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Integrated Nitrogen Committee (INC)

Draft Interim Summary (April 8)

Introduction

Biologically active, photochemically reactive, and radiatively active nitrogen compounds are collectively referred to as reactive nitrogen (Nr). At the global scale, human activities now create more Nr than natural terrestrial ecosystems produce or can assimilate, thus Nr is now accumulating in the environment. As Nr moves through the environment, it can cause adverse effects such as photochemical air pollution, reduced visibility, ecosystem fertilization, acidification and eutrophication, global warming and stratospheric ozone depletion. However, Nr also dramatically improves food production and is used as a feed stock in many chemical processes. Therefore, the challenge is to maximize the beneficial uses of Nr, while minimizing adverse environmental impacts. One approach to meeting this challenge is the deliberate integration of Nr research, management, and control strategies.

Regulatory bodies have addressed well-recognized problems resulting from excess Nr. They have lowered level of Nr as ammonium and nitrate in sewage, as a precursor to photochemical smog and acid rain, as inputs to coastal systems, in the form of fine particulates in the atmosphere and as leachate from crop and animal production systems. As beneficial as those efforts have been, each focuses on a specific system without consideration of the interaction of their particular system with other systems downstream or downwind. While single-media approaches may result in short term benefits for a particular system, they are likely only to delay larger scale impacts on other systems. Thus, there is a need for an integration of nitrogen management programs, to ensure that efforts to lessen the problems caused by nitrogen in one part of the environment do not result in increased problems elsewhere.

In that regard, the objectives of the INC are:

1. Identify and analyze, from a scientific perspective, the problems nitrogen presents in the environment and the links among them;

2. Evaluate the contribution an integrated nitrogen management strategy could make to environmental protection;

3. Identify additional risk management options for EPA's consideration; and

4. Make recommendations to EPA concerning improvements in nitrogen research to support risk reduction.

Background

Nr is necessary for all life, but makes up only a small part of the nitrogen found in the environment. A few species of Bacteria and Archaea can convert the nitrogen gas (N_2), comprising 78% of the atmosphere, from N_2 to Nr (Nr). However, even with natural adaptations to use nitrogen efficiently, many ecosystems of the world are limited by nitrogen.

With the advent of agriculture, local sources of Nr were used (soil stocks, crop residue, manures) to increase productivity of landscapes. In the 19th century, long range transport of Nr to sustain food production increased in the form of bird guano from the Pacific Islands and nitrates from South America. By the beginning of the 20th century, these sources were not sufficient to sustain the growing global population requirements for food. This deficiency led to what has been called one of the world's most important discoveries—how to extract N_2 from the atmosphere and convert it to NH_3—the Haber-Bosch process. Today this process and cultivation-induced biological nitrogen fixation (C-BNF) introduce over 120 Tg N of Nr into the global environment to sustain food production. Another 45 Tg N are introduced by the Haber-Bosch process for the chemical industry, and 25 Tg N are introduced via the combustion of fossil fuels. The total global anthropogenic Nr creation rate is 190 Tg (2005), substantially larger than the median of estimates for Nr creation by natural terrestrial processes (~100 Tg N yr^{-1}). The fact that humans are more effective than nature in Nr creation means that on average, there is enough Nr available to sustain food production. There are, however, great regional discrepancies in the use of Nr, leading to large regions of the world where there is malnutrition due to lack of available Nr.

Because Americans have deliberately introduced Nr into most agricultural regions of the US, the availability of food has greatly increased. However, it has also greatly increased a wide variety of environmental problems. Much of the Nr applied to agroecosystems is lost to the environment during the food production process or after human consumption. Additional Nr is released through combustion processes by industry, transportation, buildings and electric power generation. This injection of Nr into the US environment increases photochemical smog, decreases atmospheric visibility, increases and can decrease productivity of grasslands and forests, acidifies soils and freshwaters, increases coastal eutrophication, increases the emission of greenhouse gases to the atmosphere and decreases stratospheric ozone concentrations. All of these changes in environmental conditions lead to a variety of negative impacts on both ecosystem and human health.

Nitrogen differs from other element-based pollution problems in an important way. One N-containing molecule, as it moves through the environment, can contribute to all the environmental issues mentioned above. The biogeochemical movement, the environmental changes that result from it and the consequences to humans and ecosystems comprise the nitrogen cascade (Figure 1). The' biogeochemical' component includes Nr creation from N_2 by chemical, food and energy production, Nr use in food and chemical production, Nr losses to the environment, Nr species residence times in environmental reservoirs, Nr transfers among reservoirs and Nr conversion back to N_2. The 'environmental changes' component arises from the fact that increased Nr levels in the environment contribute to photochemical smog, atmospheric particulate loading, ecosystem fertilization, acidification, and/or eutrophication, greenhouse effect and stratospheric ozone depletion. The 'consequences' component includes negative ecosystem and human health impacts at local, regional, national and global scales. The duality of nitrogen being a critical resource and also a contributor to many of the environmental issues facing the US today, makes it imperative not only to understand how human action has altered N cycling in the US, but also the consequences of those alterations on people and ecosystems. The over-arching dynamic is how do we protect society while also providing the materials, food and energy required that society requires?

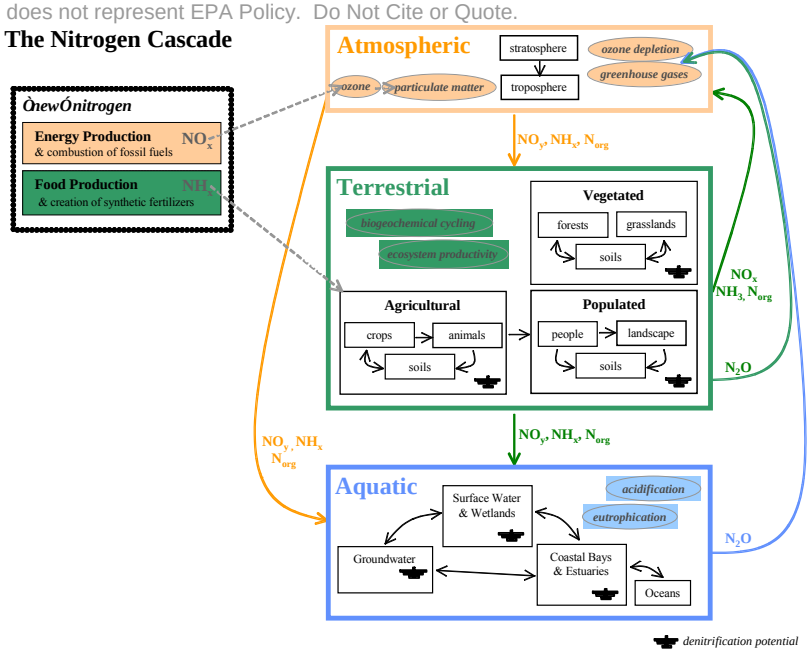

Figure 1: The Nitrogen Cascade: The popular concept of the nitrogen cascade highlights that once a new Nr molecule is created, it can, in sequence, travel throughout the environment contributing to major environmental problems (Galloway et al., 2003). This adaptation of the cascade was developed by the Integrated Nitrogen Committee to provide a context for considering nitrogen-related issues and ecosystem effects in the US. To consider the cascading effects of Nr in the US, we examine the relative sizes of the various Atmospheric, Terrestrial, and Aquatic compartments where Nr is stored, and the magnitudes of the various flows of nitrogen to-, from-, and within them. The nitrogen cascade concept implies the cycling of Nr among these compartments. The important process of denitrification is the only mechanism by which Nr is converted to chemically inert N_2, 'closing' the continuous cycle.

The "new" nitrogen box depicts the two primary sources by which Nr originates, energy production and food production, and where they enter ecosystems. Energy production includes both fossil fuel and biofuel combustion. Food production includes N fertilizer produced in the US, cultivation-induced biological nitrogen fixation in the US, production of animals and crops in the US for human consumption, and imports of N-containing fertilizer, grain and meat to the US.

The Atmospheric compartment indicates that tropospheric concentrations of ozone, particulate matter and nitric acid are increased due to NOx emissions to the atmosphere. The ovals illustrate that the increase in N_2O concentrations, in turn, contribute to the greenhouse effect in the troposphere and to ozone depletion in the stratosphere. Except for N_2O, there is limited Nr storage in the atmosphere. Losses of Nr from the Atmospheric compartment include NOy (which includes HNO_3 and particulate nitrate), NHx, and Norg deposition to Terrestrial and Aquatic ecosystems of the earth's surface. These depositions contribute to both acidification and eutrophication of land and water. There is little potential for conversion of Nr to N_2 via denitrification in air.

The Terrestrial compartment depicts Nr entering agricultural lands via food production and is introduced to the entire terrestrial landscape via atmospheric deposition. Within 'agricultural' regions there is cycling among soils, crops and animals, and then a transfer of Nr as food to 'populated' regions, from which there are Nr losses (e.g., sewage, landfills). The ovals showing 'ecosystem productivity' and 'biogeochemical cycling' reflect that Nr is actively transported and transformed within the Terrestrial compartment, and that as a consequence there are significant impacts on ecosystem productivity due to fertilization and acidification, often with resulting losses of biodiversity. There is ample opportunity for Nr storage in both biomass and soils. Losses of Nr from the Terrestrial compartment occur by leaching of NOy, NHx and Norg to Aquatic ecosystems and by emissions to Atmospheric ecosystems as NOx, NH_3, Norg, and N_2O. There is some potential for conversion of Nr to N_2 via denitrification in the landscape.

The Aquatic compartment shows that Nr is introduced via leaching from Terrestrial ecosystems and via deposition from Atmospheric ecosystems. Connected with the hydrological cycle, there are Nr fluxes downstream with ultimate transport to coastal systems. Within the Aquatic compartment, the ovals highlight two significant impacts of waterborne Nr—acidification of freshwaters and eutrophication of coastal waters. Except for Nr accumulation in groundwater reservoirs, there is limited Nr storage within the hydrosphere. Losses of Nr from the Aquatic compartment are primarily N_2O emissions to Atmospheric ecosystems. There is a very large potential for conversion of Nr to N_2 via denitrification in water and wetlands.

Nr Inputs to US

A century ago, the natural biological activity of a few organisms was the only major process converting atmospheric nitrogen gas (N_2) to reactive forms of nitrogen (Nr). At present, reactive forms of nitrogen created by human activities associated with energy and food production provide the primary Nr inputs to the environment, exceeding contributions from natural sources; here we present Nr fluxes for the contiguous USA in 2002.

Energy production adds Nr to the environment. Fossil fuel burning releases Nr among the combustion products and leaves Nr residues behind as atmospheric emissions (5.4 Tg N). These Nr emissions are significant in magnitude nationally and globally, and subsequently provide inputs of Nr to terrestrial and aquatic ecosystems via atmospheric deposition. Nr emissions stem from all sectors that burn fossil fuels and biofuels -- including stationary sources (e.g., electricity generating utilities; industrial, commercial, and residential fuel consumption), area sources (e.g., forest fires and clearing of lands via burning), and transportation sources (e.g., highway and off-highway vehicles).

Food production also adds Nr to the environment. Vast quantities of Nr are produced by the creation of nitrogenous fertilizers, where Nr is synthesized from inert N_2 via the industrial Haber-Bosch process. Fertilizer N is produced (9.4 Tg), exported (2.4 Tg) or imported (2.4 Tg) to this country. Most of this fertilizer is used for food production (90%) with the remainder applied to golf courses, urban parks, lawns, and gardens. Nr is also introduced to the environment in agricultural lands by cultivating leguminous crops, which host microorganisms capable of producing Nr biologically, via biological nitrogen fixation (7.7 Tg N), and lastly imports of grain and meat commodities (0.15 Tg) are another source of Nr to the USA.

Food production creates large amounts of nitrogen-containing wastes (e.g., manure) and, though some of this Nr is transformed naturally in the landscape into inert N_2, a significant fraction accumulates in the terrestrial landscape or appears in surface or ground waters. Point-sources of waste (e.g., treated human waste from sewage treatment plants) and nonpoint sources of waste (e.g., from leaching of Nr from manure) are leading sources of Nr pollution in the US. Significant quantities of Nr may also be introduced to the environment through world trade, with imports (and exports) of Nr-containing fertilizer, grain, and meat to the US.

Inputs of Nr to agricultural ecosystems include atmospheric N deposition, biological N fixation, additions of synthetic nitrogenous fertilizers, and animal manure (which in turn is affected by net imports or exports of nitrogen in animal feed). In response to those N inputs, N is assimilated by crops and animals (eating a protein, or N-rich, diet). Change in agricultural soil N storage is an important fate of the N inputs to agroecosystems, where accumulation of N in soils can act as an important sink for N inputs. Losses of N from agricultural lands include volatilization from fertilizers and manure (to the atmosphere), denitrification (to the atmosphere), export of N as food in harvested crops and in animal products (to terrestrial, populated ecosystems), and leaching and runoff (to aquatic ecosystems, including ground water and surface waters).

The exchange of agriculturally emitted trace gases between the biosphere and the atmosphere is not yet well understood. For example, after deposition, NH_3 can be re-emitted when the ambient concentration decreases and the equilibrium is shifted. Furthermore, N-fertilized fields can first act as an emission source, but deposition might occur downwind when the ambient concentration increases because of nearby sources. The atmosphere-biosphere exchange is largely driven by this equilibrium, which is highly spatially and temporally variable. The challenge will be to model fluxes of gases and particulate matter on the regional or landscape scale where both emission and deposition take place at the same time.

Current research issues include better quantification of point and nonpoint sources, and the dynamic controls on biosphere-atmosphere exchange of nitrogen (e.g. ammonia). What are the largest sources of Nr and how are past trends relevant to the future? Within the major Nr source systems (e.g. agriculture, transportation, power generation, etc), which subsystem components are responsible for the most Nr, what are the major loss pathways, what forms does this Nr take (NO_x, N_2O, NH_x, etc), and where does it go (deposition, leaching, etc). Furthermore since different forms of Nr produce different environmental impacts, which emissions cause the greatest costs to the environment or to human health? Finally, based on recent trends, can we expect changes in Nr amounts and sources, and if so why, and what are the most promising and cost-effective technologies for managing Nr loads?

There are large uncertainties in our current estimates and understanding of Nr cycling. Statistics on nitrogen fertilizer use in agriculture and on urban/recreational turf systems are not available with sufficient detail to determine actual rates of geospatial distribution of application on all the major crops. Although there are good estimates of nitrogen use efficiency from small-scale experiments at research stations, measurements from production-scale field studies on the major crops and cropping systems are limited, especially those covering a wide range of soil types and climate conditions. Thus, existing estimates of inputs and outputs from agricultural and urban/recreational turf systems must be used with caution.

Similar large uncertainties exist for current agricultural air quality modeling as a result of a number of factors including: (1) inaccurate emission inventories as a result of missing and sometimes erroneous application levels, the failure to use uniform emission factors, inaccurate temporal variations, poor spatial resolution, inconsistent source categories, and inconsistency in the methods used; (2) inaccurate meteorological predictions (e.g., temperature, wind speed, wind direction, and precipitation); (3) a lack of a detailed information on terrain characteristics and land use at a fine scale (e.g., topography, surface roughness and vegetation); (4) missing or inadequate model treatments of chemical and physical processes (e.g., gas- and aqueous-phase chemistry for NH_3 and NO_x, gas/particle partitioning, aerosol dynamics, and dry and wet deposition); (5) inability to simulate both the short-range dispersion and deposition of NH_3 near the ground and the long-range transport and fate of NH_4^+ at higher elevations downwind of sources; (6) high uncertainty in the dry deposition of agriculturally emitted Nr, sulfur, and carbon compounds; and (7) a paucity of observations of emissions, concentrations, and deposition suitable for model verification and evaluation. Reconciling modeled results with measurements is further complicated by the weather which has a profound effect on ambient concentrations and dry deposition. Small changes in temperature, wind speed or humidity may change the ambient concentration and dry deposition regardless of emissions. Given climate change predictions, the exponential increase in trace gas emissions with temperature due to gas/solution partitioning is particularly important in this respect.

There are also uncertainties in the air emissions of Nr from the energy sector that need to be resolved. The impacts of these emissions on health, forests, grasslands and aquatic systems need to be quantified in terms of quantity and damage costs. The many unquantified damages of Nr emissions on climate, stratospheric ozone depletion, biodiversity and fisheries need further research. Finally, a more integrated approach to Nr air and water pollution management and regulation could lead to more cost efficient and effective nitrogen management strategies.

Research over the next decade and beyond should focus on decreasing these uncertainties. Their resolution will improve the basis for policy and program decisions on local to global scales. Such decisions will profoundly impact air quality, human health, the agro-eco environment, and biodiversity. Progress on these challenges will require an integrated effort both nationally and globally from scientists, engineers, policy-makers, managers, and the public.

Agroecosystems provide humans with a tremendous benefit—abundant low-cost food. However, in the process, some of the Nr that is not incorporated into the vegetable and animal protein is lost to the air, soils, and waters and some is retained in the agroecosystem. The next section of this summary discusses the fate of the Nr that is injected into the environment from energy and food production.

Nr Transfer and Transformations in and between Environmental Systems

This section of the summary addresses how Nr moves through the overall conceptual view of the nitrogen cascade. As Nr moves through and between environmental systems, losses from one part of the system become the inputs to others. The specific locations along these flow paths where nitrogen fluxes may be controlled are called control points. This approach identifies where the largest uncertainties are for inputs and flows; it also identifies where the control points (including denitrification) would be if it were decided to decrease the nitrogen fluxes.

Transfer of Nr from the atmosphere to terrestrial systems

Downward transport from the atmosphere is a major source of Nr to the Earth's surface, but the characteristics and absolute magnitude of the flux are uncertain. Pollutants not deposited are exported from the continent and alter the composition and radiative balance of the atmosphere on a large scale. Based on observations and model estimates, total estimated deposition of all forms of Nr to for the entire 48 States for 2002 was ~5.9 (4 ─ 9) Tg N yr^{-1}. The following critical research needs are identified:

- Increase the scope and spatial coverage of the N concentration and flux monitoring network (such as CASTNET) for the US and appoint an oversight panel.
- Monitor NH_3, NH_x, NOy, NOx, and PAN concentrations and measure or infer deposition.
- Measure deposition directly both at the CASTNET sites and nearby locations with non-uniform surfaces such as forest edges.
- Continued research into convective venting of the planetary boundary layer.
- Improved monitoring of NOx from vehicles.
- Develop techniques and measurements of atmospheric organic N compounds in vapor, particulate, and aqueous phases.
- Improve the ability to predict the contribution of Nr to global warming and stratospheric ozone depletion, and quantify the impacts on terrestrial systems (including agriculture).
- Develop indices of impacts that are not possible to quantify such as biodiversity loss from excess Nr.
- Measurements of NH_3 emissions from agricultural practices.
- Research on improved regulatory integration of clean water and clean air policies

Transfer of Nr from terrestrial to aquatic ecosystems

Within the nitrogen cascade Nr flows from the atmosphere and terrestrial systems into aquatic systems. Aquatic systems include groundwater, streams and rivers, lakes and the coastal marine environment. Nr is deposited directly into surface aquatic systems from the atmosphere. Some Nr is stored and other Nr is removed in products from terrestrial systems. The remaining Nr eventually moves into aquatic systems. Major concerns from too much Nr in aquatic systems include unsafe drinking water and eutrophication which causes harmful algal blooms and coastal hypoxia. Major points for consideration include:

- Nitrogen loading to large watersheds such as the Gulf of Mexico is a major challenge to ecological science and its applied field of ecological engineering
- Application of Nr numbers to large watersheds in NE US Nitrogen Cascade suggest that Nr research needs to focus on understanding the "denitrification" loss term in this analysis. The losses occur in the terrestrial landscape, before Nr enters the river. Where do these losses occur, within the agricultural field, in drains and ditches near the agricultural field, in riparian areas, or wetlands? Understanding this term may help in the management of Nr in watersheds to decrease nitrate movement into aquatic systems as well as to limit N_2O emissions to the atmosphere.

Storage of Nr within terrestrial ecosystems

Roughly 1.7 Tg of Nr, reported as N, is stored annually of Nr in all terrestrial ecosystems in the continental US. Annual storage in agricultural, grassland and forest soil and in forest biomass is approximately 6 to 10 % of annual Nr input. All of the input and outflow numbers are highly uncertain, but N loss through denitrification appears to be the loss mechanism, which dominates the budget.

Biophysical and technical controls on transfer and transformations of Nr in and between environmental systems

There are a number of places within the nitrogen cascade where the flow of Nr is constrained or regulated. These control points may restrict the flow of Nr species within environmental systems (atmospheric, terrestrial, aquatic) or between them. The following control points highlight the need for research and educational activities:

- Decreasing the amount of fertilizer N needed through changes in human diet
- Identifying hot spots with high loss potential and then removing these croplands that are more susceptible to Nr loss from crop production
- Decreasing fertilizer N losses by increasing fertilizer use efficiency in crop and fiber production
- Managing Nr during recycling through livestock production
- Biophysical controls on transfer of nitrate from agricultural lands to aquatic systems: Restoration of natural removal systems such as wetlands to decrease nitrate loading of aquatic systems

- Technical controls on transfer and transformations of nitrogen oxides in and between environmental systems
- Increasing efficiency and lowering emissions to the atmosphere from the energy and transport sectors to both protect human health, and reduce Nr damage to terrestrial and aquatic ecosystems
- Improving treatment technologies for sewage, landscape effects (e.g. hardening of the landscape) and nonpoint and stormwater management

Critical numbers on budgets and flows

- Total denitrification in animal feeding operations, in soils, and in aquatic systems
- The amount of N deposited in each environmental system as dry deposition
- The amount of N_2O released during nitrification/denitrification in animal feeding operations, soils and aquatic systems
- NO_x exchange between soils and the atmosphere in terrestrial systems
- Rates and amount of ammonia emission from fertilized soils and animal feeding operations.
- Quantification of the annual change in N storage in soils (agricultural, forest and grassland) and aquatic systems.
- Improved quantification of atmospheric deposition from the energy and transport sectors to aquatic and terrestrial ecosystems

<u>Impacts and Metrics for Nr</u>

Measurement of Nitrogen in the Environment

Although nitrogen is among the most abundant elements on earth, only a small fraction, the various forms of chemically and biologically Nr is responsible for impacts on the environment. Most regulations focus narrowly on specific chemical forms of nitrogen as they affect media- or location-specific problems, setting limits or specifying control technologies without regard to the ways in which nitrogen is transformed once introduced into the environment. Measurement methods are typically expressed in terms of mass loadings or concentrations of a particular form of nitrogen, e.g. ppm NO_x, mg/l total ammonia, or kg/ha of NO_3^-. However it is clear that, in addition to these metrics, there is a need to measure, compute, and report the total amount of Nr, in appropriate units, present in impacted systems.

It is also possible to translate the implications of reactive nitrogen into economic terms. Two economic measures that are used are the dollar costs of damages, and the cost of remediation or substitution. Another important economic metric is the cost/ton of remediation for each form of reactive nitrogen. Damage costs do not always scale as tons of reactive nitrogen released into the environment. If damage costs rather than tons of nitrogen were utilized as a metric, the full implications of the cascade, and the setting of priorities for intervention might differ.

Nr Impacts

The types of impacts of Nr in the environment are both media- and chemical species-dependent, while the magnitude of effects depends on loading and the nature of the system impacted. The impacts of a given source of Nr can be multiple as it is transformed in the environment and transported from sector to sector. Nr can impact multiple ecosystems including aquatic (both coastal and inland), atmospheric, and terrestrial.

Various approaches can be used to prevent, eliminate, reduce, or otherwise manage risk. In considering which approaches to apply, it is important to understand the environmental impacts that Nr can have. For this purpose, impacts are divided into several general categories within which various contaminants have a direct correlation with damage. Risk "endpoints" are typically established through reference to supporting scientific studies, location-specific conditions, and economic, safety, and social factors.

Classical impacts include categories such as global warming, eutrophication, ecotoxicity, human health (cancer and non-cancer), acidification, smog formation, and ozone depletion, among others (Bare et al 2003). Within these categories it is sometimes possible to express end points in terms of collective metrics, such as is done with greenhouse gases in the form of carbon dioxide equivalents, or acidification as H^+ equivalents. This approach has

the considerable advantage of defining a straightforward framework within which environmental standards can be derived that are protective of human health and the environment, the principal mission of the USEPA. This approach also encourages evaluation of damage from collective sources, as long as the characterization metric used is genuinely representative of the impact of a given contaminant. Thus, for example, the total impact of acidic gases such as SO_2 and NO_x on the acidification of watersheds can be expressed as a common metric. However, metrics for human health are generally not as simple to characterize nor are the appropriate end points, thus the mechanism of toxicity, number of individuals affected, value of lost workdays, medical treatment costs, and value of human lives lost may all be used.

A complementary approach to classical impact characterizations is the use of ecosystem "service" and "function" categories, in which the impairment of a specific service provided by one or more ecosystems, or function operating within an ecosystem, by causative contaminant emissions is assessed (Costanza 1997; MEA 200x). Such an approach is inherently attractive because of its basis in scientific reality, i.e. the health of humans and the environment is inextricably linked. Less clear, in some cases, are ways in which to measure and monitor such impacts.

There is value in each of the ways that nitrogen impacts are expressed. Traditional categories provide a readily adaptable framework for regulation, service and function-based categories provide a richer context for stating the complex connections among Nr inputs and transformations, and their impacts on human well-being, and dollar-based impacts provide a means of identifying those effects that have the greatest damage costs to society. The Committee recognizes that utilizing multiple metrics may provide a clearer picture of priorities for action, identify effective choke points for reducing Nr impacts, and provide insights into more effective regulatory strategy.

Tradeoffs of Nr Impacts

Because nitrogen is such an abundant element, and Nr such a critical component of the earth's biosphere, associated impacts are many and pervasive. In many cases the impacts of Nr involve tradeoffs, i.e. mitigating one type of impact may exacerbate others. Four such categories of tradeoffs are ammonia release from concentrated feed lot operations (CAFOs), human nutrition, nitrification-denitrification, and nitrogen-carbon related impacts.

Integrated Risk Reduction Strategies for Nr

While quantitative risk assessment is not always a precursor to risk management decisions, it is frequently an input. Risk management also considers other elements such as technical feasibility; economic, social and legal factors; and additional benefits of the various options to develop a suite of risk reduction strategies and select among various risk reduction activities.

The regulation of Nr in the environment by the EPA follows an impact-by-impact approach which, with few exceptions, examines specific forms of nitrogen in either aquatic, atmospheric, or terrestrial systems. The principal regulatory authority pertaining to nitrogen is derived from two major legislative initiatives, the Clean Water Act (CWA) and the Clean Air Act (CAA).

Control Strategies for Nr

There are several ways in which the release and control of Nr in the environment are approached. In general these can be classified as follows:

- Transformation—in which one form of nitrogen is converted to another form (e.g. nitrification of wastewater, denitrification),
- Removal—in which Nr is sequestered from impacting a particular resource (e.g. ion exchange)
- Source limitation—in which the amount of Nr introduced into the environment is lowered (e.g. renewable energy sources, utilization of fertilizer best management practices to limit nutrient losses, and controls on NOx generation).
- Improved use efficiency—in which the efficiency of production that is dependent on Nr is improved (e.g. increased grain yields for lower Nr applied, or less NO_x from more efficient energy sources)

- Improved practices—in which the flux of Nr that creates an impact is lowered through better management practices (e.g. on-field agricultural practices, controlled combustion conditions)
- Product substitution—in which a product is developed or promoted which has a lower dependency on Nr (e.g. switchgrass instead of corn grain as a feedstock for ethanol)

Effective management of Nr requires combinations of these approaches; no one approach is a perfect alternative for controlling Nr in the environment. Control also requires the knowledge of interactions between aquatic, land, and air impacts as well as coordinated regulation of these media.

Management of Nr in the Environment

Three types of management strategies for the control of Nr, and other pollutants, in the environment have evolved over the past 40 years:

- Command-and-Control—in which an entity's "right to pollute" is recognized through a series of permitted limitations on emissions, violations of which may result in assessing of penalties being assessed.
- Government-based programs for effecting a policy, such as directed taxes, price supports for a given commodity, subsidies to bring about a particular end, and grants for capital expansion or improvement.
- Market-based instruments for pollution control in which cap and trade markets are used to bring about a desired policy end, often at reduced overall cost.
- Societal changes and voluntary reductions that may be promoted by social marketing and through outreach and education that promote good stewardship practices.

An integrated approach to the management of Nr must of necessity use a combination of mechanisms, each most appropriate to the nature of the problem at hand, that are supported by critical research on reducing the risks of Nr, and reflective of an integrated policy that recognizes the complexities and tradeoffs associated with the nitrogen cascade.

The Role of Research in the Reduction of risk from Nr

Social and Policy Aspects of Nr Risk Reduction

Summary

Human activities have significantly altered the introduction of Nr into the US environment, and while there is tremendous benefit from food production, there is also tremendous damage to the health of both ecosystems and people due to the introduction of Nr into the nitrogen cascade. To optimize Nr's benefits and to minimize its problems will require an integrated nitrogen management strategy that not only involves EPA, but also other federal agencies (e.g., USDA, DOE, NOAA), the private sector and a strong public outreach program.