increased productivity of Nr-limited natural ecosystems; • Increased sequestration of carbon in Nr-limited ecosystems leading to amelioration of CO_2 rise and climate change; • Enhanced soil productivity through greater microbial activity and improved soil health. • Some Nr pollutants cause direct injury to plant foliage; • Ozone-induced injury to crop, forest, and natural ecosystems and predisposition to attack by pathogens and insects; • Acidification and eutrophication effects on forests, soils, and freshwater aquatic ecosystems; • Eutrophication of lakes and surface water resources; • Stimulation of algal growth and productivity in coastal waters, with possible effects on coastal food webs and fisheries including depressed concentrations of dissolved oxygen (hypoxia and anoxia); decline or elimination of submerged aquatic vegetation; promotion of certain algal species that are harmful and some that are toxic; • N saturation of soils in forests and other natural ecosystems; • Loss of biodiversity through elimination of N-poor natural habitats in terrestrial and aquatic ecosystems and shift in ecosystems to domination by nitrophilic plant species; • Changes in abundance of beneficial soil organisms that alter ecosystem functions;
Indirect effects of Nr on other societal values include:
• Increased wealth and well being of human populations in many parts of the world; • Increased yields of intensively cultivated lands, sometimes making it possible to preserve forest and other natural ecosystems and thus avoid losses in biodiversity; • Significant changes in patterns of land use; • Regional hazes that decrease visibility at scenic vistas and airports; • Depletion of stratospheric ozone by N_2O emissions; • Global climate change induced by emissions of N_2O and accumulation of tropospheric ozone; • Damage to useful materials and cultural artifacts by ozone, other oxidants, and acid deposition; • Long-distance transport of Nr, which causes harmful effects in countries distant from emission sources and/or increased background concentrations of ozone and fine particulate matter.

In addition to these effects, it is important to recognize that:
a) the magnitude of Nr flux often determines whether effects are beneficial or detrimental;
b) all of these effects are linked by biogeochemical circulation pathways of Nr;
c) Nr is easily transformed among reduced and oxidized forms in many systems; and
d) Nr is easily distributed by hydrologic and atmospheric transport processes.

Uncertainties About Effects Identified by Participants

Although many effects of increased Nr on different environmental components and on humans are known, significant uncertainties remain. Participants in the Conference were requested to describe some of the uncertainties that need to be resolved with regard to the most important beneficial and detrimental effects of Nr. Following is a selection of their responses:

- Actual health consequences of nitrate in drinking water for humans
- Causal relationships between human health and particles, including chemical and physical characteristics of injurious particles
- Molecular (physiological-biochemical) mechanisms of Nr impacts on human, animal, and plant health
- Human responses to airborne N (NO_x) and aquatic N (NO_3^-)
- The threshold at which atmospheric Nr deposition starts having detrimental impacts on various plant and animal species
- Refinement of critical levels and critical loads
- Perspective and retrospective analysis of N impact
- Chemical composition and role of organic material in N-containing aerosols
- Causal relationships between N dose, N form and response of vegetation and associated pests and diseases, on time scales from hours to decades
- Relative influence of acute episodes and chronic exposure to small amounts of Nr
- Relationship between NO_x and VOC emissions in ozone production. Long-range transport (>1000 km) of ozone precursors
- Distribution of Nr air pollutants and estimates of dry deposition of Nr in natural ecosystems in complex terrain
- Interactions with other prominent global change issues, most notably the impact of greenhouse gas emissions on the climate, in terms of both cause and effect
- The importance of N_2O in global circulation models for climate change
- Long-term effects, including interactions with global change (Nr+ CO_2+ temperature)
- The contribution from compounds typically not monitored or regulated, such as organic forms of N, on terrestrial systems
- The contribution of dry deposition to total N deposition. Uncertainties in dry deposition monitoring
- To what extent gaseous ammonia contributes to total Nr loads entering aquatic systems
- Ability to determine if contemporary changes in forest productivity are caused by increased Nr deposition over the last 60 years, land use changes, elevated CO_2, and other factors such as ozone stress
- Relative contribution of airborne Nr to forest growth
- The extent to which deposition of Nr to forests is contributing to a terrestrial carbon sink
- Determining where the major Nr sink is in forest ecosystems. How do Nr dynamics relate to C balance in forested ecosystems under various global and regional climate changes?
- Percentage recovery of the Nr applied in crop production
- The reasons for the relative inefficiency of Nr use in agriculture

- The extent of overfertilization in food production
- Methods of ascertaining the amounts of nitrous oxide and nitric oxide released from cropping systems and natural ecosystems, and methods of predicting crop N needs
- Influence of nitrogen fertilizers on carbon cycling and organic matter content in soils
- Extent of nitrogen soil pools below effective rooting zone
- Understanding of soil physical/chemical/ microbiological processes that control nitrate leaching into groundwater and surface waters
- Dynamics of soil processes, on time scales of hours and of decades
- Estimates of time intervals before Nr that is lost from crops enters underground aquifers
- Determining where denitrification sinks are and how they can be optimized to prevent eutrophication
- Rates of denitrification, retention, and immobilization of Nr in aquatic and terrestrial ecosystems
- Uncertainties in current relationships between Nr loading to aquatic environments and the effects of that loading

The Nitrogen Cascade of Effects

Nitrogen is unique among essential nutrient elements since a single atom of reactive N can have multiple beneficial and detrimental effects as it cascades through various reservoirs within a landscape and ultimately ends up in the ocean sediments or is returned to the atmosphere as non-reactive dinitrogen. We illustrate this 'nitrogen cascade' with a nitrogen flow model with several atmospheric, terrestrial and aquatic components (Figure 3). Each box within a component represents a potential beneficial or detrimental effect. The following series of possibilities illustrates the notion of a "cascade of N effects."

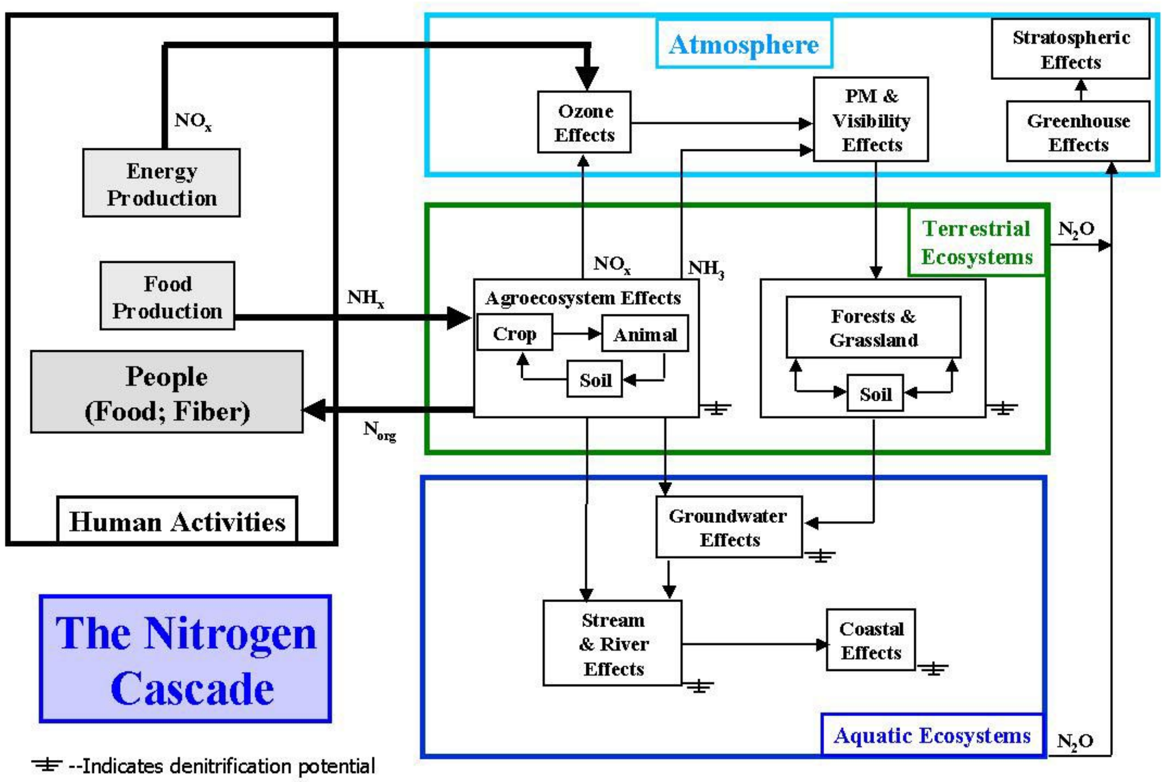

Figure 3. The nitrogen cascade illustrates the movement of human-produced reactive nitrogen (Nr) as it cycles through environmental reservoirs in the atmosphere, terrestrial ecosystems, and aquatic ecosystems (from plenary presentation by J. Galloway).

A given N atom – one made biologically active through oxidation processes as an unintended consequence of energy production and use, or another N atom made biologically active through chemical reduction processes in the Haber-Bosch fertilizer production process – can have many different beneficial or detrimental effects. It could first cause an increase in crop or forest productivity and then cause detrimental effects from increased atmospheric ozone (e.g., human health, and crop/forest damage), then, following conversion to N-containing aerosols, could result in the human health effects of increased particulate matter (PM) and decreased atmospheric visibility.

Eventually, the N atom (as NH_x or NO_y) could be deposited and cause forest effects, both beneficial and detrimental. The former is increased forest productivity and the latter are losses of biodiversity, and at higher nitrogen loadings, stresses on forest and natural ecosystem productivity growth due to N saturation. Once an Nr atom is released from soil into ground and surface water there are a number of other cascading effects, beginning with groundwater contamination, surface water acidification, and eventually coastal eutrophication. Lastly, the nitrogen atom as N_2O emitted from riverine and coastal environments can contribute to tropospheric warming, and eventually stratospheric ozone depletion.

C. Food Production and Nr

Farmers have always explored ways to increase food production per unit area of land. From earliest times they recycled nutrients in animal and human wastes. Later they imported guano as a source of Nr. Today, farmers in all but the poorest countries depend on synthetic N fertilizers to boost yields.

About 40% of the present ~6 billion global human population is dependent on synthetic N fertilizers produced by the Haber-Bosch process that converts non-reactive N_2 into biologically active NH_3. Much of the rest of the world's food is produced with N from increased biological N-fixation through planting of N-fixing legumes and paddy rice.

Food production must increase substantially in the decades ahead to meet dietary needs and food preferences of a larger and wealthier global population. Historically, preferences for animal protein in human diets have increased with every increment of per capita income. At present, about one-third of world grain production is used as feed for meat animals. In most of the world, livestock will contribute an increasing fraction of the N in human diets.

Because little additional arable land is available, site-specific precision agriculture approaches that minimize fertilizer use must be employed where feasible to produce optimum yields. This is especially necessary for high-nutrient-consuming crops including the major cereal grains of the world – maize, rice, and wheat.

Even well managed agricultural lands lose a substantial fraction of their fertilizer Nr inputs. Once lost, the released Nr can cascade through ecosystems, where it alters their dynamics and in many cases demonstrably reduces their ability to supply ecosystem services. In addition, it results in substantial increases in emissions of N_2O that contribute to global warming and stratospheric ozone depletion (see Section B).

Forage and feed grain N-use efficiency of food animals vary greatly among ruminants (cattle, goats, and sheep) and non-ruminant food animals (swine, poultry, and fish). Typical rates of on-farm N-use efficiency for production of human-digestible protein from feed grains and forages are ~50-60% for fish, ~40-50% for poultry and eggs, ~35-40% for dairy, ~30-40% for swine, and ~15-30% for beef. The remaining fraction (~40-85% of feed-grain N) can be re-used as manure-based fertilizer but often is lost as air emissions of ammonia or by leaching of nitrate to ground or surface waters.

Therefore, farmers, foresters, and aquaculturists must make significant improvements in N-use efficiency to achieve crop-, forest-, and animal-agricultural yields needed to feed, clothe, and house the world's people, while sustaining environmental quality within and beyond managed landscapes. Figure 4 illustrates the current average yield response and potential gains that can be made in yield response of corn (maize) to N fertilization with increases in yield potential and nitrogen use efficiency, primarily through improved management practices.

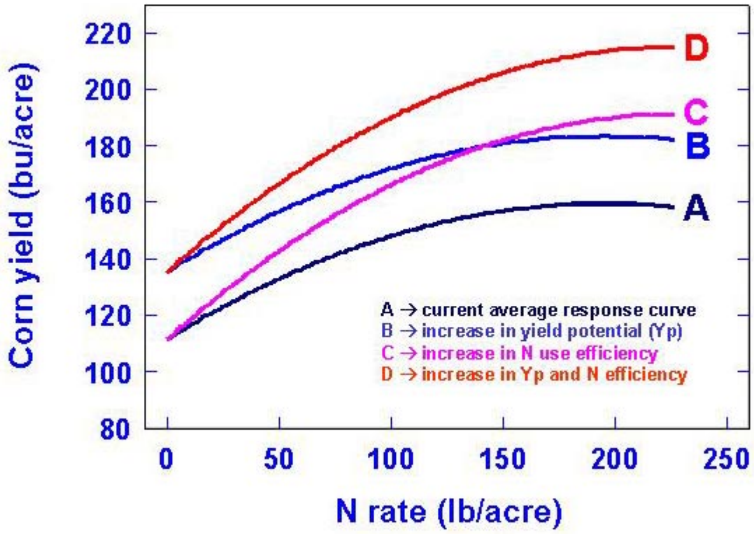

Figure 4. Current average response of corn yield to N fertilization rate, shown with response after potential increases in yield potential, N-use efficiency, and both (from plenary presentation by K. Cassman).

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 can we: 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.

Livestock production systems offer large opportunities for improvement of N-use efficiency. Where livestock are fed N-fertilized grain (mostly in North America, Europe, and China), changes in feed composition can increase N-use efficiency in food animals without affecting the quality of human-digestible protein in meat products.

In recent decades, powerful economic and social forces, including economies of scale, efficiency of specialization, cheap food and transportation policies, and global competitiveness, have transformed livestock and meat-processing industries in many countries. These changes often lead to largely unforeseen Nr-induced environmental problems mainly on local and regional scales:

Intensification in confined animal feeding operations increases ammonia emissions and nitrate discharges.

Decoupling, the physical separation of the land where feed grains are produced from the site on which food animals are raised, results in lack of economically viable systems for redistribution of nutrients in animal waste back to the land base used for crop production. As a result, much of the N and other valuable nutrients in animal manures is released into the environment – often as volatile ammonia and amines which are deposited in the vicinity of the animal rearing facility rather than returned to the (sometimes far-distant) land where the feed was produced.

Regionalization and globalization of markets increases NO_x from transport vehicles as feed, animals, manures, and finished products are transported – often from Nr-poor to Nr-rich areas.

Vertical integration has great potential to maximize N-use efficiency with integrated economic and advisory-service linkages among farmers, feed suppliers, animal-rearing advisors, and food-processing companies. But emphasis only on economic efficiency and not on Nr-induced health and environmental risks leads to externalization rather than internalization of these real costs.

In attempting to decrease the impact of livestock production on the environment, much better information is needed on the transport and fate of Nr and other nutrients from both conventional and alternative animal production systems. Economically viable technologies are needed for conservation and reuse of Nr in all sorts of animal rearing facilities. Such technologies should be aimed at one or more of three possible goals:

a) conversion of manures into marketable fertilizer products for reuse in crop production,
b) production of energy or other value-added products for use in industry and commerce, or
c) denitrification back to atmospheric N_2.

The most serious obstacles to these three options are:

a) the large distances over which feed grains are transported before delivery to animal rearing facilities – sometimes in another state or even a far-distant country,
b) lack of convenient processes for combining manure-based fertilizer products with synthetic chemical fertilizer in intensively managed cropping systems, and
c) reluctance and doubt among farmers and their advisors about the technical or economic feasibility of alternative systems for nutrient management and animal production.

Farmers must show a profit to continue farming. Because maximization of profits is generally not congruent with minimizing losses of Nr 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, as well as the costs associated with decreases in environmental goods and services.

Policies designed to promote greater N-use efficiency in agriculture should emphasize incentives to farmers (i.e., paying farmers to be good stewards) rather than punitive regulations, so as to avoid export of crop and livestock production to areas with less stringent environmental guidelines.

It is important to restore and maintain both carbon and N pools in agricultural soils, while at the same time sustaining yield increases to meet food demand and achieving substantial increases in the efficiency with which applied N inputs from both inorganic and organic sources are utilized. Indeed, maintaining soil quality, sustaining yield increases, and minimizing N losses are perhaps some of the greatest scientific challenges confronting efforts to address the global N problem.

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. In such systems, N is simply used as a 'shovel' to mine the soil of other nutrients, with the result that soils initially well supplied in other nutrients become deficient in them.

Over-consumption of protein-rich foods and consequent excretion of urea by humans is a growing source of Nr, which is processed in municipal sewage treatment systems that are rarely designed to facilitate capture of available Nr for use in agriculture and forest production. In addition, support of the meat-dominated diets of developed, and increasingly developing, countries necessitates the use of large amounts of nitrogen fertilizer and concomitant creation of Nr. Education of the public about the environmental consequences of various diet and lifestyle choices, and changes that would result in decreased environmental loadings of N as well as potential health benefits, is critical (Figure 5).

The path of future developments in the food and agriculture sectors of the various nations of the world will be determined in part by: 1) energy and food production policies, 2) world trade, economic, and environmental protection policies, 3) new discoveries in nutrient use efficiency and in technologies for reuse of nutrients in crop and animal production systems, 4) adjustments in public dietary preferences, and 5) the effectiveness of nutrient-educational programs for farmers, leaders in agribusiness enterprises, consumers, and public-interest groups. In turn, these trends will determine the degree to which environmental effects of Nr loading will be positive or negative.

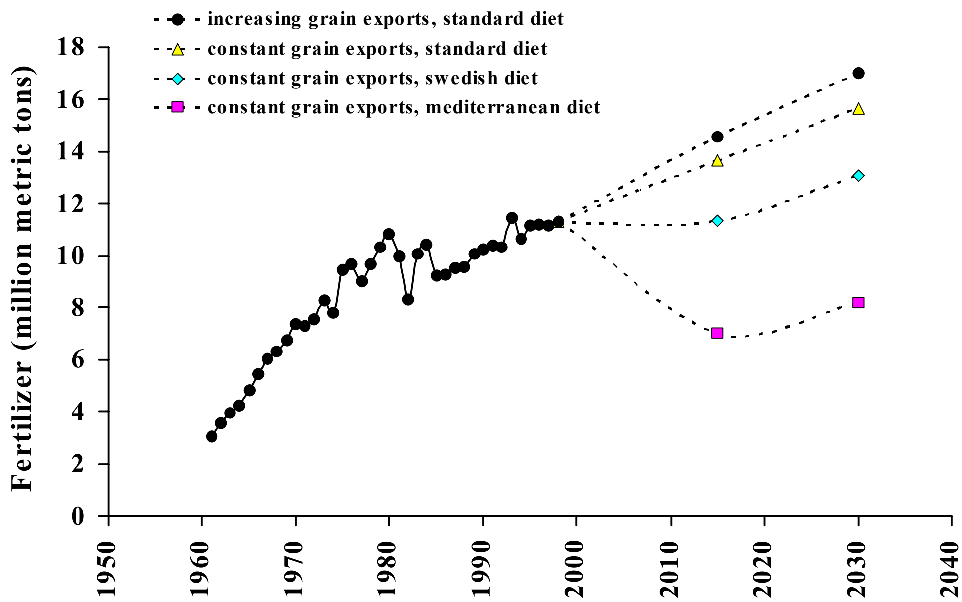

Figure 5. Projections of N fertilizer consumption in the US, based on either constant or increasing grain exports, and variations in diet. (from plenary presentation by R. Howarth).

In North America the principal foci of concern regarding N use in agriculture will be *environmental impacts* and *food safety.* Governmental policies and Nr emissions control measures will be aimed at decreasing N losses from food production systems and thus decreasing detrimental environmental impacts. Acceptable environmental thresholds will likely be established by federally mandated guidelines. Responsibility for ensuring that these guidelines are met will fall to state and local governments. Aggressive education programs and incentives for adoption of improved management practices have been the preferred method for achieving compliance, and it is likely that these approaches will continue to be used. A number of successful programs can be cited to document the effectiveness of this approach.

Europe is expected to show a continuing shift in focus in Nr management practices from the continent's already well developed *environmental awareness* towards increased concern about *food safety and quality* and *animal welfare.* These shifts in focus likely will lead to some extensification rather than just intensification of livestock production systems and increased responsiveness to animal welfare and consumer concerns. Food animals probably will be housed in systems that are less confined, and that may be more conducive to gaseous Nr losses than “closed” animal housing systems, unless appropriate strategies are developed for absorption of volatile ammonia and amines that keep the N cycling within the housing units. The currently successful "green-farm demonstration project" in the Netherlands may become a model for comparative evaluation of alternative crop and animal production systems – not only because it leads to more nearly optimal and cost-effective N management, but also because it shows the potential for cooperative research and demonstration efforts by Ministries of Agriculture, the Ministries of the Environment, and the Farmers Unions of other nations of the world.

In Asia, meeting *food demand* and achieving *food security* will continue to be the primary concerns of policy makers, although increased standards of living also will lead to more diverse diets, greater consumption of livestock products, and demand for higher food quality. With limited land resources and high population density, crop production systems must further intensify to meet food demand. However, yields achieved in many of Asia’s most productive cropping systems are already approaching their yield potential ceilings and rely on high rates of fertilizer Nr input. Moreover, fertilizer N-use efficiency is relatively low in Asia; this indicates the potential for significant Nr losses and resulting negative environmental consequences. Thus, policies must be developed that foster research, extension, and crop management practices that result in greater fertilizer N-use efficiency while supporting continued improvements in crop yields. Two other Nr issues in Asia are: a) the degree to which Asian countries strive for self-sufficiency in food production or rely on food imports to satisfy a portion of human dietary requirements; and b) the degree to which large-scale confined feeding livestock production operations are developed to meet increased demand for meat products. Resolution of these two issues will greatly influence the nitrogen requirements and environmental consequences of nitrogen use in Asian agriculture in coming decades.

Agriculture is a globally competitive business, and international competition is likely to increase as the free trade movement continues to expand. The negative effects of Nr on the environment have global consequences and the effects cannot be constrained by political boundaries. Hence, regulatory approaches must strive to seek uniform standards, minimize 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. Political preferences for increased free trade among nations and decreased agricultural subsidies within nations must not have the unintended net effect of encouraging crop and animal production in regions with the least stringent environmental regulations. For this reason, further public educational programs about specific nutrient management practices and their intended and unintended consequences in various part of the world will become more important in the future. Investment in research to ensure a steady stream of innovations that both lead to decreased Nr losses and are cost-effective is another pivotal component.

Table 1. Potential value-added marketable products that can be produced from animal manuresEnergy in the form of methane, biogas, diesel fuel, or electricity for direct on-farm purposes

- Electricity for sale through co-generation contracts with public utilities
- Synthetic growth media for high-value ornamental plants or soil amendments for residential or commercial landscaping purposes
- Nitrogen- and phosphorus-rich fertilizer materials for direct application to crops such as corn, cotton, sweet potatoes, etc., or to fast-growing conifer and/or hardwood plantations
- Fertilizer materials for green-house production of floral crops and other ornamental plants
- Feed materials and nutritional supplements to enhance feed conversion efficiency in fish, poultry, and livestock production. These supplements could include dehydrated duckweed, high-protein fish meal, and amino acid and vitamin supplements
- Protein products for veterinary applications in aquaculture, poultry and livestock industries including nutritional enzymes, edible vaccines and anti-viral proteins such as interferon;Protein products for industrial applications including industrial antibodies and enzymes used in detergents, recycling, and in processing of pulp, paper, textile, and chemical products
- High-value protein-based biomaterials including adhesives, fibers such as silk, optically-active films, other biopolymers, and plastics
- Food materials for companion animalsHigher-value foods for human consumption including wholesome fish, vegetable, fruit, and dairy products

The prices of energy and fertilizer are directly linked, since 80% of the input costs of N_2 fixation is the energy and hydrogen supplied by the natural gas used in the Haber-Bosch process. Increased demand for natural gas to supply energy, concern over global warming, and the growing preference for use of natural gas in generation of electricity have created new competitive forces driving up the cost of the natural gas energy feedstock for ammonia synthesis and so the price of Nr fertilizers. Additionally, increased transport of feed grains, fertilizers, and food products and its influence on food costs is an important aspect of the linkage between the costs of energy and fertilizer N. Large potentials exist for technologies that link energy and fertilizer production and convert NO_x to value-added fertilizer and other end products (Table 1).

D. Energy Production and Nr

Combustion of fossil fuels forms NO_x as a waste product from fuel-N (organic N) and atmospheric-N (N_2). The primary sources of NO_x emissions are combustion of coal, oil, and natural gas for energy production and use (e.g., generation of electricity, transportation, industrial and construction processes, domestic space and water heating, etc.).

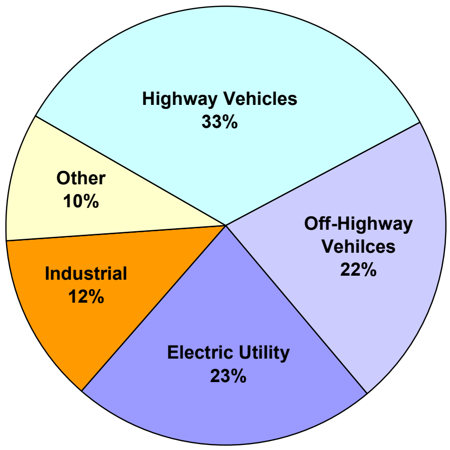

Figure 6. NO_x emissions in the US by sector in 1999 (presented by M. Bradley).

In the United States during the period 1988 to 1997, large stationary electric generators and industrial boilers accounted for roughly 9 to 10 million metric tons, or approximately 45 percent, of the NO_x entering the atmosphere from human activities. In addition to stationary point sources, transportation-related sources added between 10 and 11 million metric tons of NO_x to the atmosphere during each of the past 15 years, contributing 53 percent of all NO_x emissions. Current (1999) NO_x emissions in the US are ~23 million metric tons. The transportation sector is responsible for 55% of this NO_x production. The electric utility and industrial sectors account for 23% and 12% respectively (Figure 6).

Global energy consumption is projected to increase ~2-3% annually from 1999 to 2020 – for a total increase of ~60% over current rates. Most of this increase will occur in developing countries. For example, China's energy consumption is expected to triple by 2020, with energy consumption expected to increase by ~4.5 % per year in all of Asia (Figure 7). In the industrialized world, in contrast, growth in energy consumption is estimated at less than 2% per year due to market saturation and advances in energy efficiency.

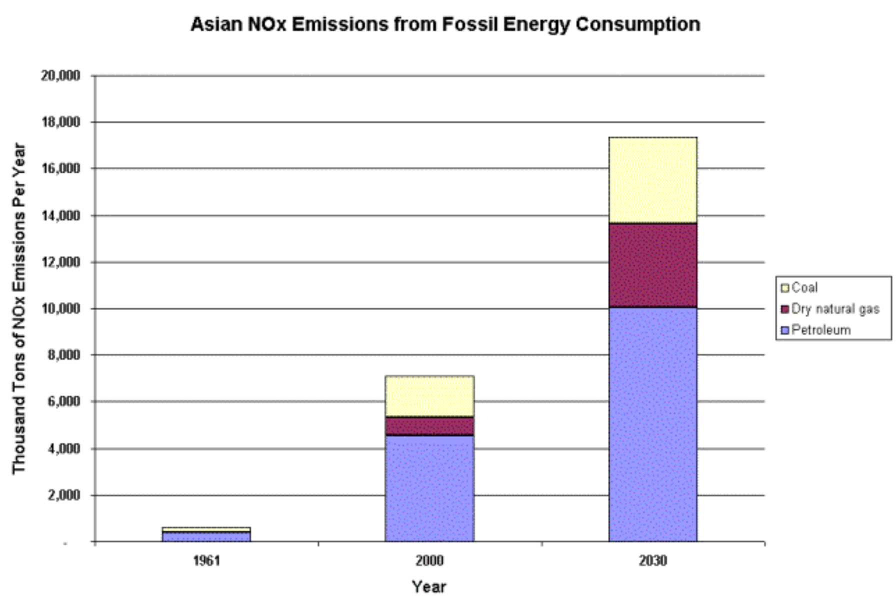

Figure 7. NO_x emissions in Asia from fossil energy consumption in the years 1961, 2000, and 2030 (from plenary presentation by M. Bradley).

Natural gas use is expected to more than double in many industrialized countries. While the energy market share for coal is projected to decline in Europe and Japan, coal is still expected to be the most common fuel for power generation in 2020 – with an estimated 31 percent share. Coal is expected to remain a major source of energy in the developing world, most notably in China and India, where heavy reliance on coal consumption is projected to continue through 2020.

Over the next two decades, transportation fuel use is expected to grow by nearly 5% per year in developing countries, compared to average annual increases of less than 2% in industrialized countries. Transportation energy use in large parts of Asia is projected to increase by ~7% per year between 1999 and 2020. Much of this growth is expected to be in the "on-road" sector – a combination of freight movement and personal motor vehicle use. Personal vehicle ownership is seen as a symbol of prosperity, and annual car sales are growing rapidly in many Asian countries.

Trends in the growth of fossil fuel use are alarming given the associated increase in air pollution and impacts on human health and the environment. Currently, the transportation and electric generation sectors are the dominant contributors to NO_x emissions in North America, Europe, and Asia. While NO_x emission trends in North America and Europe are projected to decline in the future due to regulatory measures, global NO_x emissions will probably increase as developing countries increase their standard of living by consuming more electricity and driving more.

Once nitrogen is emitted to the atmosphere as NO_x, it can cascade through the environment and contribute to smog, fine particle formation, visibility impairment, acid deposition, excess nutrient inputs to estuaries and near-coastal waters, global warming, and stratospheric ozone depletion.

These phenomena contribute to detrimental effects on human health and the environment. As a precursor to particulate matter and ozone formation, NO_x emissions can lead to premature death, chronic respiratory illness (e.g., bronchitis or asthma), and aggravation of existing respiratory conditions. Environmental impacts of NO_x emissions and deposition include forest die-back, biodiversity loss in grasslands, acidification of streams and lakes, harmful algal blooms in coastal waters, and global warming. In the United States, these human health and environmental impacts are found in many areas of the country (e.g., both eastern and western states), and cost American society tens of billions of dollars each year when taken together.

The effects of NO_x on human health and ecosystems are of sufficient magnitude to result in regulations in many countries. NO_x emissions regulations vary greatly from one country to another, but regulated source categories generally include stationary sources (e.g., power generators, industrial boilers) and mobile sources (e.g., automobiles, trucks, construction machinery).

Nr Emissions Abatement

Measures to limit NO_x emissions in the US have largely focused on efforts to decrease human health effects from tropospheric ozone, of which NO_x is a primary precursor. NO_x abatement also has been achieved as a means to address ecosystem acidification in conjunction with much larger decreases in SO_2 emissions. The role of NO_x emissions in visibility impairment, fine particulate ($PM_{2.5}$) exposure and eutrophication is receiving increased attention in the US.

NO_x emissions from stationary and mobile sources in the US are limited by efforts to comply with various current and future regulations. These include National Ambient Air Quality Standards, New Source Performance Standards, Title IV of the 1990 Clean Air Act Amendments, the Ozone Transport Commission NO_x Budget Allowance Trading Program, State Implementation Plan NO_x emissions decreases, Section 126 of the 1990 Clean Air Act Amendments, and Mobile Source Emission Limits. Some background of these regulations and the NO_x policy in the US is given in Table 2.

Table 2. US regulatory programs to control NO_x and other pollutants.

Policy Program/Pollutant	Affected Regions	Compliance Date	Decrease in NOx Emissions
NOx Reasonably Available Control Technology			
Nitrogen oxides	Nationwide	NA	Source specific/varies
Revised New Source Performance Standards			
Nitrogen oxides	Nationwide	NA	25,800 tons/yr
The Acid Rain Program (Title IV of CAA)			
Sulfur dioxide	Nationwide		
Nitrogen oxides	Nationwide	Phase I –1995 Phase II – 2000	340,000 tons per year in Phase I, 2.06 million tons/yr in Phase II
OTC NOx Budget Program			
Nitrogen oxides	12 States & DC: CT, DE, ME, MD, MA, NH, NJ, NY, PA, RI, VT, VA	2003 0.15lbs NOx/mmBtu	246,000 tons in 1999, 322,000 tons in 2003
Section 126			
Nitrogen oxides	12 States & DC: DE, IN, KY, MD, MI, NJ, NY, NC, OH, PA, VA, and WV	2003 0.15lbs NOx/mmBtu	510,000 tons in 2007
NOx SIP Call			
Nitrogen oxides	19 States & DC: CT, DE, GA, IL, IN, KY, MD, MA, MI, NJ, NY, NC, OH, PA, RI, SC, TN, VA, and WV	2004 0.15lbs NOx/mmBtu	Over 800,000 tons in 2007
Tier II Mobile Standards			
Nitrogen oxides Non methane organic compounds		New passenger cars and LDT Phase in 2004 – 2007	Vehicles 77-95%
Volatile organic compounds	Nationwide	Heavy LDT Phase in 2008- 2009	
Sulfur in gasoline		Sulfur in fuel 2006	Fuel - 97%

Total current (1997) NO_x emissions in Europe are 13 million metric tons. The transportation sector is responsible for 55% of this NO_x production. The energy and industrial sectors account for 19% and 14% of the NO_x emissions, respectively.

In Europe, the major efforts to decrease the effects of Nr emissions have been aimed at decreasing transfers to air, soil, and groundwater. Most of the measures in Europe were focused on decreasing human and plant exposure to N pollutants and to decrease ecosystem loads leading to acidification and eutrophication. Countries agreed to decrease air emissions of Nr by signing different protocols developed under the Convention on Long Range Transboundary Air Pollution (CLRTAP). Table 3 gives an overview of various emissions targets. The last protocol, the Göteborg Protocol, was unique in the sense that it requires decreases in emissions of four pollutants with the objective of abating three specific effects (acidification, eutrophication, and the effects from tropospheric ozone on human health and vegetation). The protocol, which has so far been signed by 29 European countries together with United States and Canada, was based on a gap-closure method aiming at decreasing the spatial exceedances of critical loads and levels in the most cost-efficient way. Critical loads for each European country are defined on the basis of information developed by each country. The agreed-upon decreases in emissions for the European Union (EU) member states are listed in Table 3. The outcome of the protocol is an expected decrease in the European (except Russia) emissions of nitrogen oxides of approximately 44% for the period 1990 to 2010. The corresponding figure for ammonia is 17%. The United States has not yet defined its target decreases in Nr emissions.

The protocols (Table 3) have had a major effect on emission trends in Europe, especially for SO_2. European decreases in emissions are being made with the clear objective that environmental loads, exposures, and effects should be decreased – the so-called "effects-based approach," which was initiated under the Second Sulfur Protocol. European sulfur emissions were decreased by 41% between 1980 and 1998. In the same years NO_x emissions were decreased by 21%, mainly after 1990. Emission estimates for N_2O are highly uncertain, but statistics indicate a decrease of about 10% in the EU from 1990 and 1998.

For NO_x the main means by which to decrease emissions is exhaust pipe regulations introduced in the EU countries about 1990, resulting in the application of three-way catalysts in gasoline-powered cars. Regulations on heavy-duty vehicles have decreased NO_x emissions. Furthermore, selective catalytic reduction technologies (SCR) with ammonia or urea as a reductor have been implemented in many combustion plants. In eastern Europe the main reason for decreases in NO_x emissions is the shut down of a large number of industrial plants.

Table 3. Air emissions targets for the EU.

Policy/Pollutant	Base year	Target year	Decrease (%)
UNECE-CLRTAP			
Sulfur dioxide[1]	1980	2000	62
Sulfur dioxide[4]	1990	2010	75
Nitrogen oxides[2]	1987	1994	Stabilization
Nitrogen oxides[4]	1990	2010	50
Non-methane VOCs[3]	1987	1999	30
Non-methane VOCs[4]	1990	2010	58
Ammonia[4]	1990	2010	12
5th Environmental Action Plan			
Sulfur dioxide	1985	2000	35
Nitrogen dioxide	1990	2000	30
Non-methane VOCs	1990	1999	30
Dir. On Nat. Emission Ceilings (NECD), proposed targets[5]			
Sulfur dioxide	1990	2010	78
Nitrogen dioxide	1990	2010	55
Non-methane VOCs	1990	2010	62
Ammonia	1990	2010	21

Notes:
1 Target from the 1994 Second Sulfur Protocol. The different emission ceilings for each Member State correspond to an overall 62% decrease in emissions for the EU.
2 Targets from first NOx Protocol. These are the same for individual Member States and for the EU.
3 Targets from NMVOCs Protocol. These are the same for individual Member States and for the EU.
4 Targets from the multi-pollutant Göteburg Protocol (1 December 1999). The emission targets for the EU that correspond to the different emission ceilings for each Member State (as the EU was not formally a signatory to this protocol).
5 Targets from the European Commission's 1999 proposal for a National Emission Ceilings Directive (NECD). The emissions target for the EU that corresponds with different emission ceilings for each Member State is shown.

On a global basis, energy production has not contributed to total Nr increases to the same extent as nitrogen use in agriculture, but its contribution to the fluxes to the environment are similar. There are many current examples of the technical capability to decrease NO_x emissions from fossil fuel burning sources worldwide. Over the last 30 years, technological advances have achieved significant decreases in NO_x emission rates from both mobile sources (emissions per km/mile traveled) and stationary sources (emissions per kWh). Engineering solutions currently exist to decrease most of the NO_x

emissions from power generation and mobile sources and, in many cases, can be exported to other countries with few variations.

Despite declining emissions rates, however, total NO_x emissions have remained constant or even increased over the same period in North America and Europe due to increases in vehicle kilometers/miles traveled, electricity usage, and the sometimes-differing regulatory frameworks applied to various sectors. Decreasing total NO_x emissions likely means that continuing technological advances may need to be combined with regulatory approaches (e.g., emissions caps).

It is now technically feasible and likely economically possible to further decrease NO_x emissions from fossil fuel combustion to the point where they become only a minor disturbance to the nitrogen cycle at all scales. Clean electric generation and transportation technologies are commercially available today, or will be commercially available within one to two decades. They have the potential to further decrease NO_x emissions in industrialized countries and to decrease NO_x emissions from projected business-as-usual amounts in developing countries. In addition, technologies currently under development, such as renewable energy and hydrogen-based fuel cells, could operate with zero NO_x emissions.

The vast majority of the world's population lives in regions where decreases in NO_x emissions have not occurred. In many countries, significant increases in NO_x emissions are projected to occur over the next several decades due to both population growth and per capita increases in fossil fuel use. The biggest opportunity for decreases in NO_x emissions in the developing world involves a "technology leap" through adoption of advanced technologies such as zero emission-distributed power (e.g., photovoltaic, wind, small hydro, and fuel cells) and both near-zero and zero emission electric transportation vehicles (e.g., electric, hybrid electric and fuel cells).

During the 1970s, major attention was given to energy conservation measures designed to avoid depletion of coal, crude oil, and gas reserves. Since then, the known reserves of natural gas have increased from 40,000 to 146,400 billion m^3 in 1998. The current world coal, crude oil, and natural gas reserves are estimated to be 143,400 Mtoe, 500 Mtoe and 131.800 Mtoe, respectively (Mtoe = Mton oil equivalents). Thus there appears to be enough fossil fuel available for at least the coming 50-100 years, and it is expected that these estimates will increase as new technologies become available with which to discover and add new sources of fossil fuels.

The current world concern about fossil fuel combustion is driven by the apparent necessity to decrease CO_2 emissions. Continuing increases in CO_2 concentrations in the atmosphere and associated climate change may necessitate drastic changes in our energy production and use. Focusing only on NO_x as a pollutant from energy production and use will not lead to drastic changes in energy systems. In order to abate NO_x emissions from energy production, a multiple-pollutant approach should be used; that developed within the Göteborg Protocol appears to be very promising. Unless yet-to-be-developed carbon sequestration technology emerges, decreasing CO_2 emissions will automatically decrease NO_x emissions. On the contrary, NO_x abatement nearly always leads to increased energy use and thus to increased CO_2 emissions. These technologies are focused on enhanced combustion – producing less NO_x (lean burn) or by using "end-of-pipe" technologies, such as selective catalytic reduction (SCR). Both technologies decrease energy efficiency, and the majority of SCR technologies require ammonia or urea as a reductor, which is produced from natural gas. When considering abatement options for NO_x, the options for decreases in CO_2 emissions should be considered first, followed by options to decrease energy-related Nr emissions.

Carbon Management Addressing Greenhouse Constraints for Energy Nitrogen

If the energy system of the world remains based on fossil fuels throughout the 21^{st} century, and little is done to target atmospheric emissions of CO_2, it is plausible that atmospheric CO_2 concentration will reach triple its "preindustrial concentration" of about 280 parts per million by the year 2100. The specific implications for climate change, sea level rise, and ecological disruption are uncertain, but they could be severe. Strategies to slow the rate of build-up of atmospheric CO_2 are now being developed worldwide, and all of them appear to have the positive effect of decreasing energy-related Nr emissions.

First among these strategies is an increase in the efficiency of energy use throughout the global economy, resulting in less energy required to meet the variety of amenities that energy provides: mobility, comfort, lighting, material goods. Greater energy efficiency directly decreases energy-related Nr emissions.

Other strategies to decrease CO_2 emissions address the mix of energy supply sources:

1) Nuclear energy and renewable energy are non-fossil alternatives, resulting in CO_2 emissions only to the extent that fossil fuels are used to create non-fossil energy production facilities. Neither nuclear nor renewable energy sources produce energy-Nr.
2) The mix of coal, oil, and natural gas in the energy supply affects carbon dioxide emissions because they have different carbon intensities (carbon content per unit of thermal energy). Specifically, of the three, coal has the highest and natural gas the lowest carbon intensity. Thus, shifts from coal to oil or natural gas and shifts of oil to natural gas, other factors held constant, decreases the greenhouse impact of fossil-fuel-based energy systems. The nitrogen emissions intensity of fossil fuels (nitrogen content per unit of thermal energy) differs in the same way (i.e., on average, of the three, the N intensity of coal is largest and the N intensity of natural gas is the smallest). Thus, fuel shifts within the fossil fuel system that reduce greenhouse impacts will also reduce fossil-N.
3) Many countries around the world are investing in research, development, and demonstration projects that explore various means to capture carbon from combustion processes before it reaches the atmosphere and sequestering it on site or off. Several currently available technologies can be used to separate and capture CO_2 from fossil-fueled power plant flue gases, from effluents of industrial processes such as iron, steel, and cement production, and from hydrogen production by reforming natural gas. CO_2 can be absorbed from gas streams by contact with amine-based solvents or cold methanol. It can be removed by absorption on activated carbon or other materials or by passing the flue gas through special membranes. However, these technologies have not been applied at the scale required to use them as part of a CO_2 emissions mitigation strategy. The goal is to sequester the carbon in a cost effective way, for example as carbon dioxide injected deep below ground in saline aquifers. This is a relatively new area of research and development, and little attention has yet been given to the consequences of fossil carbon sequestration for energy-related Nr emissions, but decreases in energy-N are a likely result. For example, to capture and sequester the carbon in coal will require gasification of coal and subsequent production of hydrogen and a CO_2 gas stream. Coal-Nr should be amenable to independent management, with outcomes that include conversion to saleable by-products or co-sequestration of Nr below ground together with CO_2. The first of these outcomes is one of many "polygeneration" strategies for coal, where products could include electricity, hydrogen, process heat, hydrocarbons, dimethyl ether, and nitrogen-based fertilizers or other by-products. The long-term goal is to run the economy on non-carbon secondary energy sources, specifically electricity and hydrogen, while sequestering emissions of CO_2 and replacement of fossil fuels by renewables.

E. Summaries of Round Table Discussions and Contributed Papers in Science and Policy Sessions

This section consists of summaries provided by moderators of the contributed paper and poster presentations that were held each day during the Conference. For specific titles of these presentations, please see the Conference Schedule in Appendix B. Abstracts of all contributed papers and posters are available on the internet at http://www.thescientificworld.com.

The Round Table Discussion about Nitrogen Around the World and Its Effects
Hans Paerl, Moderator

Several questions/issues concerning sources, sinks and cycling of nitrogen in the context of ecosystem function, response and service were discussed in this round table session. They included the following.

1. Should we manage Nr on its own or in relation to other elements?

Terrestrial and aquatic ecosystem responses to Nr inputs are moderated by both the amount and rates of Nr input (loading) and the proportionality of those loads in relation to other essential elements. In many freshwater and brackish water bodies, phosphorus (P) is the element most limiting to primary production. In addition, N and P may be co-limiting in the transition zone between fresh and saltwater, and even some estuarine and coastal waters may exhibit periods and places of N and P co-limitation. Therefore, *both* N and P loadings must be considered contemporaneously and contiguously. In addition, the ratio of N to P to silicon (as well as other potentially-limiting nutrients such as iron) loading must be incorporated in evaluations of ecological responses to nutrient loading in estuarine and coastal environments. These ratios can be important in structuring biological communities as well as their overall responses to enhanced nutrient loading. Lastly, N loading must be considered (and controlled) on the watershed- and airshed-scale (not just in downstream lands adjacent to Nr-sensitive water bodies). While it is agreed that (within watersheds) site-specific decreases in Nr loadings must be considered, these decreases in loadings must be incorporated in the context of basin-wide decreases in Nr concentrations entering the head of the estuary (i.e., the overall prescribed decreases in Nr loading at the entrance to the estuary or coastal system must be met if perceptible improvements in water and habitat quality are to be achieved).

2. Can a consensus statement be developed that: a) conveys general agreement that decreases in Nr loadings are needed to improve water quality in Nr-sensitive estuarine and coastal ecosystems; and b) indicates that there is reasonable agreement that target decreases in Nr inputs (to Nr-sensitive waters) are reasonably close to N outputs from agricultural and urban lands?

Agreement was reached that some simple (easy to understand and articulate in management and political circles) statements addressing these important points are needed if we are to have any impact on reducing the global N "glut" from water quality, fisheries and other coastal ecological and economic resource perspectives. We need a straightforward description of and prescription to the "N problem."

We should seriously strive to reduce the outputs of N from agricultural systems so that N and P inputs to freshwater, estuarine and coastal systems can be reduced. We should have a serious and achievable goal. The reduction of agricultural outputs should be targeted to be challenging and sufficiently significant that the reduction in inputs to estuarine/coastal systems will be measurable and have a noticeable, positive impact. In the US, Total Maximum Daily Loads (TMDL's) could serve as a rough guide on the basin-level. In Europe, similar guidelines are being developed.

We need to include key identifiable externalities into the economic calculus and develop a more systems-integrative approach to the economic analyses and (then) replace the domain-specific, narrow calculus of optimization currently in use.

We need to recognize the risks the farmers (as food producers) are responding to (and adjusting for) in their fertilizer application, plus the risks being exported to fisherman (as food producers) and society (including users of coastal resources, tourism, recreation, etc.) and develop a societally sensitive and responsible approach to mitigating the risks, supporting the food producers and improving the environment.

Each watershed differs in its ability to retain nitrogen, depending on the specific land cover, land use history, and geologic/hydrologic properties.

The Round Table Discussion about Nitrogen Production and Movement
Stan Smeulders, Moderator

This Round Table discussion began with a general assertion that "cheap food policies" and "low energy costs" in many countries of the world were major obstacles to fulfilling the general theme of the Second International Nitrogen Conference – "Optimizing Nitrogen Management in Food and Energy Production and Environmental Protection." The discussion can be summarized in the following three parts.

Policy
The need for alterations in the current imperfect market situation was generally recognized by all participants. Continuing externalization of environmental costs inevitably will lead to continuing unintended disruption of the global nitrogen cycle. This fact will need the sustained attention of policymakers on the highest international level, especially within organizations that understand and seek to manage global marketing systems – for example, the World Trade Organization (WTO), the General Agreement on Tariffs and Trade (GATT), and the Food and Agriculture Organization (FAO) of the United Nations (UN). Although some progress can be made by smarter infrastructure planning with regard to local and regional transportation and energy production systems and by education, economic incentives, and increased environmental awareness with regard to food production systems, it was generally agreed that the social and economic forces favoring cheap food policies and low energy costs will continue to cause serious disruption of the global nitrogen cycle. It also was noted that efforts should be made to attract more agricultural, natural resource, energy, and environmental economists into discussions and debates about probable, possible, and preferable nitrogen management futures for various nations and the world as a whole.

Consumers
Changing our own behavior can contribute to a very large extent to decreasing the circulation of Nr in the atmosphere and biosphere of the Earth, but is extremely difficult to enforce. Statistics show that an increase in meat consumption accompanies increased incomes. No clear conclusion was reached about the extent to which this linkage can or should be altered.

Science
It was generally agreed that many ecosystem responses to increased Nr loads occur above a certain threshold, and we should better communicate and present the data that demonstrate this phenomenon. However, many effects occur below a specific threshold or do not show a threshold-type response, so that we see a gradually changing environment. Society must determine how much change we are willing to accept. Focusing only on thresholds can be misleading.

The Round Table Discussion about Innovation With Nitrogen
Oene Oenema, Moderator

Question 1. What are the top priorities for innovations in Nr research and policy, needed to meet the requirements of a sustainable society in, for instance, 2030?

- Developing economically sound and applicable policies and measures
- Developing incentives for improving N-use efficiency in society
- Integration of plant and animal production systems
- Developing economically and environmentally sound management measures
- Developing flexible and practical approaches, using also experiences from other countries
- Conversion of agriculture from reliance on synthetic Nr fertilizers to a reliance on BNF
- Site-specific measures; stop farming and industries at vulnerable sites
- Integrated nutrient management, i.e. all essential nutrients must be considered and not only N
- Controlled release fertilizers
- Education, training, and information transfer
- Communication
- Involving consumers in Nr-related environmental problems
- Novel molecular techniques to develop plants with higher nutrient-use efficiency
- Accurate and site-specific test for estimating soil-mineralizable nitrogen

Note: This list easily could have been extended, if the discussion had continued. It is also likely that other suggestions would have been made, if the question were known in advance.

There was also a strong plea for more synthesis and for more integrative policy and research. The building blocks for novel and highly improved agricultural systems are more or less known. Talented scientists should work together with people from industry, retail, consumers, policy, and green action groups to synthesize and design new and much improved systems that meet the criteria of all of the actors, at farm and/or landscape level. There should be room for experimentation in the field to test, demonstrate, monitor and further improve and adjust such novel systems. These novel systems may be farming systems or may include multiple industries in whole catchments or drainage basins.

Question 2. This Conference reveals again the wealth of knowledge and resources applied to Nr problems in rich countries and the dearth of knowledge and resources (and participants) from the developing world. How can we bridge this chasm?

- Capacity building in the developing countries is indeed a great challenge, just as the transfer of knowledge is a great problem.
- Suggestions were made to locate fundamental research programs in developed countries, and to increase and improve the applied research pursued in developing countries.
- More cooperation between research institutions in developed and developing countries is needed, via the concept of sister institutions and via exchange of students, data, equipment, and scientists. This holds for economic, agronomic, technical, and environmental aspects.
- Mechanisms should be developed so that environmental problems of industrialized countries are not transferred to developing countries, and that the developing countries get the technology and information necessary to anticipate the problems that they may encounter with economic growth, i.e. pro-active strategy.

Question 3. There has been little mention about US EPA's pending developments of nutrients criteria in surface waters for protection of ecosystems; the regionalization approach in USA is a particularly significant approach. Can you comment on the future role of these criteria in research needs, implementation and performance checking?

- The emissions of ammonia into the atmosphere and their effects on atmospheric chemistry and on eutrophication, acidification, and damaging natural environments is seriously underestimated in the US.
- A holistic approach is needed, in which all Nr sources and pathways and receptors are considered. Such integrated approaches may provide hints about optimum strategies, but holistic approaches may not be the most successful strategy.
- Much more attention should be paid to education and training of students to think holistically and to encourage them to develop innovative ways to pursue integrated research.

Nitrogen Management in Animal Agriculture

Rick Kohn, Chair

Nitrogen losses from several different commodity production systems including beef feedlot, sheep, and dairy farming systems are the subject of significant research. Seventy to 80% of Nr inputs to animal production systems are lost via volatilization of ammonia, runoff, and leaching. Because production animals use forages, byproducts, and grains that can be produced with minimal environmental impact, animal production still compares favorably to row crop production directly for human consumption from an environmental point of view. Most of the losses from animal production are in the form of volatilized ammonia. Most inorganic manure Nr is volatilized to ammonia from feedlot or barn facilities, manure storage, and after application to crops.

Manure is not used as efficiently as inorganic fertilizer as a source of nutrient nitrogen because of the propensity for volatilization and uncertainty about the rate and extent of organic N availability. Extent and timing of manure N mineralization is difficult to predict, resulting in higher application rates of manure N compared to inorganic fertilizer. Thus, more Nr may be available for leaching compared to using inorganic fertilizer. Better understanding of manure N mineralization and volatilization is important to improving manure N utilization. Immediate incorporation of manure N and inexpensive covers for manure storage facilities were suggested to be management strategies that are currently available for decreasing N losses from animal agriculture.

The most cost-effective means currently available to decrease N losses from animal agriculture was suggested to be decreasing feed N inputs through optimal nutrition. For swine and poultry, balancing diets on the basis of required amino acids was considered a major breakthrough for decreasing N inputs and losses from the system. Such technology is not widely applied to cattle owing to the complexity of their digestive system. Acceptance of current recommendations for animal feeding should decrease total Nr losses from animal agriculture by approximately 10%. Further decreases will require development of new technology in animal feeding. These technologies include developing methods to balance the risks of underfeeding and overfeeding of domestic animals, developing feed additives to improve nutrient utilization efficiency, genetic or management manipulation to improve the efficiency of feed N utilization, and improving our understanding of animal nutrient requirements.

Application of current technology could decrease N losses from animal agriculture by 10 to 15%. However, current regulatory and incentive programs do not provide adequate incentives to adopt these technologies. Current programs emphasize runoff from feedlots, which accounts for 3% of total N losses. Rewarding producers who decrease fertilizer and legume inputs, or taxing N inputs, would provide further encouragement to improve animal nutrition and decrease Nr volatilization from farms. Further research and development related to manure volatilization and mineralization processes, and animal genetics, production, and feeding is needed to further decrease N losses.

Forests and the Nitrogen Cycle
John Aber, Chair
Recent research has explored several novel and important aspects of the role of forests in the nitrogen cascade.

In the front range of the Colorado Rocky Mountains, even modest increases in anthropogenic inputs of Nr to poorly buffered forest and surface water systems have been shown to change soil chemistry, species composition, and ecosystem productivity. Effects were seen at deposition rates as low as 4-6 kg N/ha yr.

Long-term measurements of ^{15}N redistribution with model predictions highlighted a new mechanism for incorporation and release of added N within the mineral soil and the need for a soil N immobilization process decoupled from microbial carbon cycling in soils.

Discrepancies between modeled and measured N mineralization rates were used to hypothesize the existence of direct uptake of organic N as an important component of the N cycle in N-poor forests.

A clearcut watershed in the Catskill Mountains of New York state showed very high rates of loss of nitrate immediately after the disturbance. Both N mineralization and net nitrification were high in the watershed before cutting, leading to the large nitrate loss rates. In another area, the removal of slash (logging residues) from recently clearcut areas following cutting lead to smaller nitrate losses. Large fertilizer applications several years prior to cutting had little effect.

European data showed that both N deposition rate and soil C:N ratio are related to rates of nitrate leaching losses from conifer forests. For deciduous forests, only N deposition rate was related, as soil C:N ratios held to a narrower range of C:N values.

Rates of Nr cycling and loss for high-elevation forests in the Great Smoky Mountains were shown to be high. While overall loss rates were high, due to both high deposition and forest decline, spatial variability was also significant.

Ammonia: Sources, Emissions and Transport
Robin Dennis, Chair
Ammonia is expected to become an increasingly important source of nitrogen deposition, not only in North America, but also across the northern hemisphere. This suggests there is a potential for continued Nr impacts on estuaries and freshwater systems. An analysis of the measurements of inorganic species of oxidized and reduced nitrogen and their ratios compared to predictions from a simple, box-equilibrium model of inorganic chemical and physical processes confirms other studies indicating the inorganic nitrogen system in the atmosphere is reasonably well-understood on this scale. Ambient measurements of ammonia/ammonium concentrations, even in areas with large swine populations, are fairly new, difficult to make, and require long averaging times. This is still a nascent area for North America with great promise for the future as we continue to apply and learn new measurement approaches. New techniques that are sensitive and provide real-time measurements have not yet been deployed in North America, but represent the direction that is needed. In Europe ammonia has been recognized as a pollutant to the environment and devices for real-time measurements are available and implemented.

Ammonia emissions are quite varied across the United States and around the world. They emanate mostly from animal agriculture, rather than crop agriculture or direct human activity, except for fertilizer industry and traffic. A major need in North America is developing better ammonia emissions inventories, but the many emissions factors are still highly generalized. While significant progress has been made since the first ammonia inventories of the US National Acid Precipitation Assessment Program (NAPAP) and estimates have been significantly improved, uncertainties still remain. In particular, the seasonality of ammonia emissions has a high degree of uncertainty. The seasonality not only affects deposition but also fine particle concentrations and human health. Regional inverse modeling against wet ammonia concentrations that is independently tested against ambient data has real promise to illuminate the seasonality of ammonia emissions. Seasonality appears to be larger than was generally anticipated. Inverse modeling techniques will help greatly if they can be extended to study seasonality of ammonia emissions from various economic sectors. The combination of inverse modeling and monitoring is powerful, but this work shows that lack of ammonia emissions measurements in North American monitoring networks is a significant gap. Measurements in different seasons at swine facilities indicate that a single emission factor approach does not capture variation in conditions. Seasonal behavior has many causes, not all related to meteorology. Thus, estimates of the seasonality of ammonia emissions by "bottom up" approaches will be complex, will require diverse information, and will be very necessary for development of effective ammonia management strategies.

Ammonia emissions estimates have been developed that are multi-state in size. Modeling analyses also have provided three-dimensional budgets of ammonia emissions. Nevertheless, there is still a lack of consensus about ammonia budgets, transport distances, transformation rates, and rates of deposition. Global modeling, regional modeling, regional-scale monitoring analysis and some European experiments suggest strong ammonia emissions are transported rapidly up and away and quickly become part of a diffuse regional background. The scientific community appears to have a hard time accepting some of these interpretations, suggesting careful experiments are in order to better inform scientists working on various aspects of nitrogen issue.

Atmosphere-Biosphere: N_2O-NO Emissions

Sybil Seitzinger & Carolien Kroeze, Co-Chairs

Future trends in worldwide riverine Nr transport and related nitrous oxide emissions have been predicted with a global model. Calculations showed how changing diets in industrialized regions (towards less meat consumption) would decrease Nr inputs to the North Atlantic Ocean and European Seas and N_2O emissions from those areas. In addition, there are possible side effects of air pollution control for NO_x in Europe on the Nr inputs to, and N_2O emissions from, aquatic systems.

An updated review of soil emissions of NO and N_2O from forests, savannas and cattle pastures of Brazil showed that conversion of land from forest and cerrado ecosystems to cattle pastures can result in a long-term decrease in emissions of these N gases from soils. In another study, average N_2O fluxes in pasture sites were found to be lower than in forest sites.

Emissions of nitrous oxide from different land types show temporal variability on different scales. Diurnal patterns in emissions have been reported and emphasize the importance of temporal variation.

Both terrestrial and aquatic systems are important global sources of natural and anthropogenic N_2O and NO. Considerable advances continue to be made in understanding rates of N_2O and NO emissions and factors controlling those emissions, especially from anthropogenically influenced terrestrial sources. However, the difficulties of making accurate field measurements at various spatial and temporal scales will require more attention in the future.

Policy implications include decisions about choices such as optimization of crop production with localized heavy use of nitrogen, or more dispersed but possibly less economically efficient production with lower rates of Nr application. Policies such as those used in the Netherlands may mandate decreases in nitrogen use to meet regional and international emissions goals.

Atmospheric Deposition of Nitrogen

Richard Artz, Chair

For certain ions, deposition estimates are pretty good: sulfate, nitrate, and even ammonium in precipitation, as well as dry deposited sulfur (sulfur dioxide and sulfate) are not too bad, especially away from coastal regions. For other ions, the situation is not as good. Nitrogen deposition estimates are a decidedly mixed bag, with serious methodology questions present along the coast, and a nearly complete lack of dry deposition estimates of ammonia.

A number of general conclusions from this session are presented in the following bullets:

- Regardless of what changes are made, we cannot sacrifice routine deposition monitoring programs. Improvements to the basic programs, or measurements of additional analytes should not be made by redirecting support away from existing programs or existing stations. Monitoring programs become more valuable with age and the current NADP and CASTNet programs are extremely useful.
- The US needs to develop better ammonia deposition estimates. This is particularly true for dry deposition but may also be a budding problem for wet deposition measurements. At present, gaseous Nr deposition estimates are few, and no routine monitoring effort is in place covering large parts of the US. For wet deposition, we are seeing changing air chemistry, particularly in parts of the midwestern US and western Europe, that suggests a shift from ammonium sulfate, to increasing amounts of ammonium nitrate, as Title IV requirements for decreases in SO2 emissions become evident and ammonia emissions continue to rise. Furthermore, there are now cases where there are no longer enough sulfate or nitrate ions available to bond with ammonium ions. This suggests that we should also be monitoring for dissolved ammonia in precipitation, especially in some regions of the upper Midwest.
- Spatial estimates of total inorganic nitrogen deposition (usually calculated as the sum of ammonium N plus nitrate N in air and precipitation) are still questionable, partially because of measurement methodology problems, but also because of the usual problem of extrapolating dry deposition measurements from point measurements and the recent discovery that precipitation contains substantial amounts of organic forms of nitrogen. Some participants suggested that geographical information systems (G.I.S.) tools might help us extrapolate from point to area measurements through use of detailed land use records and improved gridded meteorological measurements from National Weather Service models.
- US atmospheric deposition scientists need to ground truth the dry deposition inferential method to better understand the effects of surface inhomogeneities and of drought on deposition estimates. This is typically done using eddy flux measurements.
- Air quality modelers also need better Nr emissions estimates. Current values are very crude. Ammonia emissions values are particularly suspect.
- The role of atmospheric organic nitrogen is still an open question.
- Coastal deposition estimates will require development of different methodologies to account for the effects of sea salt and local wind circulation. Traditional methods of flux calculation require well-defined wind flow information and often do not account for effects of large particles.
- "Cap-and-trade" programs set up to decrease nitrogen emissions based on the philosophy of minimizing clean up costs are assumed to work well anywhere. This may or may not be true.

Agricultural Nitrogen Losses to Ground and Surface Waters
Mary Ann Rozum, Chair
Progress on several newer remediation methods of treating agricultural nitrogen losses is ongoing. One method involves water table management through tile drainage lines in agricultural fields to decrease leaching of nitrates – a system currently used in various parts of the US and Canada. Another method is planting of cover crops over the winter to help retain fertilizer N for the following crop season. Another method is to identify preferential flow patterns of nitrate-rich water and intercept it with biofilters.

In the Netherlands, mathematical models are used to project Nr losses and prescribe mandatory changes in agricultural practices. Accurate calibration of these models has made the recommendations acceptable to farmers.

The effectiveness of some practices such as riparian buffers was challenged in situations where preferential flow of waters containing nitrate passed underneath the root zone of the buffer vegetation, with little decrease in losses of nitrates.

Nitrogen Use in Agricultural Crop Production
Robert Wright, Chair
Increased nitrogen use-efficiency by crops. Breeding and selecting crop cultivars that make more efficient use of soil and fertilizer N 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 Nr losses to air and ground water. These nitrogen-efficient cultivars could also be useful in areas of the world where limited-resource farmers are unable to afford synthetic N fertilizers. There is concern that current high-yielding crop cultivars will not perform adequately when fertilizer N inputs are decreased. However, recent research from Japan has demonstrated that high-yielding rice cultivars still produced higher grain yields and had higher nitrogen use-efficiency than competing cultivars under low Nr application rates. These results suggest that these high yielding rice cultivars could provide benefits to limited-resource farmers even if nitrogen application rates were low.

Decreasing nitrogen deficits in developing countries. Many developing areas of the world have significant N deficiencies in cropping systems because the soils are degraded and limited-resource farmers cannot afford fertilizer inputs. To address this problem, management practices are being developed to make more efficient use of renewable nitrogen sources through improved biological nitrogen fixation by leguminous crops, shrubs and trees, and by increased use of green manures. In Kenya, improved management practices using grain legumes and leguminous fallows have resulted in annual N inputs into these systems of up to 200 kg N/ha/yr. Improved Rhizobia inoculation of legumes such as faba bean in Ethiopia have resulted in 2-3 fold yield increases. Nitrogen management by use of green manure in rice production systems in India has resulted in significant yield increases without use of synthetic N fertilizers. Development of these and similar practices will decrease dependence on commercial fertilizers, improve soil quality, and decrease input cost for limited-resource farmers.

Remote sensing methods to characterize the nitrogen status of crops. Rapid methods for assessing within-field nitrogen status of crops are needed for better nitrogen management using site-specific, variable-rate application technology. Two basic remote sensing approaches have been employed to address this problem: multispectral and hyperspectral reflectances from remotely sensed images. Multispectral approaches emphasize linear combinations of broad spectral bands (known as vegetation indices) while the hyperspectral approach analyzes reflectance signatures from narrow spectral bands. Research to date indicates that vegetation indices are not good predictors of crop N status.

Hyperspectral reflectance bands have been related quantitatively to changes in crop N status over the growing season. However, several problems still need to be solved before producers can be encouraged to use remotely sensed crop N status maps to guide N applications.

Forest Soils and the Nitrogen Cycle

Gary Lovett, Chair

One theme that emerged consistently during the Conference was the complexity of the N cycle in forests soils and our lack of knowledge of key processes. Past research has focused on explaining or predicting hydrologic Nr losses from forests (mostly as NO_3, and to a lesser extent as dissolved organic N). The mechanisms reported to regulate N losses varied substantially in different studies and different regions. For instance, in watersheds near the Pacific coast in Oregon, Nr losses may be controlled by presence of an N-fixing species in the watershed and the deposition of sea salt-derived chloride. Some research documents apparent abiotic retention of NO_3 on soil organic matter in soils from Massachusetts. Nitrate leaching in some European forests is controlled by a combination of atmospheric deposition and soil C:N ratio. In forests of West Virginia, N processing was controlled by topographical factors and the presence of certain species, especially Ericaceous shrubs, which suppress N cycling rates. Some work has shown hydrological and topographical control of NO_3 loss from forests in southern Ontario. This emerging research, taken as a whole, may allow us to understand why one set of factors controls N cycling and loss in one area, while another set of factors is predominant elsewhere.

Nitrogen Dynamics in Asia

Guangxi Xing, Chair

In 1998, consumption of synthetic N fertilizer in Asia accounted for about 58% of the world total. There also was a significant increase in other anthropogenic sources of reactive N. Human activities have severely disturbed the natural N cycling in Asia. Using the situation in China as an example, the annual consumption of synthetic N fertilizer has dramatically increased from ~0.006 TgN to ~25 TgN in merely a 50-year span (1949-1999). NO_x from fossil fuel combustion has increased from ~0.08 TgN to ~4.60 TgN. N fixed by legume crops and non-symbiotic N has increased from ~1.24 TgN to ~3.19 TgN. In 1999, synthetic N fertilizer and fossil fuel combustion consist of about 79% and 15% of anthropogenic reactive N, respectively. In China, the amount of atmospheric wet N deposition reached ~11 TgN (~12 Kg N/ha/yr). In contrast, wet N deposition in forested regions of Japan reached as high as 15-30 Kg N/ha/yr. Direct emission of Nr from croplands has increased from ~26 GgN/yr to ~373 GgN/yr within the 1949-1999 time span. In 1949, N_2O emissions from synthetic N fertilizer were estimated to be ~27% of total Nr emissions; this percentage increased to ~74% in 1999.

In Eastern China, N and P pollution of surface water and coastal zone water bodies has reached alarming amounts. Many big lakes in the region have become eutrophic. The scope and frequency of red tide have increased yearly. Similar situations also have been reported in India. In China, the major source of Nr pollution comes from untreated sewage in city and direct discharge of human and domestic animal excrement onto farmland. Other sources of increased Nr pollution are wet deposition from the atmosphere and fish farming.

In Asia, although the adverse effects on the environment of Nr transport into water bodies and emissions to the atmosphere are obvious, the actual amounts causing specific harmful health and environmental effects remain unclear. With respect to N management, the efficiency of utilization of synthetic N fertilizer in Asia is lower than in North America and Europe. The productivity gains from increased use of synthetic N fertilizer usage decrease yearly.

Nitrogen in Surface Waters

Jeff Stoner, Chair

Understanding Nr sources and cycling in upland catchments as well as subsequent transport through major river systems to estuaries is vital for implementation of measures to decrease diffuse nutrient loading to surface waters. Whether dominant N sources are derived from air, point sources, or land applied fertilizers and animal manure, most participants recognized the importance of biogeochemical processes in soil and benthic systems for denitrification, particularly in upland and wetland surface waters. Once in large rivers, however, Nr, and in particular nitrate, can move great distances from its source and enter estuaries and oceans. Many freshwater systems as well as estuaries are Nr limited or at least co-limited with phosphorus in terms of promoting eutrophication and upsetting the balance of these ecosystems. Also, nitrate concentrations in some waters used for drinking do not meet health standards.

For surface waters in upland catchment areas, studies both in Europe and the US show the importance of the form and seasonal variability of Nr in streams to assess the biological impacts of excess Nr from the land and atmosphere. The ratio of the annual flux of dissolved inorganic N (DIN) to dissolved organic N (DON) in stream waters may provide a robust and sensitive method for determining the N-status of ecosystems from a variety of biomes. For shallow lakes in the Netherlands, model simulations showed that several processes are important: transport and settling of suspended solids, denitrification, nutrient uptake by marsh vegetation (increasing nutrient retention), and improvement of habitat conditions for predatory fish. Within limits, the presence of a wetland zone around lakes may effectively increase 'critical nutrient loading' and thus increase the ability of lakes to cope with nutrients.

Very high concentrations of nitrate (in excess of 50 mg N L^{-1}) were found in selected agricultural ditches, especially those receiving tile drainage. Surprisingly, a subset of agricultural ditches remained high in nitrate concentrations during and after rain events, indicating that nitrate was not being flushed out of the soil profile. Authors hypothesize that the shallow groundwater is nitrate saturated in tile-drained fields due to long-term nitrogen loading from agricultural practices.

Research using historic and current data in the corn and soybean region of the midwestern US show that inputs are not balanced by exports in grain, and lead to large surpluses of Nr on the landscape in Illinois. Rivers export approximately 50% of this surplus Nr, mostly as nitrate, and large amounts appear to be denitrified. Directly linking surplus Nr to riverine export is problematical because of various hydrologic factors. In the Potomac River Basin of the eastern US, agriculture practices dominate the inputs, and climate dominates year-to-year variability of riverine outputs from 1980-2000.

In a national US assessment of water quality related to land use, total Nr loads (nitrate, nitrite, ammonia, ammonium, and organic form of Nr) in streams and nitrate concentrations in ground water are related mainly to nonpoint sources of Nr, such as fertilizer and animal manure applied to agricultural land, fertilizer applied to suburban areas, and atmospheric deposition in general. More than half of the streams studied nationwide showed over enrichment by Nr, which can lead to eutrophication of surface waters. Results from this national assessment suggested that shallow ground water also is a major reservoir of nitrate lost from nonpoint inputs of Nr onto agricultural and suburban land that could be stored and/or slowly released by seepage to surface waters.

Nr from the Mississippi River Basin in the US is believed to be a major cause of the expanding hypoxic zone that develops each spring and summer on the Louisiana shelf of the Gulf of Mexico. Analysis of existing data show that concentrations and flux of Nr in the Mississippi River have increased significantly during the past 100 years, and especially since the 1970's. The increased annual nitrate flux to the Gulf can be largely explained by three factors: 1) increased fertilizer use, 2) annual variability in precipitation and increased streamflow, and 3) the year-to-year variability in the amount of Nr available in the soil-ground water system for leaching to streams. Nr loss rates in streams (per unit of water travel time) decline substantially from small streams to large rivers, reflecting the effects of channel size (depth, water volume) on particulate Nr settling times and denitrification. The rates of loss in lakes and reservoirs are also related to physical and hydraulic properties that influence the contact and exchange of water with benthic sediments.

From a management perspective, some promising processes have been developed for treatment of ammonium-rich effluents. In these new processes, nitrification is blocked at the stage of nitrite, followed by further reduction to gaseous dinitrogen. Isotope dilution and isotope redistribution provide a powerful tool to assess N transformation rates and to identify pathways for N removal to evaluate - both qualitatively and quantitatively - Nr removal via anoxic ammonium oxidation.

Effects of Atmospheric Deposition of Nitrogen
Kathy Tonnessen, Chair

In southern California, atmospheric deposition of Nr compounds is extremely high (up to 45 kg/ha/yr) and is affecting both forested ecosystems and grasslands along the California coast. The most consistent indicators of Nr enrichment are soil microorganisms. The dominant form of Nr deposition ranges from ammonium compounds in the southern Sierra Nevada to oxidized forms of N in coastal southern California. Both chronic ozone and Nr exposure have resulted in decreases in biomass and carbohydrate concentrations in plant roots. Further north in coastal California ecosystems in the San Francisco Bay area, Nr deposition rates are close to 10 kg/ha/year. N-poor grasslands on serpentine-derived soils are enriched by atmospheric deposition of Nr, resulting in the dominance of exotic grasses, that are affecting the habitat of a threatened species, the Bay checkerspot butterfly. Agencies in California have developed a mitigation strategy to allow new Nr sources to locate in this area in return for preservation of serpentine grassland habitat and management of that habitat to maintain native grasses.

In the Colorado Rocky Mountains atmospheric deposition rates of 3-5 kg N/ha/yr have resulted in N saturation in alpine and subalpine areas. A high-resolution map of Nr deposition has been constructed for the US Rocky Mountains by combining National Atmospheric Deposition Program/National Trends Network (NADP/NTN) wet deposition data and snowpack accumulation data. This map shows "hotspots" of Nr deposition downwind of urban areas, power plants, and agricultural activities. Analysis of trends in Nr deposition shows some sites in the Rockies experiencing significant increases in Nr, from a combination of climate change and changes in ammonium deposition.

Forested ecosystems of the northeastern US are being affected by both N and S deposition, resulting in loss of calcium from soils and increases in nitrate being flushed into streams during storm events. Organic-rich soils tend to release more nitrate into streams during precipitation and snow-melt episodes, resulting in surface water acidification. This response is still observed in spite of the decrease in amounts of sulfate in precipitation and deposition to stream waters as a result of the Clean Air Act Amendments of 1990. Forests in the Chesapeake watershed are retaining about 87% of deposited Nr, based on results of a forest ecosystem model, PnET-CN. Increases in Nr deposition are expected to decrease the retention of Nr in watershed soils and result in large leaching losses to streams, and ultimately to the Bay, where Nr loading is implicated in eutrophication and loss of shellfish populations.

A modeling exercise, using the air quality model CALPUF in the Chesapeake watershed, allows for the evaluation of the sources of N in deposition and verification of model predictions using NADP/NTN data and Clean Air Status and Trends Network (CASTNet) data. An economic analysis estimated the effects of improved animal waste management on ammonia emissions and formation of fine particles that affect human lung function. The model results showed that a 10% decrease in ammonia emissions can lead to greater than $4 billion annually in public health benefits.

Policy Options to Improve Nitrogen Use in Agriculture
Teresa Gruber, Chair
Several research and management topics were presented and discussed by diverse international participants. These included:

- Changing farmer behavior regarding nitrogen use/management;
- Decreasing Nr use through such methods as organic farming and matching Nr fertilization to crop needs;
- Decreasing Nr contamination in surface and ground water;
- Tools for estimating Nr losses from agricultural operations; and
- Correcting the mistakes of post-war Nr fertilization abuses, which included discussion of post World War II abuses of Nr fertilization in Germany to increase productivity in plant and animal agriculture.

The costs and benefits of having no agricultural production at all as a means of decreasing Nr concentrations in the environment in France were contemplated; the benefits were found to far outweigh the costs.

Mapping techniques have been developed to monitor physical, chemical, and biological characteristics of surface and subsurface areas to assess Nr concentrations and behavior. A global-positioning-system (GPS) method for mapping of bulk soil Nr concentration using electrical conductivity measurements was demonstrated. Topographic position can be an important influence on Nr availability in soil and can be used to help improve soil tests for proper determination of Nr status in the future.

Comparison of post-harvest soil Nr concentrations with Nr leaching under varying conditions can provide a valuable prediction tool that can be used by policy makers to create guidelines for responsible Nr management.

Nitrogen Management in Agricultural Systems
Thomas Christensen, Chair
Agriculture plays a major role in the nitrogen cycle of the Earth. Current research investigates innovative ways Nr use can be optimized while minimizing associated detrimental effects, utilizing existing and cutting edge technology as ways to improve the efficiency of nitrogen N-use for crop production and as an alternative energy source.

In eastern and southern Africa, decline in soil fertility is largely brought about by continuous cultivation without application of fertilizer or manure. Trees, particularly the legumes that fix nitrogen, have the potential for increasing the biologically active pools of soil organic matter, thereby contributing to soil fertility improvement. Legumes can be grown for their ability to capture and fix N and then incorporated it into poor soils to improve crop yield.

Results of an optimization analysis showed that control of N_2O is more cost-effective than control of NH_3 in European agriculture. A web-based model has been developed to do multi-year Nr simulation modeling specific to a crop field. With the necessary computer capability and software available off-site, this model is able to evaluate many scenarios for the optimization of nitrogen management, thereby balancing crop production and environmental protection.

Throughout the midwestern US there is a tendency to over-apply N fertilizers to ensure an adequate Nr supply for the crop during better-than-average weather conditions. When weather conditions do not permit above-normal yields, the excess nitrogen that remains in the soil profile may contribute to leaching losses in the following seasons. When nitrogen use efficiency was calculated based on the nitrogen application rate, there were differences among years and soils; weather had a greater impact on yield than any other single component.

Forests, Nitrogen and Surface Waters

Bruce Peterson, Chair

Nitrate export from watersheds can be correlated with a number of factors including defoliation; species composition, with oaks having an inhibitory effect on soil nitrification; groundwater flow paths; hyporheic processing; and stream channel retention. Several additional aspects of Nr retention, including variable source contributing areas and N saturation, are important. In some systems there is a very long time scale associated with N saturation, while in others, such as in Japan, systems are already well saturated. No currently available models take even these few factors into account when predicting nitrate exports. Gaps in our understanding are created now by lack of synthesis and by lack of knowledge of flow paths and residence times for water. For example, riparian systems are important in some locations but ineffective in taking up Nr in other locations where groundwater flows are deep. In some cases the lower portions of catchments (near streams but not necessarily riparian) have long residence times and may almost completely control the chemistry of the watershed including the flow of major ions within a catchment.

Market Mechanisms and Nitrogen Management

Richard Haeuber, Chair

General Issues – Nitrogen Control and Regulation

Governments are increasingly called upon to arbitrate between conflicting demands from various parts of society, often requiring choices among competing demands upon air, water, soils, and other resources. In general, governments desiring to decrease and mitigate Nr pollution should:

- Find implementable, target-based solutions that recognize the integrated nature and effects of Nr in various parts of the nitrogen cascade;
- Focus initial efforts on control measures that can influence Nr impacts before it cascades through the environment, or target secondary impacts that cause the most damage (for example, N-rich grains fed to cattle);
- Direct control or mitigations efforts that affect multiple pollutant problems rather than focus on one pollutant problem at a time (for example, by decreasing emissions of NOx, VOC, and CO simultaneously;
- Focus new short-term research on defining implementable, measurable actions that can be taken and on simple mechanisms and/or approaches that can be improved, adapted or modified as new data or knowledge becomes available (adaptive management – some market mechanisms can accommodate this need for on-going modification);
- Where possible, use market- or incentive-based mechanisms to achieve targets while encouraging innovative technical and non-technical, but manageable solutions.

General Issues – Market-based Approaches

- An important goal for achieving sustainable development involves internalizing environmental costs, making the use of scarce resources (e.g., clean air) part of the economic decision process and the distribution of wealth.
- Establishment and distribution of property rights throughout society (e.g., tradable permits, flexible performance standards) is a means towards efficient use of scarce natural resources.

- Market-based instruments are important tools for solving conflicting resource use demands more easily and in more flexible ways. They provide a useful mechanism for internalizing the external costs of Nr pollution in its many human health and ecological manifestations.
- Market-based approaches are designed to achieve aggregate emissions decreases at lower costs, tailored to the specific needs and resources of a country or region.
- In order to function properly in practical situations, credible market-based programs should be designed to embody the principles of simplicity, flexibility, certainty, accountability, and ease of administration.
- Clear, consistent rules that emphasize transparency, funding flexibility, and market performance are key factors in creating investor certainty, and facilitate success of market-based approaches.

Cap-and-trade (and variant) Market-based Approaches
Several important issues must be considered before deciding whether a "cap-and-trade" type of market-based program will be appropriate and effective, or if an alternative approach (e.g., flexible emission allocation) may be better suited for the particular situation at hand. While the questions below provide an analytical framework specific to determining the applicability of a cap-and-trade program to address an environmental problem, they frame a set of critical issues for determining the applicability of market-based approaches in general:

- Can the environmental or human health problem of concern be addressed through the flexibility allowed in cap-and-trade?
- Is a thorough and complete emissions inventory available?
- Are there sufficient emissions sources for an active market to develop?
- Does the range of control costs among sources vary widely enough for trading to achieve the overall costs of the targeted decrease in pollutant emissions?
- Are control technologies available that can achieve the emissions-decrease goal embedded in the "cap" that has been chosen?
- Are accurate and consistent emission measurement techniques available or possible that can be applied to all affected sources?
- Does adequate centralized and/or cooperative authority exist to establish cap-and-trade program for the relevant emissions sources?
- Are there adequate political and market forces to enable a cap-and-trade program to work effectively?

Impacts of Anthropogenic Nitrogen on Coastal Ecosystems
Hans Paerl, Chair
Nitrogen is the key nutrient limiting plant growth in estuarine and coastal ecosystems.

Excessive Nr loading has been linked to enhanced primary production, or eutrophication, increases in hypoxia and harmful algal blooms, and decreases in submersed aquatic vegetation in coastal waters worldwide.

In developed regions, man-made (anthropogenic) Nr loading has increased by 20 to over 50% in estuarine watersheds/airshed. Similar decreases in the magnitude of Nr loading will be needed to reverse eutrophication and its harmful effects

Sources and forms of Nr loading often are changing: In regions experiencing agricultural expansion and growth of intensive animal-rearing operations, ammonium ions are becoming an increasingly important fraction of total Nr load (30% to over 50%).

The changing chemical composition of Nr loads differentially impacts plant growth response. In particular, phytoplankton community composition may be altered by the changing proportions of N species in various Nr compounds (ammonium, nitrate, nitrite, dissolved organic N) discharged to Nr-sensitive waters.

Atmospheric deposition of Nr is an important fraction of externally supplied or "new" N in estuarine and coastal waters. Estimates range from 10 to over 40%.

The implementation and management of various means to decrease Nr emissions in order to protect estuarine and coastal waters from accelerating eutrophication must be on the watershed and airshed (i.e., regional) scale.

Policy Responses to Increased Environmental Nitrogen

Wim de Vries, Chair

In areas with high traffic density and intensive animal husbandry, large emissions of Nr into the environment lead to a series of environmental impacts, as presented at the Conference. Measures that have been taken to control Nr emissions and limit its effects up to this point have been directed towards different environmental themes such as acidification, eutrophication, climate change, etc. Results were presented of a study that analyzed the Nr problem in the Netherlands in an integrated way; all relevant aspects were taken into account simultaneously, specifically protection of biodiversity of natural areas and protection of ground water and surface water quality. It was shown that for agriculture, nitrogen ceilings provide a good basis for regulating Nr through fertilizer use and feed import. Furthermore, the effectiveness of policies to decrease Nr inputs to agriculture is evaluated in an integrated way. Ammonia emissions appeared to be the most important environmental problem in this case study.

It was further shown that the great complexity of the nitrogen cycle can be modeled by a Material Flow Accounting method, which is a useful tool to direct local policy towards sustainable management of Nr. It focuses on the quantification of input-output flows of nutrients and provides information related to data gaps.

A presentation was given of the ammonia recovery process (ARP), which is an award winning, low cost, environmentally responsible method of recovering Nr in the form of ammonia, from various dilute waste streams and converting it into marketable ammonium sulfate. This process was used successfully in a recent large-scale field demonstration at New York City's Oakwood Beach Wastewater Treatment Plant, located on Staten Island. Independently validated data from this field demonstration showed that the ARP process consistently recovered nearly 100% of the ammonia emissions from this plant.

Interactions of Carbon and Nitrogen at Regional and Global Scales

Arvin Mosier, Chair

Data from a nitrogen deposition measurement network in tropical Africa revealed that Nr deposition across tropical Africa is relatively high and is comprised mainly of dry rather than wet deposition. In fact, dry deposition was the main source across a wide range of precipitation regimes.

Data from urban study sites in several countries showed that Nr movement from urban landscape watersheds is quite large and an important component of regional Nr movement.

Finally, a discussion of anthropogenic sources of Nr into riverine systems indicated that Nr loading from northeastern US watersheds is relatively high and can be related to atmospheric deposition, fertilizer application, agricultural and forest biological N fixation, and the net import of Nr in human food and animal feed, depending upon the drainage basin. This watershed N-balance approach appears to be a good integrative tool for analyzing regional Nr. Although a number of poorly understood "black boxes" remain within this approach, it is apparent that an integrated approach is needed to understand the fate of Nr across systems as it reaches riverine systems through surface runoff, leaching into ground water aquifers, and/or atmospheric deposition.

The Nitrogen Game

Jan Willem Erisman

NitroGenius, a decision support system in the form of a game, was specially developed for the Conference in order to support scientists and policymakers as they seek solutions to the nitrogen problems in the Netherlands' extensive agricultural, industrial, and transportation areas. The aim of NitroGenius is: (i) to improve understanding of complex relationships within the Nr pollution situation and (ii) to search for optimal solutions and policies, which can prevent Nr pollution and its effects, while incurring minimal economic costs and societal impacts. NitroGenius includes a modeling system, which describes all of the nitrogen flows at several relevant spatial and temporal scales. Outputs of this model include: (i) the annual emissions of ammonia, nitrogen oxides and di-nitrogen oxide to the atmosphere and (ii) the annual leaching and runoff of ammonium and nitrate to groundwater and surface water, including the resulting annual average concentrations of those compounds. An economic model is also included in NitroGenius to describe economic relationships occurring between all important sectors of the Netherlands, and the effect that different pollution-control and business-development actions would have on Gross Domestic Product (GDP), unemployment, energy use, and environmental quality. Several possible abatement options are described and parameterized so that their effects can be calculated using the modeling system. The modeling system and abatement options form the heart of NitroGenius.

The NitroGenius game was set up in two rooms at the Conference. The outcome of each session was stored and the results were analyzed. More than 85 people in about 50 groups played the game during the Conference. The results of each round (actions taken and changes in parameters) were stored in a database, together with the end results of each game. Several groups were able to solve the Dutch nitrogen problem, defined as resulting in effect parameters that were below the targets set by the Dutch government. Many of these teams, however, came to the result with large social and/or economic consequences. The environmental score was calculated as the weighted average of all environmental parameters including emissions to the atmosphere, effects on ecosystems, human health, and climate change. It is clear from the outcome of the games that when very little environmental progress is made, the growth in the GDP is high. However, very high environmental progress can be made both with very high and very low GDP growth! This shows that it is very important to have a good strategy and sequence when exercising management/abatement options. The team that scored best did not initially start by selecting abatement options, but first acted to increase their budget by increasing production. Then, after their budget had grown they implemented abatement options to reach the targets. The results showed that it is possible to solve the Dutch nitrogen problem by annually using for abatement options only ~0.5% of the annual growth in GDP, which is ~2.5–3% per year.

The feedback received from those who played NitroGenius was very positive. Many expressed their opinion that NitroGenius could be used for educational purposes not only in the Netherlands, but also in other countries for demonstrating the complexity of the nitrogen problem, and as a decision support system and a tool to help different kinds of community stakeholders communicate better and understand and appreciate each other's points of view.

III. Recommendations for Research and Education

During each of the Roundtable Discussions and the Contributed Paper and Poster Sessions of the Conference, the moderators were asked to accumulate recommendations for research and education initiatives that were discussed during these sessions. Also, various suggestions were made by individual Conference participants in their responses to the nine questions that were distributed to participants before they arrived at the Conference. These ideas were considered and collated by the 19 authors of the Conference Summary Statement from which the ideas listed below were adapted by the four authors of this Conference Report.

- Foster multi-disciplinary innovations in the management of Nr, e.g.: a) research by agricultural economists on possibilities for internalization of environmental costs in crop and animal agriculture production systems, b) research by agronomists and agricultural engineers on means by which to integrate animal manures more effectively into crop nutrient management plans, and c) on possible innovations in the manufacture of Nr fertilizer materials that could result in their more efficient use in cropping systems.
- Determine and prepare maps of critical Nr loads for the atmosphere and terrestrial and aquatic ecosystems, below which no unwanted effects occur.
- Improve scientific understanding of gaseous emissions of ammonia and other Nr compounds, atmospheric transport and transformation processes at all scales from local to global, and wet and dry deposition processes.
- Improve scientific understanding of the rates of nitrous oxide emission in terrestrial and aquatic ecosystems and the relationships between Nr creation and N_2O emissions.
- Increase scientific knowledge of the fate and residence time of Nr in various parts of the nitrogen cascade through accumulation in soils, sediments, and biomass, and improve quantification of Nr flows between stages within the cascade.
- Investigate factors that regulate plant and microbial processing of Nr in natural and managed "sinks" in landscapes. These sinks include riparian buffer zones, in- and near-stream wetlands, and in-stream processes that remove Nr from upland areas.
- Determine at different spatial scales (plot, field, watershed, regional) the rates and factors controlling microbial processes by which Nr is or can be denitrified to non-reactive N_2 from each reservoir in the nitrogen cascade (Figure 3).
- Uncertainties associated with the flow of Nr should be estimated as it flows through the pathways of the N cycle at farm, watershed, basin, and larger scales.
- Determine how much of indigenous organic-N sources and fertilizer-applied Nr is retained in the human-digestible portion of crops, in crop and forest residues and humus, in harvested timber and other fiber products, and as additions to the indigenous N reservoirs in agricultural and forest soils, with emphasis on obtaining more accurate estimates under actual production conditions for both crop and forest production systems.
- Evaluate alternative cropping and domestic animal rearing systems, including traditional practices, not only for their impact on current farm productivity and profitability, but also on both short-term and long-term N-use efficiency, on rates of loss of both indigenous and fertilizer sources of Nr, and on associated soil quality traits that govern future productive capacity and ecosystem capacity to retain Nr and minimize losses.

- Answer the "nitrogen legacy question" by determining the extent to which Nr 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.
- Determine the technological and economic feasibility, social acceptability, and environmental sustainability of innovative on-farm and centralized systems for converting animal manures and various other types of commercial, industrial, and municipal waste streams into value-added products that can be sold at a profit.
- Focus new initiatives in research on options that will reuse or remove Nr before it cascades through the environment. Especially promising target areas include: a) decreasing NO_x emissions from fossil fuel combustion in power plants and industry by pre-combustion removal of organic nitrogen, b) converting NO_x in flue gas streams into saleable fertilizer products, c) increasing N-use efficiency by crop and animal production systems, d) decreasing Nr losses from animal wastes, and e) recycling Nr back on the land from which feed grains and forages are produced.
- Further develop integrated assessment models, such as NitroGenius, to: a) explore different cost-effective options to diminish the cascade of effects of Nr, and b) communicate the integrated nature of the nitrogen cascade to both the scientific (students and researchers) and policy communities.
- Further investigate cause-effect relationships and magnitude of response to decreases in Nr inputs so as to support characterization, and as appropriate, monetization of environmental benefits.
- Develop integrated research approaches that address Nr issues in the context of linkages with other nutrient cycles, especially carbon, sulfur, and phosphorus. The potential for multiple pollutant effects from alteration of Nr management practices must also be considered. For example, some proposals for decreasing P runoff from farms may cause increased leaching losses of Nr from soils. Given the importance of phosphorus in the eutrophication of freshwater systems, both nitrogen and phosphorus need to be the focus of management in both freshwater and marine systems.
- Develop multi-pollutant multi-effect strategies to optimally combat environmental effects resulting from human activities. 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.
- Work to include the developing world more fully in the nitrogen knowledge base regarding impacts and available solutions. Establish an institutional framework that supports exchange of information between researchers on the effects of Nr in its various aspects, e.g. food production, use of fossil fuels, and the environment; and identify mechanisms, such as the World Bank, to fund researchers in the developing world to investigate specific regional impacts and solutions.
- Focus new initiatives in education on established, but under-utilized, site-specific best management practices (BMPs) known to improve N-use efficiency in crop and animal production systems. Examples include timing of Nr applications to increase crop uptake, achieve balanced crop nutrition, and ensure appropriate rates of manure application.
- Include more emphasis in medical and public health educational programs on the health, economic, and environmental advantages of balanced diets and the health risks of over-consumption and increasing reliance on meat and other animal products.
- Identify and quantify ecosystem-level factors that control Nr export from forested watersheds, and the mechanisms involved.
- Develop better ways to assess the uncertainty of current and future Nr loading to water bodies.

- Determine the parameters at the farm level, that give the best indication of harmful Nr losses, and how they can be monitored most effectively by farmers.
- Investigate ways of fixing more nitrogen by using biological nitrogen fixation, both on farms and in industrial facilities.
- Investigate genetically engineering and microbiological means by which non-nitrogen-fixing crops can be altered to include the ability to fix atmospheric nitrogen.
- Further investigate minimum nitrate and nitrite health standards for human and livestock drinking water.
- Develop methods to systematically determine and prioritize which integrated systems of soil, geology, agricultural system, and climate deserve the greatest attention for implementing improvements in N-use efficiencies. Performance monitoring and assessment would be a critical associated research need.
- Increase understanding of various aspects of animal manure use, e.g., the variability of Nr in animal manures, how best to manage the variability in crop application, the long-term effects of animal manure applications to croplands.
- Improve methods to quantify and simulate spatial and temporal variability in Nr across farm fields.
- Evaluate differences in N_2O emissions factors for different types of Nr fertilizer and various crops/fertilizer combinations; investigate whether new types of fertilizers (or old types plus additives) can decrease N_2O emissions.
- Develop ways to increase N-use efficiency through improvement of short-term and medium-term weather forecasting combined with improved agricultural advisory recommendations, thereby decreasing average Nr losses.
- Identify the molecular (physiological-biochemical) mechanisms of Nr impact on human, animal and plant health.
- Investigate ways by which market mechanisms can be used in management of Nr emissions.
- Investigate relationships between Nr deposition and changes in biodiversity with the aim of also determining how decreases in biodiversity in areas currently impacted by Nr deposition can be reversed.
- Develop well constrained Nr dose-response relationships for major classes of marine and fresh water systems.

IV. Recommendations for Decision Makers

The presently known and potential future impacts of increased circulation of Nr on human and ecosystem health and environmental quality are sufficient to warrant establishment of a quasi-permanent international research and/or research and policy assessment program. Possibilities include proposals for creating an Intergovernmental Scientific Panel on Nitrogen (ISPN) or an International Science and Policy Council on Nitrogen (ISPCN) through the United Nations (e.g., UNEP, UNESCO, and FAO) or other international bodies.

A firm commitment is needed to long-term monitoring programs, in order to support evolving research and evaluate the effectiveness of environmental policies and programs. Chemical and biological monitoring systems should be established, and maintained or expanded in areas where they currently exist, to provide current data on the magnitude and temporal and spatial extent of emissions, transport, transformation, and deposition of Nr compounds. In addition, ecological effects monitoring networks should be established, or maintained and expanded, to track the short-term and long-term effects of Nr emissions and deposition on terrestrial, freshwater, and coastal marine ecosystems.

Coordinate actions by stakeholder groups involved in nitrogen science and policy. Such coordinated action will greatly increase the effectiveness of educational, extension, and public-outreach programs by universities, government agencies, private consultants, professional societies, environmental groups, and private-sector trade and commodity associations.

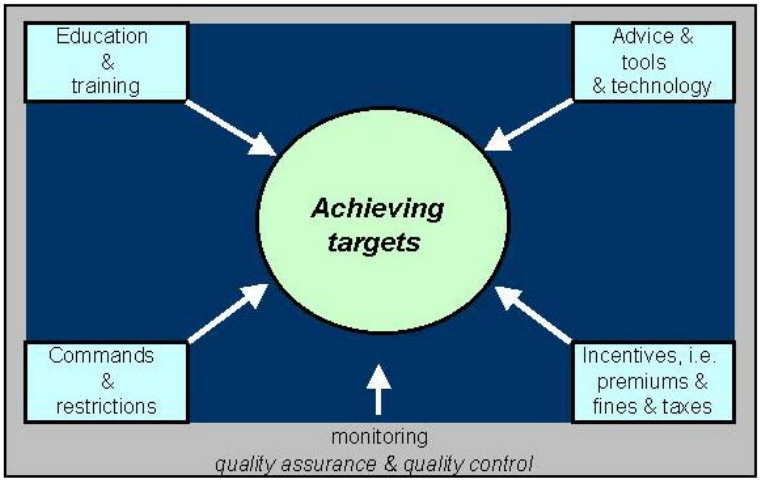

Figure 8. Framework showing tools for achieving targets in improvement of Nr management (from plenary presentation by O. Oenema).

Policies to promote environmental awareness and stewardship should be strengthened. This could be done by levies or taxes, e.g. an eco-tax on products that incorporates the environmental costs related to production, transport and waste processing, or incentives paid for adoption of improved practices that decrease Nr loads. Comparative evaluations should be made of the effectiveness of education and incentive policies compared to regulation and control policies, especially for crop and animal production systems (Figure 8).

Cost-benefit analyses, particularly benefit quantification aspects, need to be improved in order for major regulations in the US, Europe and other parts of the world to be changed or improve.

Wherever possible, evaluations of benefits and costs of nitrogen management methods should emphasize:

a) Practical means to internalize both the tangible benefits and the detrimental costs of increased circulation of Nr compounds in all parts of the nitrogen cascade;
b) Multiple-pollutant/multiple-effects approaches that recognize biogeochemical and physical linkages within the chemical climate systems and the physical climate systems of the Earth as well as among the economic, social, and environmental control systems in different regions;
c) Such multiple-pollutant approaches also should include progressively increased awareness of linkages and interactions among the nitrogen, carbon, sulfur, phosphorus, and other nutrient cycles of the Earth;
d) Market-based or incentive-based mechanisms should be aimed at well-defined targets that also encourage development and implementation of innovative technical and non-technical management solutions.

Investments in research should be focused on a balanced portfolio of objectives that include:

a) Fundamental understanding of the basic biological, chemical, and economic phenomena to be managed;
b) Innovative approaches that derive from "out-of-the box thinking," especially from multi-disciplinary perspectives;

c) Further improvement of existing measures that can be adapted or modified as new knowledge and understanding become available;
d) Ensuring that progress in dealing with one environmental problem does not lead to increased difficulties with other problems (e.g., improvements in catalytic converters to eliminate NO emissions leading to increased N_2O emissions; sequestering soil C with increasing N additions resulting in greater N_2O emissions; etc.).

Increased investment should be made in programs fostering education of farmers and transfer of already identified Nr-management technologies in both developing and developed countries.

Utilize nitrogen decision support systems such as NitroGenius, an interactive computer-simulation game that helps environmental managers and stakeholders: a) understand the complexity of nitrogen-management problems, b) learn to choose among available control measures, and c) improve communication among stakeholders.

Denitrification is now occurring in coastal systems, and is a major mechanism for converting Nr back to non-reactive dinitrogen in the atmosphere. But we cannot depend on coastal systems to process continuously increasing amounts of Nr. Various environmental effects have already occurred before Nr reaches coastal systems. The ability of coastal systems may be impaired as a result of eutrophication that leads to oxygen depletion with disruption in the nitrification/denitrification cycle. It is, therefore, necessary to target as much as possible of this denitrification process as far upstream as practicable.

Enhanced denitrification can be accomplished through landscape alterations such as use of natural and constructed wetlands, riparian buffer strips, and bottomland hardwood forests. It is important to re-engineer land- and water-scapes by picking points of intervention where technology and natural systems can be managed to remove Nr. Use of constructed wetlands depends on flow and residence time. Riparian buffer strips can be used for edge-of-stream uptake of Nr. These methods often will reap multiple benefits other than decreasing Nr losses to the environment. These include improvements in wildlife habitat, recreational opportunities, aesthetics, and the economic return for many of these amenities. Within this cascading scheme, wherever efforts are being made to maximize denitrification to N_2, we need to keep in mind that some N_2O also will be produced. The goal should be to maximize N_2 and minimize N_2O production.

A strong relationship exists between different sources of Nr and their eventual impact on the environment. For this reason, integrated approaches will be more effective in decreasing all detrimental impacts. An integrated approach is defined as the optimization of abatement measures taking into account the interactions between different sources and effects in such a way that a cost-effective decrease is obtained without shifts towards other detrimental environmental impacts. A successful integrated approach requires the following combination of attributes: a) the policy measure must decrease all of the environmental impacts of concern; b) it must be cost-effective and efficient in decreasing Nr exposures; c) it must be readily verifiable during implementation; d) it must be acceptable to the owners of emissions sources; and e) the effectiveness of the measure must not change over time or shift the burden of detrimental effects to other countries, constituencies, or sector groups within society. Each candidate control measure should be evaluated with these 5 attributes in mind in order to determine its advantages and limitations in comparison with both current practice and other candidate policy measures.

Increased attention should be given to the theoretical and practical strengths and limitations of the concept of critical loads for Nr in relation to the concept of ambient air and water quality standards for specific nitrogen compounds.

An optimum amount of Nr should be considered to be a limiting factor for all related environmental impacts. The optimum amount can serve as a basis for an integrated approach and integrated N management policies. 'Regional specific ceilings for reactive nitrogen' should be determined for all parts of a nation, state, or province that is concerned with optimizing Nr management. The definition of such a regional Nr ceiling is the maximum amount of Nr that is allowed to be imported or produced in a given region in order to avoid detrimental effects within or outside the region. The Nr ceiling should be based on ambient concentrations of all biologically active N compounds (NH_3, NH_4^+, NO_x, N_2O, or their secondary reaction products such as particulate matter, regional haze, and ozone or other oxidants), soil, groundwater and surface water concentrations of NO_3, etc., which are necessary to protect the environment and to prevent a cascade of other effects.

Knowing how much to decrease Nr loadings in order to foster a balance of beneficial and detrimental effects of Nr is difficult. Thresholds in ecological systems are difficult to identify because ecological processes and responses are on a continuum. In addition, both environmental and economic benefits and the harmful effects of Nr enrichment may be displaced geographically. Also, managing for one nutrient should not be undertaken without good knowledge of the roles of multiple nutrients in both the target ecosystem and those downstream.

Some targets may be clear, e.g. 10 ppm nitrate in drinking water for blue baby syndrome, but in most systems it is more ambiguous. A suite of mechanisms to develop nutrient load targets has been developed for a range of ecosystems. For instance, an effort to restore the acreage of seagrass coverage in the Tampa Bay estuary lead to a series of antecedent water quality goals, including water clarity, and both chlorophyll and eventually nutrient concentrations. Other nutrient load targets have focused on returning the nutrient load to historic concentrations prior to documentation of environmental degradation. Still others result from political compromise. In all cases, it is imperative that scientific studies be used in evaluating alternative nutrient management strategies.

When determining Nr targets, the target may be different depending on the effect of concern. For example, in determining whether NO_x, or NH_x, or total Nr is the most appropriate target, we should consider that both N forms will cause an increase in productivity, but phytoplankton community composition will vary depending on the type of Nr available for growth. These phytoplankton community shifts will affect components of the food web and transfer of carbon. It may be preferable to focus on the idea of ecological goods and services, instead of the environmental components that might be affected, and to determine at what point the loss of these goods and services is no longer publicly acceptable.

Examples of possible mechanisms for determining nutrient targets, include:

1) Critical loads, derived from field studies aimed at determining N deposition rates at which no detrimental effects are observed;
2) Total Maximum Daily Loads (TMDLs), established through watershed studies aimed at determining what specific sources of Nr must be decreased to achieve the total load allowed for the system;
3) Air quality standards, established by determining thresholds for public health and/or ecosystem effects.

Each of these methods, however, may not be suitable across an entire watershed or airshed where excess Nr is leaking into the system. Because of many problems associated with specific nutrient load goals, a more holistic approach that focuses on interventions higher in the nitrogen cascade would be more efficient.

One way to determine Nr ceilings is illustrated in Figure 9. First, limits for all Nr-related effects are defined, including Nr-deposition to nature areas, NO_x concentrations related to oxidant formation and smog, particulate matter formation, nitrate leaching to ground and surface water, increase in N_2O concentrations, soil nitrate leaching, etc. These limits will vary from place to place and often also from time to time during the year. The relationships between areas and sources of emissions and areas of significant detrimental effects are complex, especially when transport among different compartments is involved, for example, in the case of ammonia emissions and deposition of NH_x in sensitive wilderness or other natural areas. An even more complex set of air-quality or water-quality models will be needed to calculate back from the maximum allowable air concentration to maximum allowable emissions in specific regions of the airshed or watershed within the region of concern.

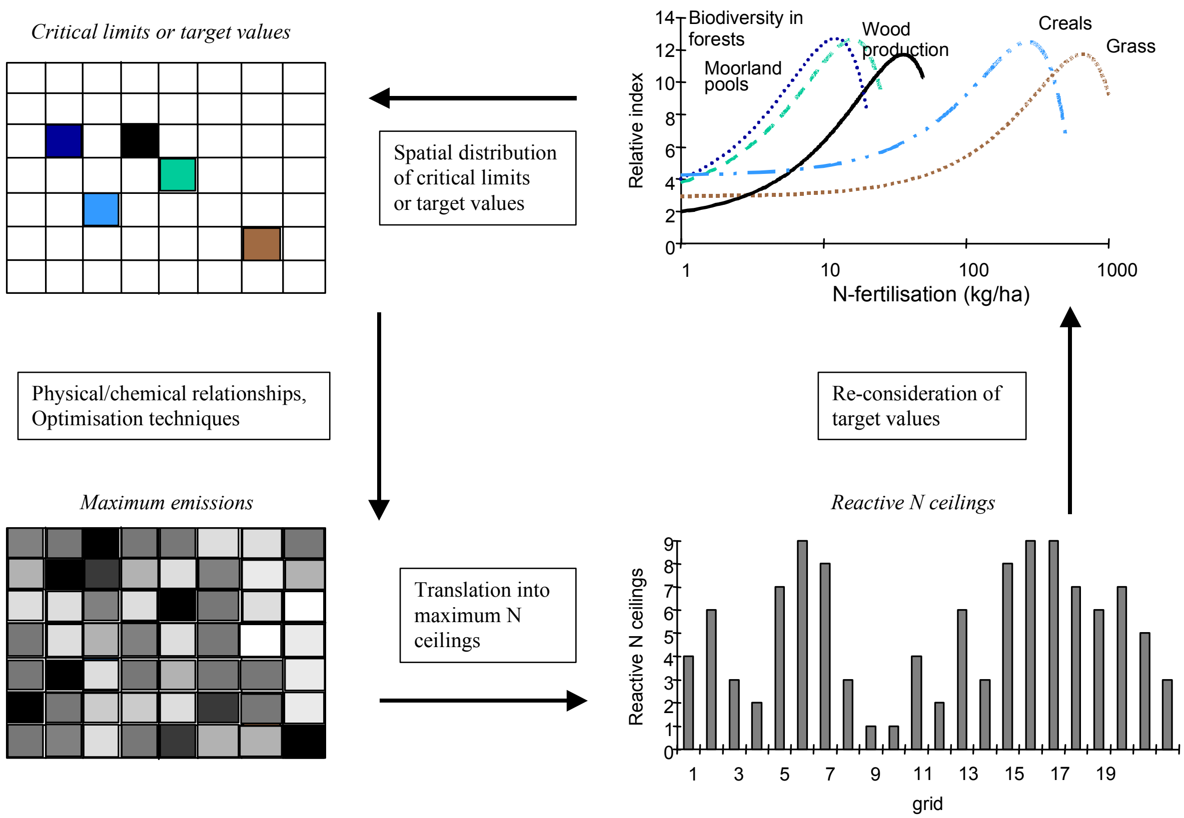

Figure 9. A process for deriving biologically active nitrogen (BAN) ceilings (presented by J.W. Erisman).

Strategies to Improve Nitrogen-Use Efficiency and Decrease Nitrogen Losses from Crop and Animal Agriculture Production Systems

The following lists provide a general outline of means by which to increase N-use efficiency and decrease N losses from agricultural food production systems.

Improvement and optimization of agricultural production systems
• Improve genetically controlled yield potentials in crop and animal agriculture • Develop non-genetic management practices to increase nutrient-use efficiency in both crop and animal production systems • Integrate the nutrient streams between intensive crop and animal production systems • Improve animal housing systems to decrease losses of gaseous N compounds • Improve nutrient balance sheets and other management tools for use by farmers, extension agents, and private consultants • Maximize efficiency of fertilizer use – including matching supply to demand in agricultural practice on scales of 100 m^2 or less, and matching application times to crop demand.
Development and implementation of Best Management Practices
• Provide sustained investment in research and development programs that target specific knowledge and technology gaps in nutrient management • Increase the effectiveness of policy-making by including experienced farmers, skilled agricultural scientists and engineers, and thoughtful policy analysts in the process of policy formulation and establishment of performance standards for nutrient management • Set specific targets for nutrient releases from agricultural systems in consultation with experienced farmers, agricultural scientists and engineers, extension agents, private consultants, and government policy players • Set up experimental farms to evaluate alternative crop and animal production and waste management systems and/or demonstration farms or pilot plants to illustrate both management practices and profit strategies by which to meet the targets set for nutrient releases • Increase nutrient-education and training of farmers, extension agents, and private consultants in agriculture
Development and implementation of "end-of-pipe" technologies
• Install riparian buffer-strips to decrease Nr run-off and volatilization losses from farm fields • Increase the effectiveness of crop irrigation and drainage systems in maximizing crop production while decreasing Nr losses to the environment • Design and install constructed wetlands in farm drainage networks • Develop and implement new manure-management technologies that will: – increase cost-effective recycling of nutrients in crop production, – maximize conversion of nutrients in animal manures into value-added products for use in industry and commerce, and/or – increase the rate of conversion (denitrification) of biologically active oxidized and reduced forms of N in animal manures to non-reactive N_2.
Development and implementation of advanced nutrient management and related information technologies
• Increase the precision of fertilizer-application and integrated manure-and-fertilizer application technologies • Invest in advanced information technology systems for farmers, extension agents, and private consultants in agriculture

New Approaches to Nitrogen Management in Energy Production

In order to decrease energy-related Nr pollution of the environment, various technological and regulatory options must be considered. Technological options for decreasing N emissions from energy production and use are listed below.

For transportation:

- Catalytic converters for gasoline- and diesel-fueled vehicles
- Low sulfur content gasoline (improves catalyst performance)
- Low sulfur content diesel (improves catalyst performance)
- Reformulated gasoline
- Heavy duty diesel retrofits
- Electric/diesel hybrid trucks and buses
- Electric/gasoline hybrid cars (ex: Honda and Toyota)
- Vehicle tailpipe inspections – in-use performance
- Transportation control measures that decrease vehicle use
- Economic/market incentives (e.g., tax policies - European gas tax)

For electric power generation (coal, oil, natural gas):

- Combustion modification technologies (such as low NO_x burners and overfired air combustion)
- End of pipe technologies, such as:
    - Selective non-catalytic reduction (with urea reductor)
    - Flue gas recirculation
    - Flue gas reburn recirculation
    - Selective catalytic reduction (with urea reductor)
    - SONOx catalytic reduction (without urea)
    - Fuel switching – coal to natural gas
- Energy Policy/Regulation
- Demand Side Management (energy efficiency measures)
- Renewables/Fuel Cells - zero emission resources (hydro, wind, solar)
- Distributed generation technologies (micro turbines and fuel cells)

Options to decrease N_2O emissions include catalytic conversion in stacks at high temperatures where N_2O is decomposed or using propane as a reductant, at lower temperatures. Other possibilities are modification of nitric acid and/or nylon production process, but this is very costly and mainly suitable only for new plants. There currently are no options for decreasing N_2O emissions from mobile sources. There are no incentives to decrease N_2O emissions because it is not regulated in any country of the world. As one of the greenhouse gases with a 310 times greater global warming potential compared to CO_2 and contributing to stratospheric ozone destruction, these regulations are clearly needed.

There are several legislative/regulatory strategies that potentially could be adopted to decrease Nr emissions from power generation, including:

- Achieving NO_x emission decreases within a multi-pollutant integrated control cap and trade program that also achieves simultaneous decreases in emissions of CO_2, Hg, and SO_x.
- Ensuring that meaningful decreases in CO_2 emissions are achieved. This will be the most important factor influencing investment decisions.
- Using national or regional cap and trade programs as a means to achieve the most cost-effective emission decreases.
- Including large industrial sources that generate their own power such as (iron and steel, cement, pulp and paper, petroleum refining, and chemical).

- Setting N emissions caps (for both NO_x and other Nr species) based on both protecting public health and sensitive ecosystems. This could include critical loads for ecosystems, similar to the European model.

Additional measures can be taken in electric power generation, such as:

- Comprehensive implementation of energy conservation and energy efficiency measures and standards with the goal of decreasing per capita energy use.
- Creating incentives and promoting implementation of distributed electric generation systems.
- Creating incentives to promote technology advancements and increased deployment of renewable energy technologies.

Currently available legislative/regulatory policies to decrease Nr emissions from transportation in the United States may include:

- Updating corporate average fuel efficiency (CAFÉ) standards to reflect emissions rates achieved by current efficient vehicles (60 miles per gallon).
- Including light duty trucks and sport utility vehicles in the CAFÉ program for light-duty vehicles.
- Providing financial incentives for development and deployment of zero emission vehicles – hydrogen powered, fuel cell powered, and pure electric vehicles.
- Requiring bus and truck fleets to purchase advanced technology vehicles – hybrid electrics, and natural gas- or fuel cell-powered vehicles, etc.

Effective Nitrogen Management Policies

The following list describes current nitrogen management policies that were considered to be especially effective by some participants.

- Some organic farming practices, where organic residues and manures are emphasized over synthetic fertilizer use.
- Incentive policies for non-point sources in situations where resulting societal benefits help justify the use of incentives. Benefits should be measured and monitored.
- Matching the appropriate source, rate and timing of application with the cropping system.
- Effective integration and accounting for all sources of nitrogen (leguminous, manure, fertilizer) in cropping systems.
- Applying only enough Nr fertilizer to meet crop requirements for a realistic yield goal.
- Development of fertilizer regimes based on "best management practices." Advice on the most efficient method of fertilizer application to decrease losses by volatilization and leaching.
- Field trials performed around the world and the development of extension services to teach farmers about balanced and optimal fertilization.
- Mandated policies requiring assessment of Nr requirements for each farm.
- Procedures to inject animal manures into soil in areas dominated by intensive livestock production.
- The use of nitrification inhibitors, urease inhibitors, and knifing anhydrous ammonia into soil.
- Awareness of farmers of nutrient balances at the farm level.
- Replacement of synthetic Nr fertilizer with composting and recycling of animal wastes for crop production.
- Precision agricultural techniques.
- Implementation of a NO_x emissions control program, perhaps an emissions trading program modeled after the SO_2 program.
- Modifications/additions to existing combustion sources.

- Denitrification at sewage treatment plants (after biological treatment).
- Policies to encourage alternatives such as hybrid automobiles, solar energy, fuel cells, and to revamp transportation and energy sectors to cleaner and more efficient forms of fuel.
- Low Nr in fuels.
- Compulsory use of catalytic converters to remove NO_x etc from car exhausts.
- Policies that encourage energy efficiency.

Development of Nitrogen Management Policies

The following areas were identified by participants in response to the question, "What are the most important areas where nitrogen management policies need to be developed?"

- Regulation of agricultural runoff, especially in tile-drained areas where fertilizer use is intense.
- Combination of intensive livestock management with fodder production.
- It is important to maintain and minimize damage to those systems most important to national and international sustainability, especially for food, feed, and fiber production. These systems include not only agricultural production, but also the sustainability of fishery and other marine resources.
- In the developing world, Nr management could take the form of encouraging different small-scale agricultural practices, such as agroforestry, use of leguminous plants etc. to minimize the need for synthetic fertilizers.
- Development of technologies to convert nitrogenous wastes into usable fertilizer – this may mean separating waste water streams from industry and households at source to avoid large concentrations of heavy metals and persistent organic pollutants (POPs) in sewage sludge.
- As we move into the 21st Century it is increasingly pressing for an action plan to enhance biological nitrogen fixation (BNF) especially in the main cereals of the world – rice, wheat and maize.
- The rate, application method, and timing of Nr fertilizer applications are critical in determining off-site movement; therefore policies controlling particularly the rate (e.g., no more than the "economic optimum" rate) and timing (e.g., no fall fertilization of corn) would be important.
- There is a need to improve the overall N use efficiency in agriculture – particularly with regard to the recycling of animal manure:
- Only half the protein in our food supply is necessary for well-being and the other half is wasted or overconsumed. A reasonable goal would be to decrease protein wastage and overconsumption by a third – roughly matching the suggested improvement in fertilizer use.
- Regulations for emissions of NH_3 and N_2O from agriculture.
- Policies regulating disposal of animal manures.
- Life-cycle analyses of fixed N production and use, including estimates of environmental costs and benefits and not simply cash costs. Transfer of costs to beneficiaries, not simply to society as a whole (whether regionally, nationally or globally).
- Uniform adoption and application of all Nr management policies.
- Nitric acid vapor, the air pollutant toxic to plants and humans, should be evaluated from the point of view of setting legally permissible exposures. This is especially important in areas adjacent to large urban sources of photochemical smog, such as Los Angeles, Atlanta, and Mexico City.
- Forest management practices to decrease Nr inputs to streams. In the future, due to increasing occurrences of N saturation in

forested catchments, Nr exports from forests are likely to increase. We do not have a good understanding of what management practices, if any, could decrease these exports.

- Standardization of water quality monitoring across states and other regulatory agencies that monitor water quality.
- Management of groundwater chemistry.
- Policies regulating use of fossil fuels in Nr fertilizer production.
- Larger decreases in NO_x emissions from motor vehicles and power plants.
- Exploit the co-benefits of improving transportation technology and public transportation (decreasing both CO_2 and NO_x emissions)

V. Plans for the Third International Nitrogen Conference

The Second International Nitrogen Conference was designed to facilitate communications among all stakeholders in the global "nitrogen community." The Conference participants' goal in the years and decades ahead is to help nations make better choices about nitrogen management in food production, energy production and use, and environmental protection.

Actions must be taken and the dialogue among stakeholders must continue. Towards that end, the Third International Nitrogen Conference will be held in Nanjing, Peoples Republic of China, in October 2004 under the sponsorship of the Chinese Academy of Sciences and the Soil Science Society of China. The first announcement of the Conference will be issued in October 2002.

It is fitting that the Third Conference be held in Asia. The population of Asia consumes about 60% of the world's fertilizer and a growing percentage of the world's fossil fuels. These percentages will increase in the future as populations grow and per capita resource use increases. The importance of issues related to nitrogen will continue to increase in developed nations. But, in many ways, the future issues involving nitrogen management will be centered on the Asian continent.

VI. Products and Expected Outcomes from the Second International Nitrogen Conference

The principal products from the Second International Nitrogen conference are six publications whose titles and sources of supply are indicated below:

Cowling, E. B., J. N. Galloway, C. S. Furiness, M. Barber, T. Bresser, K. Cassman, J. W. Erisman, R. Haeuber, R. Howarth, J. Melillo, W. Moomaw, A. Mosier, K. Sanders, S. Seitzinger, S. Smeulders, R. Socolow, D. Walters, F. West, and Z. Zhu. 2001. Optimizing Nitrogen Management in Food and Energy Production and Environmental Protection: Summary Statement from the Second International Nitrogen Conference. Ecological Society of America, Washington, DC. 16 pp.

Cowling, E. B., J. N. Galloway, C. S. Furiness, and J. W. Erisman. 2002. Optimizing Nitrogen Management in Food and Energy Production and Environmental Protection: Report from the Second International Nitrogen Conference. Ecological Society of America, Washington DC. 75 pp.

Ecological Society of America. 2001. Program and Abstracts – N2001 – The Second International Nitrogen Conference – Optimizing Nitrogen Management in Food and Energy Production and Environmental Protection. Bolger Conference Center, Potomac, Maryland October 14-18, 2001. Ecological Society of America, Washington, DC. 120 pp.

Galloway, J. N., E. B. Cowling, J. W. Erisman, J. Wisniewski, and C. Jordan (eds.). 2001. Optimizing Nitrogen Management in Food and Energy Production and Environmental Protection: Proceedings of the Second International Nitrogen Conference (Electronic Version). *TheScientificWorldJOURNAL* 2001 Vol. 1(S2). pp. 1-996. http://www.thescientificworld.com

Galloway, J. N., E. B. Cowling, J. W. Erisman, J. Wisniewski, and C. Jordan (eds.). 2002a. Optimizing Nitrogen Management in Food and Energy Production and Environmental Protection: Contributed Papers from the Second International Nitrogen Conference, Potomac, MD, 14-18 October 2001 (Printed Version). A.A. Balkema Publishers, Lisse/Abingdon/Exton, PA/Tokyo. 1008 pp.

Galloway, J. N., E. B. Cowling, S. P. Seitzinger, and R. Socolow (eds.). 2002b. Optimizing Nitrogen Management in Food and Energy Production, and Environmental Change. Special Issue. *AMBIO* Vol. 31 No. 2. pp. 59-199.

The organizers of the Second International Nitrogen Conference are now engaged in a series of Post-Conference Briefings for Decision Makers in which at least the last five of these published documents will be used as background sources of information. These briefings and published outputs will be used as a foundation/stimulus for progress in four important arenas:

1) New initiatives in research aimed at filling gaps in scientific knowledge of Nr enrichment and its beneficial and detrimental effects on society,
2) Development of improved policies for management of Nr in food production, energy production and use, and environmental protection,
3) Increased public understanding of the nitrogen cycle of the earth and its linkages with social and economic dimensions of the food/energy/environmental management systems of various nations, and, ultimately,
4) Increased harmony in the relationship between humans and nature in various localities, regions, and nations around the world.

Appendix A. Pre-Conference Questions.

The following questions were sent to participants in the Second International Nitrogen Conference about a month before the Conference, in order to solicit the unique ideas and perspectives of the very diverse group of individuals attending.

1) What are the most important beneficial effects of N?

2) What are the most important detrimental effects of N?

3) For 1 and 2 above, what are the major uncertainties that need to be resolved?

4) Given the current world food situation and need for energy, are the detrimental effects of N severe enough to necessitate spending resources on N management?

5) What current N-management policies are especially effective?

6) What are the most important areas where N-management policies need to be developed?

7) For areas you identify in 6 above, what research questions need to be addressed before management policies can be developed or implemented?

8) Would restrictions on N emissions limit production? How would that affect the economy?

9) Looking to the future, what do you think will be the biggest challenges related to N in food production, energy production, or environmental protection?

Appendix B. Schedule for the Second International Nitrogen Conference.

<u>Introduction to the N – Game: NitroGenius</u>
Jan Willem Erisman, Energy Research Foundation (ECN), Petten, The Netherlands

Sunday October 14	7:00 PM, Rm 4
Monday October 15	12:30 PM, Rm 4

Monday October 15

8:30 AM – 9:00 AM	**Opening Addresses** (Gymnasium) Moderators: Stan Smeulders and Rona Birnbaum Marjanne Sint, Secretary General, Ministry of Housing, Spatial Planning, and Environment, Netherlands Linda Fisher, Deputy Administrator, Environmental Protection Agency, USA
9:00 AM – 12:30 PM	**Nitrogen Production and Movement** (Gymnasium) Moderator: Ellis Cowling
9:00 AM	James Galloway, Professor, Department of Environmental Sciences, University of Virginia, USA *Nitrogen and the World*
9:30 AM	Peter Vitousek, Clifford G. Morrison Professor in Population and Resource Studies, Stanford University, USA *Nitrogen and Nature*
10:00 AM	Break
10:30 AM	William Moomaw, Professor of International Environmental Policy, Fletcher School of Law and Diplomacy, Tufts University, USA *Energy, Industry and Nitrogen*
11:00 AM	Paul Fixen, Senior Vice President, Potash and Phosphate Institute, USA *Nitrogen Fertilizers … Meeting the Challenge*
11:30 PM	Henry Tyrrell, National Program Leader, US Department of Agriculture's Cooperative State Research, Education, and Extension Service *Nitrogen and Animals*

Tuesday October 16

8:30 AM – 12:00 PM	**Nitrogen Around the World and its Effects** (Gymnasium) Moderator: James Galloway
8:30 AM	Klaas van Egmond, Director, National Institute of Public Health and the Environment, The Netherlands *The European Nitrogen Case*
9:00 AM	Bob Howarth, Senior Marine Scientist, Environmental Defense, USA *The North American Nitrogen Story*
9:30 AM	Congbin FU, Director, START Regional Center for Temperate East Institute of Atmospheric Physics, & Professor, Institute of Atmospheric Physics, Chinese Academy of Sciences *The Asian Nitrogen Story*
10:00 AM	Break
10:30 AM	Jonathan Patz, MD, MPH, Assistant Professor, School of Hygiene & Public Health, Johns Hopkins University *Nitrogen and Human Health: Direct and Indirect Impacts*
11:00 AM	Pam Matson, Richard and Rhoda Goldman Professor in Environmental Studies, Stanford University, USA (presented by Peter Vitousek) *The Globalization of Nitrogen: Consequences for Terrestrial Ecosystems*
11:30 AM	Nancy Rabalais, Professor, Louisiana Universities Marine Consortium (LUMCON), USA *Nitrogen and Aquatic Ecosystems*

Wednesday October 17

8:30 AM – 12:30 PM	**Innovation with Nitrogen** (Gymnasium) Moderator: Jan Willem Erisman
8:30 AM	Rabindra N. Roy, Senior Officer, Food and Agriculture Organization of the United Nations, Rome *Reduced Reliance on Mineral Nitrogen, Yet More Food*
9:00 AM	Michael Bradley, Principal, Senior Consultant, M.J. Bradley & Associates, USA *Reducing Global NO_x Emissions: Encouraging the Development of Advanced Energy and Transportation Technologies*
9:30 AM	Ken Cassman, Department Head, Agronomy, University of Nebraska, USA *Agroecosystems, Nitrogen Management, and Economics*
10:00 AM	Break
10:30 AM	Jerry M. Melillo, Co-Director, The Ecosystems Center of the Marine Biological Laboratory, Woods Hole, USA (presented by Ellis Cowling) *Nitrogen and Public Policies for Environmental Protection*
11:00 AM	Robert Brenner, Deputy Assistant Administrator for Air and Radiation, U.S. Environmental Protection Agency *Perspectives on Decreases in Nitrogen Emissions – Current Efforts and Future Directions*
11:30 AM	Oene Oenema, Principal Research Scientist and Manager, Alterra Green World Research, The Netherlands *Nutrient Management in Food Production: Achieving Agronomic and Environmental Targets*

Thursday October 18

8:30 AM - 12:30 PM	**Futures: Probable, Possible, Preferable** (Gymnasium) Moderator: Bill Moomaw
8:30 AM	*Future Visions for Optimizing N Management in Agriculture – Point-Counter Point* Ronald Follett, Agricultural Research Service, Department of Agriculture, USA Klaas van Egmond, Director, National Institute of Public Health and the Environment, The Netherlands
9:30 AM	*Future Visions for Optimizing Nitrogen Management in Energy – Point-Counter Point* Rona Birnbaum, Chief, Assessment and Communications Branch, Clean Air Markets Division, U.S. Environmental Protection Agency Robert Socolow, Princeton University, USA
10:30 AM	Break
11:00 AM	*Challenge to Participants* Johan Sliggers, Ministry of Housing, Spatial Planning, and Environment, The Netherlands Paul Stolpman, Director, Office of Atmospheric Programs, Environmental Protection Agency, USA
11:45 AM	*Conference Summary Statement and Concluding Remarks* James Galloway, N2001 Conference Co-Chair Ellis Cowling, N2001 Conference Co-Chair

CONCURRENT ORAL SESSIONS

1:30 PM – 4:00 PM. Monday – Wednesday

Monday, October 15 - Nitrogen Production and Movement

Oral Session #1: **Nitrogen Use in Agricultural Fertilization Practices**. Rm 1
Chair: John Havlin, North Carolina State University.

1:30 SIMARD, R.R., **N. ZIADI,** M.C. NOLIN, and A.N. CAMBOURIS. Prediction of N fertilizer needs for corn by soil N mineralization indicators.

1:45 **OLNESS, A.,** and D. ARCHER. Factors affecting microbial formation of nitrate-N in soil and their effect on fertilizer-N use efficiency.

2:00 **HADERLEIN, L.,** T. JENSEN, and A. BLAYLOCK. Matching nitrogen release to crop needs, controlled release urea.

2:15 **WILLIAMS, P.H.,** C.S. TREGURTHA, R.J. MARTIN, and G.S. FRANCIS. Managing nitrogen fertilizer for winter vegetable production in New Zealand.

2:30 **MESIC, M.**, A. BUTORAC, F. BASIC, and I. KISIC. Influence of nitrogen fertilization on NO_3- N concentration in lysimeter water.

2:45 **ASADI, M.E**., R.S. CLEMENTE, A.D. GUPTA, R. LOOF, and N. IZUMI. Effect of N fertigation on nitrate leaching and corn yield.

3:00 **CHEN, J.**, Y. HUANG, C.A. ROBINSON, and R.D. CALDWELL. Nitrogen, groundwater, containerized plant production.

3:15 **BAH, A.R.,** and A.R. ZAHARAH. Gliricidia (***Gliricidia sepium***) green manures as a potential N source for maize production in the tropics.

Oral Session #2: **Nitrogen Management in Animal Agriculture.** Rm 17 Chair: Rick Kohn, University of Maryland-College Park.

1:30 **HONEYCUTT, C.W.,** R.J. WRIGHT, M.D. JAWSON, B.J. WIENHOLD, B. EGHBALL, K.R. SISTANI, G.E. BRINK, T.S. GRIFFIN, S.L. ALBRECHT, J.M. POWELL, R.A. EIGENBERG, R.K. HUBBARD, S.L. McGOWEN, B.L. WOODBURY, and H.A. TORBERT. Nitrogen mineralization from animal manure: USDA-ARS Nationally Coordinated Research.

1:45 SINGH, U., K.E. GILLER, C.A. PALM, J.K. LADHA, and H. BREMAN. Presented by **R. KOHN.** Controlling N release from organic residues: Integrated approach to management of N.

2:00 **MARTIN, J.H., JR.,** and K.F. ROOS. Desorption of ammonia from swine waste lagoons: An evaluation of predictive models.

2:15 MILLER, L.R., W.A. HEAD, N.C. HANSEN, and C.R. DAHLEN. Presented by **ALFREDO DICOSTANZO**. The impact of dietary protein manipulation of feedlot nitrogen balance.

2:30 **ERICKSON, G. E.,** and T. J. KLOPFENSTEIN. Nutritional methods to decrease N volatilization from open-dirt feedlots in Nebraska.

2:45 **ERICKSON, G. E.,** and T. J. KLOPFENSTEIN. Managing N inputs and the effect on N volatilization following excretion in open-dirt feedlots in Nebraska.

3:00 **JONKER, J.S.,** R.A. KOHN, A. GROVE, and A. HIGH. Impact of management practices on nitrogen utilization efficiency in lactating dairy cattle.

3:15 **ONDERSTEIJN, C.J.M.,** G.W.J. GIESEN, A.G.J.M. OUDE LANSINK, and R.B.M. HUIRNE. Limitations to the reduction of nitrogen and phosphate surpluses through nutrient efficiency improvement: Evidence from Dutch dairy farms.

Oral Session #3: **Forests and the Nitrogen Cycle.** Rm 4
Chair: John Aber, University of New Hampshire.

1:30 **BARON, J.S.,** H.M. RUETH, A.P. WOLFE, K.R. NYDICK, B. MORASKA, and M.PAGANI. Ecosystem responses to nitrogen deposition in the Colorado Rocky Mountains.

1:45 **CURRIE, W. S.,** and K. J. NADELHOFFER. Decadal-scale C/N interactions in temperate forests assessed with 15N tracer redistributions.

2:00 **BEIER, C.,** H. ECKERSTEN, and P. GUNDERSEN. Modelling nitrogen cycling in a Norway spruce plantation in Denmark by the SOILN model.

2:15 **AKSELSSON, C., O.** WESTLING, and H. SVERDRUP. Nitrogen leakage from clearcuts.

2:30 **BURNS, D.A.,** and P.S. Murdoch. Effects of a clearcut on net nitrification rates and nitrate leaching in a deciduous forest, Catskill Mountains, New York, USA.

2:45 RING E., **L. HOGBOM,** J. and H.Ö. NOHRSTEDT. Effects of brash removal after clearfelling on soil and soil-solution chemistry and field-layer biomass along an experimental N-gradient.

3:00 **EICHHORN, J.,** W. VRIES, and T. HAUSSMANN. European wide assessments of nitrogen cycling in beech forests (*Fagus sylvatica*) - Results from the ICP forests programme.
3:15 **GUNDERSON, P.,** H.L. KRISTENSIEN, and I.K. SCHMIDT. Nitrogen input, cycling and leaching in European forests: Differences between conifer and broad leaf stands.
3:30 **VAN MIEGROET, H.,** N.S. NICHOLAS, and I.F. CREED. Spatial variability in N saturation in high-elevation spruce-forests of the southeastern U.S.A.
3:45 **MURDOCH, P.S.,** and D.A. BURNS. Effect of clearcutting on nitrogen export from a watershed in the Catskill Mountains, New York.

Oral Session #4: **Ammonia: Sources, Emissions and Transport.** Rm 9
Chair: Robin Dennis, US Environmental Protection Agency/ National Oceanographic and Atmospheric Administration.
1:30 **DENTENER, F.** Global modeling of NH_3: what do we know?
1:45 **BAEK, B.H.,** and V. P. ANEJA. Measurement, analysis, and modeling of the relationship between ammonia, acid gases, and fine particles.
2:00 **ALEBIC-JURETIC, A.** Airborne Ns (NO_2 and NH_3) in the Rijeka Bay area (Croatia).
2:15 **DENNIS, R.L.** Ammonia deposition and airsheds and their relation to inorganic nitrogen deposition.
2:30 **ANDERSON, N. J.,** R.S. STRADER, and C. I. DAVIDSON. Ammonia emissions and their sources across the United States.
2:45 **GILLILAND, A.B.,** R.L. DENNIS, S.J. ROSELLE, and T.E. PIERCE. Inverse modeling to estimate the seasonality of airborne ammonia emissions.
3:00 **HARRIS, D.B.,** R.A. SHORES, C.A. VOGEL, J.A. WALKER, D.F. NATSCHKE, and K. WAGONER. Seasonal emissions of ammonia from tunnel ventilated swine finishing barns.
3:15 **ROBARGE, W.P.,** D. WHITALL, B. HENDRICKSON, H. PAERL, J. WALKER, G. MURRAY, J. CHAUHAN, and T. MANUSZAK. Comparison of atmospheric ammonium at three sites in eastern North Carolina, USA.
3:30 **SKYBOVA, M.** The decreasing of ammonia emission in the Czech Republic.
3:45 **HENSEN, A.,** and J. MOSQUERA. Sources of N: NH_3 & N_2O plume measurements.

Oral Session #5: **Atmosphere-Biosphere: N_2O and NO Emissions.** Rm 18
Co-Chairs: Sybil Seitzinger, Rutgers University, & Carolien Kroeze, Wageningen University.
1:30 **KROEZE, C.,** and S.P.S. SEITZINGER. Future trends in worldwide river nitrogen transport and related nitrous oxide emissions
1:45 **DAVIDSON, E.A.,** M. M. C. BUSTAMANTE, and A. S. PINTO. Updated review of soil emissions of NO and N_2O from forests, savannas, and cattle pastures of Brazil.
2:00 **WICK, B.,** E. VELDKAMP, W. ZAMBONI DE MELLO, and M. KELLER. Linking microbial activities and nitrogen availability to nitrous oxide fluxes in forest-derived pasture sites in the humid tropics of Brazil.
2:15 **HARRISON, J.,** and P. MATSON. Nitrous Oxide (N_2O) emission from drainage waters of an intensively farmed, subtropical valley.
2:30 **KHALIL, M.I.,** A.B. ROSENANI, O. VAN CLEEMPUT, C.I. FAUZIAH, and J. SHAMSHUDDIN. Nitrogen management in a maize-groundnut crop rotation of humid tropics: effect on N_2O emission.
2:45 **WALLENSTEIN, M.D.** Environmental and microbial controls on denitrification under elevated nitrogen inputs.
3:00 **TSURUTA, H.,** H. AKIYAMA, Y. NAKAJIMA, W. CHENG, and S. SUDO. Nitrous oxide and nitric oxide emissions from fertilized soils and mitigation options.
3:15 **SMITH, K.A.,** and K.E. DOBBIE. N_2O emissions from temperate agricultural soils: main drivers, possible mitigation procedures, and implications for inventory calculations.
3:30 YAMULKI, S. Presented by **O. OENEME.** Nitrous oxide emissions from grassland systems: Interactions between soils, management and animals.
3:45 **ROELLE, P.A.,** and V. P. ANEJA. Modeling NO emissions from biosolid amended soils.

Oral Session #6: **Atmospheric Deposition of Nitrogen.** Rm 3
Chair: Richard Artz, National Oceanographic and Atmospheric Administration.
1:30 **LYNCH, J.A.,** and V.C. BOWERSOX. Annual and seasonal trends in nitrate concentration in the USA and their relationship to emissions.
1:45 **NILLES, M.A.,** and B.E. CONLEY. Trends in wet deposition of ammonium and nitrate in the United States, 1985-2000.
2:00 **SICKLES, J. E.,** II. Deposition of oxidized nitrogen in the Eastern United States.
2:15 **LEAR, G.G.,** and D.W. SCHMELTZ. Spatial and temporal trends in total nitrogen deposition for the U.S.
2:30 **TARNAY, L. W.,** and A.W. GERTLER. Nitrogen deposition in the Lake Tahoe Basin: Scaling from leaf to landscape using G.I.S.

2:45 **RUSSOW, R.W.B**., F. BOHME, and H-U. NEUE. A new approach to determine the total airborne N-input into the soil-plant system using the 15N isotope dilution (ITNI): Results for agricultural used areas of central Germany.

3:00 STENSLAND, G.J., **V.C. BOWERSOX,** B. LARSON, and R.D. CLAYBROOKE. Comparison of ammonium in USA wet deposition to ammonia emission estimates.

Tuesday, October 16 – Nitrogen Around the World and its Effects

Oral Session #7: **Agricultural Nitrogen Losses to Ground and Surface Waters.** Rm 17
Chair: Mary Ann Rozum, US Department of Agriculture.

1:30 **BURKART, M.R.,** and J.D. STONER. Effects of agricultural systems on nitrogen in groundwater.

1:45 **DRURY, C.F.,** C.S. TAN, T.O. OLOYA, and J.D. GAYNOR. Reducing tile nitrate loss with watertable management systems.

2:00 OVERBEEK, G.B.J., **A. TIKTAK,** and A.H.W. BEUSEN. Validation of the Dutch model for emission and transport of nutrients (STONE).

2:15 **STAVER, K.W.** Increasing nitrogen and carbon retention in coastal plain agricultural watersheds.

2:30 **STROCK, J.S.,** M.P. RUSSELLE, and P.M. PORTER. Environmental variability and cover crop capacity for reducing nitrate losses from tile drainage.

2:45 **TOTH, J.D.,** Z. DOU, J.D. FERGUSON, and D.T. GALLIGAN. Nitrate leaching losses affected by nutrient inputs and crops.

3:00 **WALTHALL, C. L.,** and T. J. GISH. An innovative approach for locating and evaluating subsurface losses of nitrogen.

Oral Session #8: **Nitrogen Use in Agricultural Crop Production.** Rm 3
Chair: Robert Wright, US Department of Agriculture.

1:30 **USHERWOOD, N.R.,** and W.I. SEGARS. Nitrogen interactions with phosphorus and potassium for optimum crop yield, nitrogen use effectiveness and environmental stewardship.

1:45 **BAKER, J.L.** The potential of improved nitrogen management to reduce nitrate leaching and increase use efficiency.

2:00 SULLIVAN, W.M., and **Z. JIANG.** Nutrient monitoring and management for turfgrass sod farms and golf courses.

2:15 **WIESLER, F.,** T. BEHRENS, and W.J. HORST. The role of nitrogen-efficient cultivars in sustainable agriculture.

2:30 **HASEGAWA, H.** High-yielding rice cultivars perform best even at reduced nitrogen fertilizer rate.

2:45 **YANG, C.M.** Estimation of leaf nitrogen content from spectral characteristics of rice canopy.

3:00 **NÄSHOLM, T.,** J. ÖHLUND, A. NORDIN, and J. PERSSON. Plant uptake and use of organic nitrogen sources.

3:15 **SNAPP, S.,** D. ROHRBACH, and S. SWINTON. Improving nitrogen efficiency: Lessons from Malawi and Michigan.

3:30 PALM, C.A, D.N. MUGENDI, P. MAPFUMO, B. JAMA, and K.E. GILLER. Presented by **PAUL SMITHSON.** Reversing N deficits on African smallholder farms.

Oral Session #9: **Forest Soils and the Nitrogen Cycle.** Rm 4
Chair: Gary Lovett, Institute of Ecosystem Studies.

1:30 **FOSTER, N.,** F. BEALL, P. HAZLETT, R. SEMKIN, S. SCHIFF, I. CREED, and D. JEFFRIES. Sources of exported nitrogen from first-order forested basins at the Turkey Lakes watershed.

1:45 **COMPTON, J.E.,** M.R. CHURCH, and S.T. LARNED. Controls on nutrient losses from a forested basin in the Oregon Coast Range.

2:00 **GILLIAM, F.S.,** B.M. YURISH, and M.B. ADAMS. Temporal and spatial variation of nitrogen transformations in nitrogen-saturated soils of a central Appalachian hardwood forest.

2:15 **AUSTIN, A.T.** and O. E. SALA. Controls on nitrogen cycling along a natural rainfall gradient in Patagonia, Argentina.

2:30 **BALSER, T.**C., P. MATSON, and P. VITOUSEK. Impact of soil nutrient availability on microbial community composition in Hawaiian tropical soils.

3:45 **NADELHOFFER, K.J.,** B.P. COLMAN, W.S. CURRIE, A.H. MAGILL, and J.D. ABER. Decadal scale movements of N tracers into vegetation and soil at the Harvard Forest Chronic-N Addition Study: Implications for C sequestration.

3:15 **MAYER, P.,** JORGENSEN, E., and A. WEST. Effects of exogenous N addition, mammalian exclusion, and detritivore diversity on decomposition in old fields.

3:30 **DAVIDSON, E.A.,** D.B. DAIL and J. CHOROVER. Rapid abiotic immobilization of nitrate in an acid forest soil.

3:45 **GUNDERSEN, P.,** N.B. DISE, W. DE VRIES, B. EMMETT, M. FORSIUS, J. KJØNS, E. MATZNER, K. NADELHOFFER, and A. TIETEMA. Carbon - nitrogen interactions in forest ecosystems (CNTER) – Estimates of soil N and C sequestration based on empirical relationships.

Oral Session #10: **Nitrogen Dynamics in Asia.** Rm 18
Chair: Guangxi Xing, Chinese Academy of Sciences; Earle Ellis, U of Maryland, Baltimore County.

1:30 **VAN DER HOEK, K.W.** Nitrogen requirements for human food and animal feed production in the European Union and India.

1:45 **XING, G.X.,** and Z.L. ZHU. Nitrogen and environment in China.

2:00 **ELLIS, E. C.,** R.G. LI, L.Z.YANG, and X. CHENG. Measuring and mediating nitrogen saturation in densely populated Chinese villages.

2:15 **YAGI, K.,** Y. HOSEN, R. ZHANG, Y. ZUO, and Z. LI. Nitrogen flows in agro-ecosystems of Lingxian County, Shandong Province, China.

2:30 **PATEL, K.S.,** K. SHRIVAS, K. AGRAWAL, R.M. PATEL, G.L. MNUDHARA, and M. L. NAIK. Nitrogen production, extent, movement and impact in central India.

2:45 **SHINDO, J.,** N. OURA, T. FUMOTO, H. TODA, and H. KAWASHIMA. Nitrogen cycle in East Asian ecosystems affected by increasing emission of anthropogenic nitrogen compounds.

Oral Session #11: **Nitrogen in Surface Waters.** Rm 9
Chair: Jeff Stoner, U.S. Geological Survey.

1:30 **CHAPMAN, P.J.,** and A.C. EDWARDS. The nitrogen and phosphorus content of upland streams in the UK: Form, concentration and biological significance.

1:45 JANSE, J.H., W. LIGTVOET, S. VAN TOL, and **A.H.M. BRESSER.** A Model study: The role of wetland zones in lake eutrophication.

2:00 **WILLIAMS, M.W.,** E. HOOD, and W.H. MCDOWELL. A novel indicator of ecosystem N status: Ratio of DIN to DON in annual riverine flux.

2:15 **VALETT, H.M.,** J.R. WEBSTER, P.J. MULHOLLAND, C.N. DAHM, and C.G. PETERSON. Nitrate processing and retention in streams (NPARS): Distinguishing benthic and interstitial contributions to energy flow and nutrient retention.

2:30 **DAVID, M.B.,** G.F. McISAAC, T.V. ROYER, J.L. TANK, and L.E. GENTRY. The nitrogen mass balance of an agricultural and artificially drained state: Past and current.

2:45 STONER, J.D., D.K. **MUELLER,** and B.T NOLAN. Nitrogen in streams and shallow aquifers in the United States-The land-use connection.

3:00 **GOOLSBY, D.A.,** and W.A. BATTAGLIN. Nitrogen sources and fate in the Mississippi River Basin.

3:15 **McISAAC, G.F.,** M. B. DAVID, and D. A. GOOLSBY. Net Anthropogenic N Input to the Mississippi River Basin and Nitrate flux in the Lower Mississippi River 1955-1998.

3:30 **ALEXANDER, R.B.,** R.A. SMITH, and G.E. SCHWARZ. The regional transport of nitrogen in streams and reservoirs: Insights from experimental observations and empirical watershed models.

3:45 VAN DRECHT, G., A.F. BOUWMAN, J.M. KNOOP, C. MEINARDI, and A. BEUSEN. Presented by **A.H.M. BRESSER.** Global estimation of the N loading of riverine systems from diffuse and point sources.

Oral Session #12: **Effects of Atmospheric Deposition of Nitrogen.** Rm 1
Chair: Kathy Tonnessen, National Park Service.

1:30 **CAMPBELL, D.H.,** M.A. MAST, D.W. CLOW, L. NANUS, G.P. INGERSOLL, and T. BLETT. Response of aquatic ecosystems to nitrogen deposition in the Rocky Mountains.

1:45 **BYTNEROWICZ, A.,** M. FENN, P. PADGETT, M. ARBAUGH, and M. POTH. Deposition and effects of nitrogen deposition in California ecosystems.

2:00 **ALLEN, E.B.,** L. EGERTON-WARBURTON, C. SIGUENZA, and A.G. SIRULNIK. Effects of N deposition on plants and soil microorganisms on an urban to rural gradient in southern California.

2:15 **WEISS, S.B.** Mitigation strategies for N-deposition sources in South San Jose, CA: Checkerspot butterflies, power plants, and the information superhighway.

2:30 **LAWRENCE, G.B.** Accumulation of nitrogen in forest soils continues to cause episodic acidification of streams in calcium-depleted watersheds.

2:45 BREWER, P.F., T. SULLIVAN, B. J. COSBY, and R. K. MUNSON. Presented by **N. NICHOLAS.** Responses of forests and streams in Southern Appalachian mountains to changes in S, N, and base cation deposition.

3:00 **PAN, Y.,** J. HOM, K. MCCULLOUGH, and J. ABER. The impacts of increasing atmospheric nitrogen deposition on forest ecosystems and watersheds in the Chesapeake Bay Region.

3:15 SHERWELL, J. Presented by **MARK GARRISON.** Evaluation of the Calpuff model using NADP/NTN and CASTNET data.

3:30 MCCUBBIN, D.R., **B.J. APELBERG,** S. ROE, and F. DIVITA. Animal feeding operations, ammonia, and particulate health effects.

Wednesday, October 17 - Innovation with Nitrogen

Oral Session #13: **Policy Options to Improve Nitrogen Use in Agriculture.** Rm 17
Chair: Teresa Gruber, Council for Agricultural Science and Technology.

1:30 **DABERKOW, S.,** H. TAYLOR, N. GOLLEHON, and M. MORAVEK. Farmer behavioral changes in response to a regulatory and education program to improve nitrogen use and management.

1:45 **DALGAARD, T.,** J.C. KJELDSEN, N.J. HUTCHINGS, and J.F. HANSEN. N-losses and energy consumption in regional scenarios for conversion to organic farming.

2:00 **DINNES, D.L.,** D.B. JAYNES, D.W. MEEK, C.A. CAMBARDELLA, T.S. COLVIN, D.L. KARLEN, and J.L. HATFIELD. Reducing N contamination of surface waters from tile-drained soils at the watershed scale.

2:15 **FRATERS, B.,** L.J.M. BOUMANS, and T.C. VAN LEEUWEN. Monitoring effectiveness of the Dutch mineral policy in agriculture in clay regions by monitoring shallow groundwater nitrogen.

2:30 **OSMOND, D.L.,** L. XU, N.N.RANELLS, S.C. HODGES, R. HANSARD, and S.H. PRATT. Nitrogen loss estimation worksheet (NLEW): An agricultural nitrogen loading reduction tracking tool.

2:45 **SCHARF, P.C.,** N.R. KITCHEN, J.G. DAVIS, K.A. SUDDUTH, and J.A. LORY. Innovative nitrogen management systems for maize: Matching crop needs across variable landscapes.

3:00 **SLAK, M.F.,** L. COMMAGNAC, and P. POINTEREAU. Nitrogen exchanges: Testing the hypothesis of a country without agricultural production.

3:15 **VAN DER PLOEG, R.R.,** and P. SCHWEIGERT. About use and misuse of nitrogen in agriculture: The German story.

3:30 **ASMAN, W.A.H.,** B.E. MÜNIER and J.M. ANDERSEN. A decision tool for local ammonia policy.

Oral Session #14: **Nitrogen Management in Agricultural Systems.** Rm 1
Chair: Thomas Christensen, U.S. Department of Agriculture.

1:30 **POWER, S.A.,** C.G. BARKER, and J.N.B. BELL. Habitat management as a tool to modify ecosystem impacts of nitrogen deposition.

1:45 **SMITHSON, P.C.,** B. JAMA, F. AKINNIFESSI, and P.M. MAFONGOYA. Organic and inorganic integration for nitrogen management in Eastern and Southern Africa.

2:00 **WILSON, E.,** P. J. CHAPMAN, and A. McDONALD. Merging nitrogen management and renewable energy needs.

2:15 **BRINK, J.C.,** E.C. VAN IERLAND, and L. HORDIJK. Interrelations between abatement of ammonia, nitrous oxide, and methane from European agriculture: A cost-effectiveness analysis.

2:30 **SHAFFER, M.J.,** B. J. NEWTON, and C.M.GROSS. An internet-based simulation model for nitrogen management in agricultural settings.

2:45 **HATFIELD, J. L.,** and J.H. PRUEGER. Increasing nitrogen use efficiency in Midwestern cropping systems.

3:00 HUTMACHER, R. B., R. L. TRAVIS, **R.L. NICHOLS,** W. RAINS, B. ROBERTS, R. VARGAS, W. WEIR, D. MUNK, S. WRIGHT, B. MARSH, and F. FRITSCHI. New guidelines for nitrogen use in California cotton.

Oral Session #15: **Forests, Nitrogen and Surface Waters.** Rm 4
Chair: Bruce Peterson, Woods Hole Marine Biological Laboratory.

1:30 **DISE, N.B.,** and E. MATZNER. Regional patterns in nitrogen dynamics across Europe.

1:45 **SCHLEPPI, P.** Nitrate leaching from forests: Different processes at different time scales?

2:00 **MERILÄ, P., A.** SMOLANDER, and R. STRÖMMER. Soil nitrogen transformations along a primary succession transect on the land-uplift coast in western Finland.

2:15 **ESHELMAN. K.N.,** D.A. FISCUS, N.M. CASTRO, J.R. WEBB, and F.A. DEVINEY, Jr. Regionalization of disturbance-induced nitrogen leakage from mid-Appalachian forests using a linear systems model.

2:30 **WILLIARD, K.W.J.,** D.R. DEWALLE, and P.J. EDWARDS. Geologic control of stream nitrate concentrations from forested watersheds of the northeastern United States.

2:45 **DISCUSSION**

3:00 **LOVETT, G.M.,** K.C. WEATHERS, and M.A. ARTHUR. Factors controlling stream water nitrate concentrations in forested watersheds of the Catskill Mountains, New York.

3:15 **HOOD, E.W.,** M.W. WILLIAMS, and D.M. MCKNIGHT. Quality and sources of DON in forested and alpine catchments, Colorado Front Range.

3:30 **DEWALLE, D.,** M.T. GOCKLEY, M. O'DRISCOLL, and J. CHOROVER. Upland versus hyporheic nitrogen losses on an Appalachian forest watershed.

3:45 **PETERSON, B.J.** Nitrogen transformations in stream channels of small watersheds.

Oral Session #16: **Market Mechanisms and Nitrogen Management.** Rm 18
Chair: Rick Haeuber, Clean Air Markets Division, US Environmental Protection Agency; Chris Dekkers, Dutch Ministry of Environment.

1:30 **BENKOVIC, S.R.,** and J. KRUGER. To trade or not to trade? Criteria used in determining the applicability of cap and trade to environmental problems.
1:45 **DUNHAM, S.,** and A. MINGST. NOx Emissions trading in the United States: Lessons from program development and implementation.
2:00 **VAN AMBURG, B.** An enhanced rate-based emission trading program for NOx : The Dutch Model.
2:15 **DEKKERS, C.P.A.** NOX emission trading in an European context: Discussion of the economic, legal and cultural aspects.
2:30 **GREENHALGH, S.,** and P. FAETH. A nitrogen reduction strategy addressing the 'Dead Zone' in the Gulf of Mexico.
2:45 **VAN DER LINDEN, J.** Tradeable manure production rights as a tool for tackling the mineral surplus in the Netherlands.
3:00 FAETH, P., and **S. GREENHALGH.** Nutrient trading - The pathway to the future?
3:15 DORING, O.C., R. HEIMLICH, F. HITZHUSEN, R. KAZMIERCZAK, L. LIBBY, W. MILON, A. PRATO, and **M. RIBAUDO.** Economics as a base for large scale nitrogen control decisions.

Oral Session #17: **Impacts of Anthropogenic Nitrogen on Coastal Ecosystems.** Rm 3
Chair: Hans Paerl, Univ. of North Carolina at Chapel Hill.

1:30 **BOYNTON, W. R.** Chesapeake Bay eutrophication: Historical and recent patterns of nutrient inputs, effects on water quality, fate of nutrients, and likely responses to load reductions.
1:45 **ELMGREN, R,** and U. LARSSON. Nitrogen and the Baltic Sea.
2:00 BINTZ, J., B. BUCKLEY, and S. GRANGER. Presented by **S.W. NIXON.** Nutrient enrichment and temperature increases in coastal lagoon ecosystems.
2:15 **HOPKINSON, C.S.,** and R.W. HOWARTH. Predicting estuarine susceptibility to eutrophication from nutrient loading.
2:30 **GREENING, H.S.,** and B.D. DEGROVE. Implementing a nitrogen management strategy in Tampa Bay, Florida: A public/private partnership.
2:45 **PAERL, H.W.,** D.R. WHITALL, and R.L. DENNIS. Integrating atmospheric deposition of nitrogen in estuarine and coastal nutrient cycling and eutrophication dynamics.
3:00 **DETTMANN, E.H.,** and H.A WALKER. Sensitivity of nitrogen concentrations in estuaries to loading and water residence time: Application to the Potomac estuary.
3:15 **DORTCH, Q.,** M.L. PARSONS, R.E. TURNER, and A.F. MAIER. Harmful algal blooms in Louisiana coastal waters clearly linked to N inputs.
3:30 **GLIBERT, P.M.** Organic nitrogen and harmful algal blooms.

Oral Session #18: **Policy Responses to Increased Environmental Nitrogen.** Rm 19
Chair: Wim de Vries, ALTERRA Green World Research

1:30 **DE VRIES, W.,** H. KROS, O. OENEMA, and J.W. ERISMAN. Assessment of nitrogen production ceilings on a regional scale avoiding adverse environmental impacts.
2:00 **DE VRIES, W.,** H. KROS and O. OENEMA. Impacts of structural agricultural changes and farming practices on nitrogen fluxes in the Netherlands, present and future levels of nitrogen concentrations and depositions in Europe.
2:30 **FASSBENDER, A.G.** Ammonia recovery process economics.
3:00 **BARTROLI J.,** M.J. MARTIN, and M. RIGOLA. Material flow analysis for nitrogen cycle management at local level: The example of Catalonia (Spain).

Oral Session #19: **Interactions of Carbon and Nitrogen at Regional and Global Scales.** Rm 9
Chair: Arvin Mosier, US Department of Agriculture.

1:30 **LACAUX, J.P.** Nitrogen Deposition In Tropical Africa.
1:45 **WALLMAN, P.,** and H. SVERDRUP. Modeling nitrogen and carbon emissions/sequestrations in a forested area in southern Sweden as a result of management during the period 1450 to 2050.
2:00 **HICKS, W.K,** P. INESON, and J.C.L. KUYLENSTIERNA. Responses of terrestrial ecosystems to nitrogen enrichment- Impacts and issues at global scale.
2:15 **PARTON, W.J.,** S.J. DEL GROSSO, E.A. HOLLAND, A.R. MOSIER, D.S. SCHIMEL, D.S. OJIMA, R. BRASWELL, OLIVER BOSSDORF, and R. MCKEOWN. Global patterns for nitrogen cycling for terrestrial ecosystems.
2:45 **BAKER, L.A.,** D. HOPE, J. EDMONDS, Y. XU, and L. LAUVER. Factors controlling N cycling in the Central Arizona-Phoenix ecosystem.

3:00 **GROFFMAN, P.M.,** K.T. BELT, L.W. BAND, and G.T. FISHER. Nitrogen fluxes in urban watersheds.

3:15 **BOYER, E.W.,** R.W. HOWARTH, and C.L. GOODALE. Effects of anthropogenic nitrogen loading on riverine nitrogen export.

POSTER SESSIONS

(On display 10:00 AM – 7:00 PM; Poster Pubs 5:30 PM – 7:00 PM)

Posters will be available for viewing throughout the day in Rooms 19 and 21 on Monday and Room 21 on Tuesday and Wednesday. "Poster pubs" will be held from 5:30 – 7:00 Monday through Wednesday to provide an opportunity to view the posters and discuss them with the authors while enjoying light hors d'oeuvres and a cash bar. Posters should be set up between 7:00am and 10:00am and removed between 7:00pm and 9:00 pm.

ROUND-TABLE DISCUSSIONS

Monday – Wednesday, 4:30 pm – 5:30 pm, Rm 3

A round-table panel discussion will be held each afternoon to synthesize, contrast and address the various ideas brought forth during the morning plenary sessions, lunch time science and policy briefings, and afternoon concurrent sessions.

<u>Monday, October 15 - Nitrogen Production and Movement</u>
Moderator: Stan Smeulders, Ministry of the Environment in the Netherlands
Panel:

- John Aber, University of New Hampshire
- Robin Dennis, US Environmental Protection Agency/National Oceanographic and Atmospheric Administration
- Paul Fixen, Potash and Phosphate Institute
- William Moomaw, Tufts University
- Sybil Seitzinger, Rutgers University
- Henry Tyrell, US Dept of Agriculture

<u>Tuesday, October 16 – Nitrogen Around the World and its Effects</u>
Moderator: Hans Paerl, University of North Carolina at Chapel Hill
Panel:

- Klaas van Egmond, National Institute of Public Health and the Environment in the Netherlands
- Congbin Fu, Chinese Academy of Sciences
- Jonathan Patz, Johns Hopkins University
- Mary Ann Rozum, US Department of Agriculture
- Peter Vitousek, Stanford University

<u>Wednesday, October 17 - Innovation with Nitrogen</u>
Moderator: Oene Oenema, Alterra Green World Research
Panel:

- Rona Birnbaum, US Environmental Protection Agency
- Michael Bradley, M.J. Bradley & Associates
- Teresa Gruber, Council for Agricultural Science and Technology
- Ellis Cowling, North Carolina State University
- Arvin Mosier, US Department of Agriculture
- Rabindra Roy, Food and Agriculture Organization of the United Nations

Appendix C. Participants in the Second International Nitrogen Conference.

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