Executive Summary

Introduction

Nitrogen (N) is an integral component of all proteins, which are the basic building blocks of life and catalysts for life-sustaining reactions in organisms. Reactive nitrogen (Nr), in contrast to non-reactive gaseous N_2, includes all biologically active, chemically reactive, and radiatively active nitrogen compounds in the atmosphere and biosphere of the earth.[1] Without an adequate supply of N in any organism's diet, it can't survive. Ironically, bioavailable N for nutrition is in short supply and indeed the productivity of most of the world's ecosystems is often limited by the availability of N. This is certainly the situation with food production. Without the creation of N fertilizer by an industrial process (the Haber-Bosch process) and the increased cultivation of leguminous crops, the world could not support the current human population or its projected increase.

As further discussed in Chapter 2 of this report, increased anthropogenic input of Nr to the environment has contributed to large increases in the mass flux of nitrogen via the nitrogen cycle. Anthropogenic sources of N now provide enough N, on average, to grow food for the world's peoples. However, a major consequence of this nearly inexhaustible supply is that most N used in food production, and all of the new Nr produced by fossil fuel combustion, is lost to the environment where it circulates through the earth's atmosphere, hydrosphere, geosphere, and biosphere. During this circulation, Nr contributes to a wide variety of consequences, which are magnified with time as Nr moves through the environment.

Impacts of reactive nitrogen on human health and the environment

Anthropogenic creation of Nr provides essential benefits for humans – first and foremost in meeting human dietary needs. A large fraction of the human population of the earth could not be sustained if synthetic nitrogen fertilizers did not significantly augment food production. Essentially all of the Nr created by human activities, however, is released to the environment, often with unintended negative consequences. As summarized in Table ES-1, it contributes to a number of adverse public health and environmental effects, including photochemical smog, decreased atmospheric visibility, acidification of terrestrial and aquatic ecosystems, eutrophication of coastal waters (i.e., harmful algal blooms, hypoxia), drinking water concerns, freshwater Nr imbalances, greenhouse gas emissions and subsequent climate change, and stratospheric ozone depletion.

In light of the magnitude of the human alteration of the nitrogen cycle, and the resulting negative consequences on humans and ecosystems, the National Academy of Engineering has identified management of the nitrogen as one of the "grand challenges" facing this country.[2]

Nr effects are manifest as direct declines in both human health (e.g., respiratory and cardiac diseases) and ecosystem health (e.g., coastal eutrophication and loss in biodiversity). In addition, there are indirect declines in human health because the negative impacts on ecosystems will diminish the services that those ecosystems provide people. The effects are often magnified because the same atom of nitrogen can cause multiple effects in the atmosphere, in terrestrial ecosystems, in freshwater and marine systems, and on human health. We call this sequence of effects the nitrogen cascade.

The nitrogen cascade

The nitrogen cascade has three dimensions: biogeochemical, alterations in the environment, and human and ecosystem consequences.

The "biogeochemical" dimension of the nitrogen cascade involves: Nr creation from N_2 as a consequence of chemical, food, and energy production; Nr use in food and chemical production; Nr losses to the environment; changes in Nr species residence times in environmental reservoirs; Nr transfers among reservoirs; and Nr conversion back to N_2. Alterations to the environment then result from increased Nr levels in the environment. These alterations have negative consequences for ecosystem and human health at local, regional, national, and global scales. Because nitrogen is a critical resource and also a contributor to many of the environmental concerns facing the U.S. today, it is imperative to understand how human action has altered N cycling in the U.S., and the consequences of those alterations on people and ecosystems. The overarching question is, how do we protect and sustain ecosystems that provide multiple benefits to society while also providing the interconnected material, food and energy required by society?

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[1] Reactive nitrogen (Nr) includes inorganic chemically reduced forms of N (NH_x) [e.g., ammonia (NH_3) and ammonium ion (NH_4^+)], inorganic chemically oxidized forms of N [e.g., nitrogen oxides (NO_x), nitric acid (HNO_3), nitrous oxide (N_2O), N_2O_5, HONO, peroxy acetyl compounds such as peroxyacytyl nitrate (PAN), and nitrate ion (NO_3^-)], as well as organic compounds (e.g., urea, amines, amino acids, and proteins).

[2] National Academy of Engineering Grand Challenges (http://www.engineeringchallenges.org/cms/challenges.aspx)

Table ES-1: Examples of impacts of excess reactive nitrogen on human health and environment

Impact	Cause	Location	Metric	Source	Reference
AIR					
Visibility decrease	Fine particulate matter	National Parks and wilderness areas	visibility impairment	NO_y and NH_x from fossil fuels and agriculture	Malm et al., 2004; U.S. EPA Clean Air Scientific Advisory Committee, 2004 EPA-CASAC-09-010
LAND - ECOSYSTEMS					
Biodiversity loss	Nitrogen deposition	Grasslands and forests in the United States receiving N deposition in excess of critical load	Decrease in species richness of grass-lands and forests	Utilities, traffic, and animal agriculture	Bobbink et al., 2010; Fenn et al., 2003.
Forest decline	Ozone and acid deposition	Eastern and West-ern United States	Decreased timber growth; increased susceptibility to disease and pests	Utilities, traffic, and animal agriculture	Johnson & Siccama, 1983; MacKenzie & El-Ashry, 1990
LAND - AGRICULTURE					
Crop yield loss	Ozone	Eastern and West-ern United States	$ 2-5 billion/year	Utilities & traffic	Heck et al., 1984
WATER					
Acidification of surface waters; loss of biodiversity	Acidification of soils, streams and lakes is caused by atmospheric deposition of sulfur, HNO_3, NH_3 and ammonium compounds.	Primarily mountain-ous regions of the United States	Out of 1,000 lakes and thousands of miles of streams in the Eastern United States surveyed, 75% of the lakes and 50% of the streams were acidified by acid deposition	Fossil fuel combus-tion and agriculture	U.S. EPA, 2008a http://www.epa.gov/acidrain
Hypoxia of coastal waters	Excess nutrient loading, eutrophi-cation, variable freshwater runoff	Gulf of Mexico, other estuarine and coastal waters	Benthic finfish/shell-fish habitat loss, fish kills, sulfide toxicity, costs >$50 million annually	N, P from energy and food production	Bricker et al., 1999; Verity et al., 2006; U.S. EPA SAB, 2007; Rabalais et al., 1999; Mitsch et al., 2001
Harmful Algal Blooms	Excessive nutrient loading, climatic variability	Inland and coastal waters	Fish kills, losses of drinking and recreational waters costs >$100 million annually	Excess nutrient (N & P) loading	Paerl, 1988; ECOHAB, 1995; NRC, 2000
HUMAN AND ENVIRONMENTAL HEALTH DAMAGES					
Human mortality	$PM_{2.5}$, O_3 and related toxins.	U.S. urban and nearby areas	Pollution related deaths estimated at 28,000-55,000 per year (a range of cardiovascular and respiratory system effects are associated with this pollution).	NO_y and NH_x from fossil fuels and agriculture	Mokdad et al., 2004; Ezzati et al., 2004.
Total damage to public health and environment	NO_x into air	Chesapeake Bay Watershed	$3.4 Billion; 200,000 MT	Mobile sources	Moomaw and Birch, 2005; Birch et al., 2011
Total damage to public health and environment	NH_x and nitrate into air and water	Chesapeake Bay Watershed	$1.5 Billion; 400,000 MT	Agriculture	Moomaw and Birch, 2005

Nr inputs to the nation and the world have been increasing, largely due to human activities associated with food production and fossil fuel combustion. Despite the obvious benefits of a plentiful supply of food and energy, the adverse consequences associated with the accumulation of Nr in the environment are large, with implications for human health and the environment.

The greater the inputs of Nr to the landscape, the greater the potential for negative effects caused by greenhouse gas (GHG) production, ground level ozone, acid deposition, and Nr overload that can contribute to climate change, degradation of soils and vegetation, acidification of streams, lakes and rivers, estuarine and coastal eutrophication, hypoxia, and habitat loss.

The growing nature of the Nr problem, and the adverse and intertwined consequences associated with Nr inputs to air, land, and water as exhibited in the N cascade underscore the need for researchers and managers to explore integrated strategies that minimize N inputs, maximize its use efficiency, promote Nr removal processes, and protect humans and natural resources.

The 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). The adaptation of the cascade in Figure ES-1 was developed by the SAB Integrated Nitrogen Committee (INC) to provide a context for considering nitrogen-related issues and ecosystem effects in the U.S. To consider the cascading effects of Nr in the U.S., we examined the various atmospheric, terrestrial, and aquatic environmental systems where Nr is stored, and the magnitudes of the various flows of N to, from, and within them. The nitrogen cascade concept implies the cycling of Nr among these systems. The process of denitrification is the only mechanism by which Nr is converted to chemically inert N_2, "closing" the continuous cycle (Figure ES-1 shows only flows of reactive nitrogen, not N_2). Denitrification can occur in any of the indicated reservoirs except the atmosphere.

The "new" N box in the Nitrogen Cascade depicts the two primary anthropogenic sources by which Nr originates – energy production and food production – and where Nr from these sources enters ecosystems. Energy production includes both fossil fuel and biofuel combustion. Food production includes N fertilizer produced in the U.S., cultivation-induced biological N (C-BNF) in the U.S., production of animals and crops in the U.S. for human consumption, and imports of N-containing fertilizer, grain and meat to the U.S.

The Nitrogen Cascade

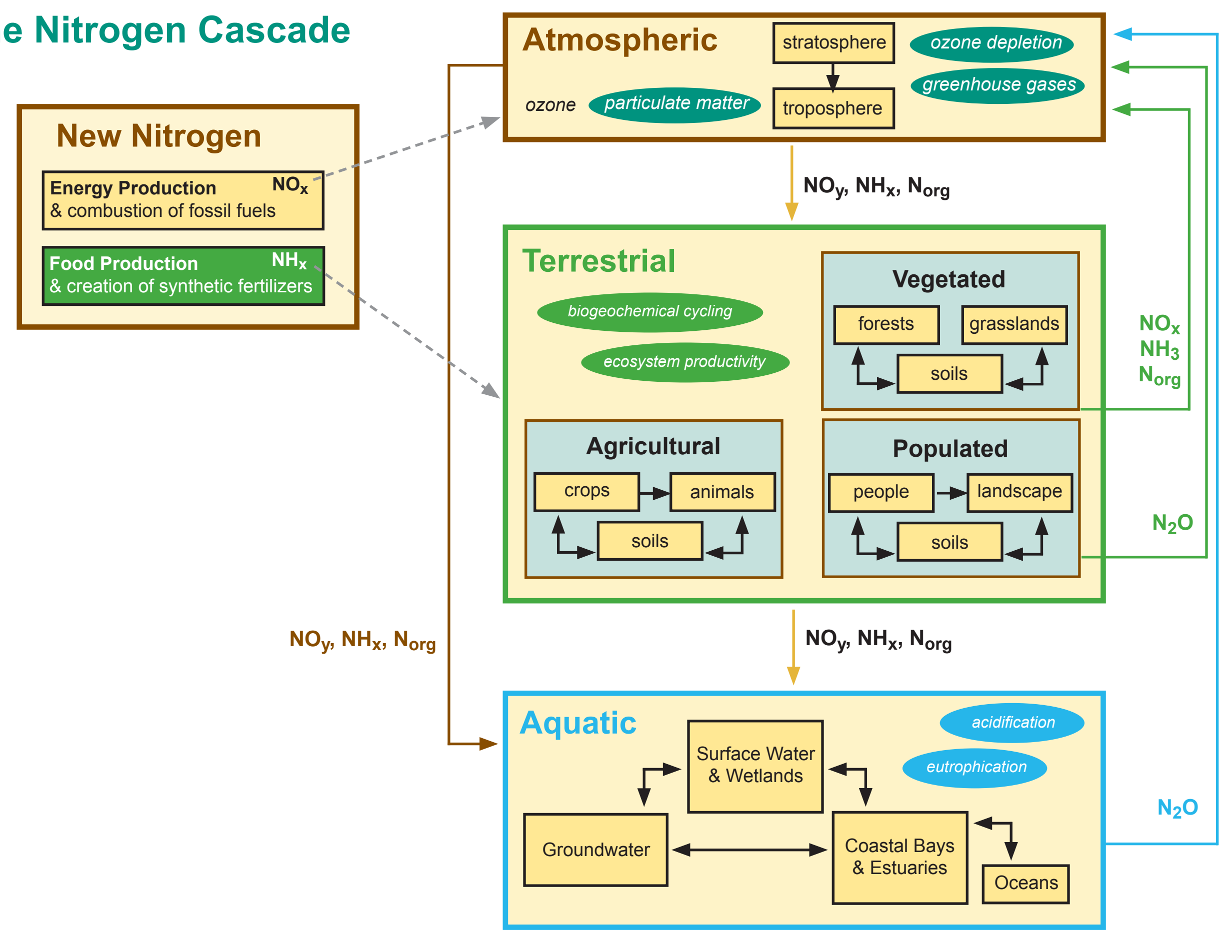

Figure ES-1: The nitrogen cascade

The atmospheric system box in the Figure ES-1 indicates that tropospheric concentrations of both ozone and particulate matter are increased due to emissions of nitrogen oxides[3] (NO_x) 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 system include total oxidized nitrogen[4] (NO_y), reduced nitrogen[5] (NH_x), and organic nitrogen (Norg) deposition to terrestrial and aquatic ecosystems of the earth's surface. There is little potential for conversion of Nr to N_2 via denitrification in air. However, once airborne deposition of Nr occurs it will be subject to denitrification pathways via soil and water.

The terrestrial system box in the Figure ES-1 depicts that Nr enters 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 to the environment (e.g., sewage, landfills). The ovals showing ecosystem productivity and biogeochemical cycling reflect that Nr is actively transported and transformed within the terrestrial system, 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 this system occur by leaching and runoff of NO_y, NH_x and Norg to aquatic ecosystems and by emissions to the atmospheric system as NO_x, NH_3, Norg, and N_2O. There is potential for conversion of Nr to N_2 via denitrification in the terrestrial system.

The aquatic system box in the Figure ES-1 shows that Nr is introduced via leaching and runoff 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 system, the ovals highlight two significant impacts of waterborne Nr acidification of freshwaters and eutrophication of fresh and coastal waters. Except for Nr accumulation in groundwater reservoirs, there is limited Nr storage within the hydrosphere. Losses of Nr from the aquatic system are primarily via N_2O emissions to the atmospheric system. There is a very large potential for conversion of Nr to N_2 via denitrification in water and wetlands.

NO_y, NH_x and N_2O are all components of Nr, but a fundamental difference is that the NO_y and NHx are rapidly transferred from the atmosphere to receiving ecosystems due to a short atmospheric residence time (≤ 10 days) where they continue to contribute to the N cascade. Because of its longer residence time (~100 years) however, N_2O remains in the troposphere where it contributes to climate change, until it is transferred to the stratosphere, where it contributes to ozone depletion.

Trends in N inputs to the United States

In 2002, humans introduced 29 teragrams (Tg) of newly formed reactive N into the U.S. through Haber-Bosch process production of fertilizers and industrial Nr, cultivation-induced biological nitrogen fixation (i.e., conversion of N_2 to NH_3 by microorganisms associated with some cultivated crops, for example, legumes), and fossil fuel combustion (Figure ES-2). By definition, prior to human presence in the U.S., there was no introduced anthropogenic Nr. Prior to 1900, no Haber-Bosch Nr was introduced, fossil fuel combustion introduced very small amounts relative to today, and cultivation-induced biological nitrogen fixation created approximately 2 Tg N. Thus, between 1900 and 2002, the amount of Nr introduced to the U.S. has increased by approximately 10-fold.

Nitrogen inputs to the United States

The EPA Science Advisory Board (SAB) Integrated Nitrogen Committee ("Committee") evaluated nitrogen inputs to the U.S. in 2002. At the global scale, human activities produced approximately twice as much Nr as did natural processes. In the U.S., however, the amount of Nr produced by human activities was approximately five times larger than natural processes. As shown in Figure ES-2, natural ecosystems in the U.S. introduce about 6.4 Tg of Nr as N per year (Tg N/yr). In contrast, human activities introduce about 28.5 Tg N/yr.

Chapter 2 of this report discusses sources, transfer, and transformation of Nr. Supporting references for the information presented on this topic are presented in Chapter 2. The largest single source of Nr in the U.S. is the Haber-Bosch process, which introduces about 15.2 Tg N/yr: 9.4 Tg N/yr from domestic Nr production and 5.8 Tg N/yr from imports of Nr in fertilizers. The 15.2 Tg N/yr of anthropogenic Nr is used in three ways: 9.9 Tg N/yr is used to produce agricultural crops; 1.1 Tg N/yr is applied to turf grasses; and 4.2 Tg N/yr is used by industry for production of nylon, refrigerants, explosives and other commercial products.

The second largest source of Nr introduced into the U.S. is enhancement of biological nitrogen fixation (BNF) by cultivation of legumes like soybeans and alfalfa that have nitrogen-fixing symbionts, or by crops like rice that have nitrogen-fixing bacteria in their rhizosphere. These Nr fixing crops introduce about 7.7 Tg N/yr. A

[3] NOx (oxides of nitrogen) includes NO + NO_2
[4] NOy (total oxidized nitrogen) includes NO, NO_2, NO_3, N_2O_5, HONO, HNO_3, NO_3–, PAN and other organo-nitrates, $RONO_2$
[5] NHx (reduced nitrogen) includes NH_3 + NH_4

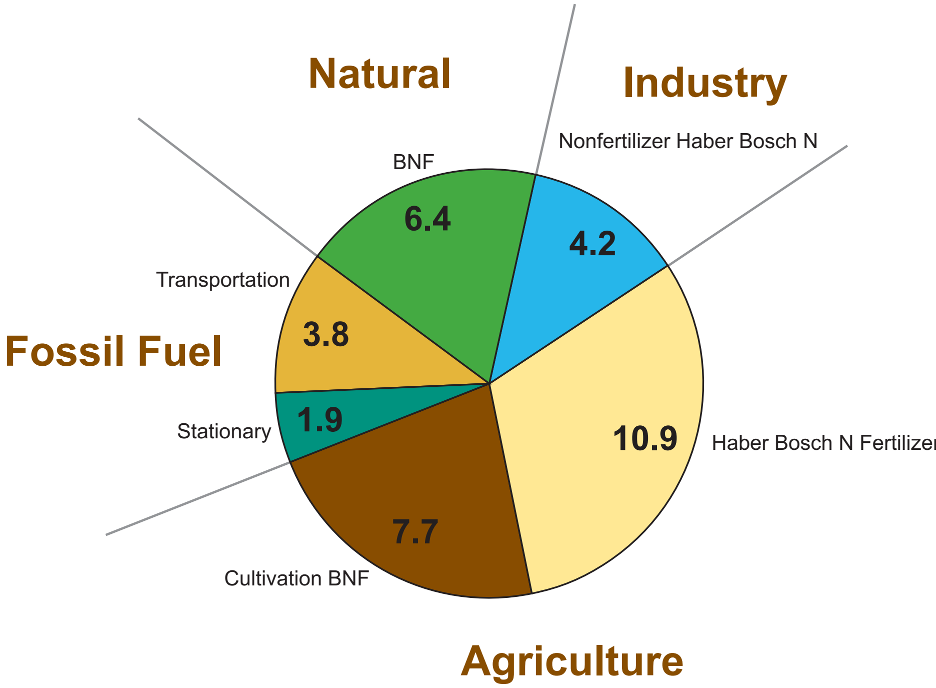

Figure ES-2: Sources of reactive nitrogen (Nr) introduced into the United States in 2002 (Tg N/yr).

Figure ES-2 explanatory notes:

Numerical units: teragram of reactive nitrogen (Nr) per year (Tg N/yr)

Natural BNF: biological nitrogen fixation in natural grasslands, rangelands, and forests,

Fossil Fuel-Transportation: combustion in vehicles, trains, airplanes, ships and off-road construction equipment.

Fossil Fuel-Stationary: combustion of fossil fuels in power plants and industrial boilers.

Agriculture-cultivation BNF: agricultural augmentation of biological nitrogen fixation – for example by planting of nitrogen fixing legumes.

Agriculture-Haber Bosch N fertilizer: agricultural (including turf production) use of synthetic nitrogen fertilizers produced by the Haber Bosch process for converting gaseous N_2 to Nr.

Industry-Haber Bosch N: Industrial sources of Nr produced by the Haber-Bosch process.

Figure ES-2 documents only the introduction of new Nr in the United States, and not the transfers of existing Nr among systems (e.g., Nr in manure).

small amount of additional Nr is also imported in grain and meat products; in 2002 this source of added Nr was approximately 0.2 Tg N/yr (not shown in Figure ES-2).

Fossil fuel combustion is the third largest source of new Nr. It introduces approximately 5.7 Tg N/yr into the environment (almost entirely as NO_x), that is, 3.8 Tg N/yr from transportation sources and 1.9 Tg N/yr from stationary sources such as electric utilities, industrial boilers and from certain industrial processes.

In summary, agriculture and domestic use of fertilizers to produce food, feed, and fiber (including bioenergy and BNF) and combustion of fossil fuels are the largest sources of new Nr released into the environment in the U.S. The percentage distribution of Nr released to the U.S. environment from human activities in 2002 was: about 65% from agricultural sources (including BNF and turf production), about 20% from fossil fuel sources, and about 15% from industrial sources (Figure ES-2).

Distribution of reactive nitrogen through the environment

Once introduced into the U.S., Nr compounds are distributed via the atmosphere, hydrosphere, geosphere, biosphere, and commerce. Distribution in the atmosphere begins with NO_x, NH_3, and N_2O. NO_x and NH_3 (and their reaction products) are distributed on a scale of hundreds to thousands of kilometers within the U.S. boundaries, and also distributed to downwind countries and oceans. Due to its long lifetime (approximately 100 years) in the atmosphere, N_2O accumulates in the U.S. atmosphere

and is also dispersed throughout the global atmosphere. All ecosystems in the conterminous U.S. receive anthropogenic Nr from the atmosphere and for many ecosystems it is their primary, albeit unintended, source of Nr. Once deposited, Nr can be stored in soils and biomass and widely distributed via the stream-river continuum to inland and coastal waters. Some of the Nr is converted to N_2O or denitrified to N_2, primarily in aquatic ecosystems, including wetlands. Commerce is a major mechanism that transfers Nr from one place to another in the U.S.; most of the Nr that is used to produce food (e.g., fertilizer) and in food products crosses state boundaries via roads, railroads and the air.

Putting values to this distribution, of the 6.3 Tg N/yr of U.S. NO_x emissions, 2.7 Tg N/yr are deposited back onto the land and surface waters of the U.S. Thus, by difference we estimate that as much as 3.6 Tg N/yr of the U.S. NO_x emissions are advected out of the U.S. via the atmosphere. Similarly, of the 3.1 Tg N/yr of NH_3 that are emitted into the U.S. atmosphere each year, about 2.1 Tg N/yr are deposited onto the land and surface waters of the U.S., and about 1 Tg N/yr is advected out of the U.S. via the atmosphere. Emissions of N_2O discharge about 0.8 Tg N/yr into the global atmosphere. In sum, 5.4 Tg N are advected out of the U.S. from all sources each year either to other nations or to the global atmospheric or ocean commons.

Riverine discharges of Nr to the U.S. coastal zone account for 4.8 Tg N/yr, while export of N-containing commodities (e.g., grain) removes another 4.3 Tg N/yr from the U.S.. Altogether, along with 5.4 Tg N/yr of atmospheric advection, these total Nr outputs out of the U.S. continental environment add up to about 14 Tg N/yr, leaving about 21 Tg N/yr unaccounted for. Of this amount, we estimate that 5 Tg N/yr are stored in soils, vegetation, and groundwater and, by difference, we estimate that about 16 Tg N/yr are denitrified to N_2. Denitrification, a process that microbially converts Nr to N_2 (as well as forming some N_2O) requires both a carbon source and anaerobic conditions, a situation that is found in wetlands, oxygen-depleted streams, rivers, and the hypolimnion of reservoirs (or their sediments), soils, and engineered denitrification systems. This process can be a major Nr sink in river basins. There are substantial uncertainties (+/- 50%) for estimated emission and deposition and terms that are arrived at by difference (e.g., atmospheric advection and denitrification) – especially those that involve NH_x. The Committee considered these uncertainties in developing the "Overarching Recommendations" of this report.

Current EPA Nr risk management and research programs

The parts of EPA most directly concerned with managing or conducting research on Nr are the Office of Air and Radiation, the Office of Water, and the Office of Research and Development (ORD). Over a dozen programs of EPA's Office of Air and Radiation reduce risks from Nr. These programs and related activities include: National Ambient Air Quality Standards standard setting and implementation; emission standards for industrial stationary sources and area sources; the Acid Rain Program; the Clean Air Interstate Rule; and programs that focus on mobile source emissions. Programs designed to save energy, such as Energy Star, tend to reduce emissions of Nr as well. EPA's Office of Water addresses Nr under both the Clean Water Act and the Safe Drinking Water Act through activities such as: criteria development and standard setting; total maximum daily load (TMDL) development; National Pollution Discharge Elimination System (NPDES) permits; infrastructure financing through the Drinking Water and Clean Water State Revolving Funds; watershed planning; wetlands preservation; and regulation of stormwater and runoff sources that include municipal separate storm sewer systems (MS4), and concentrated animal feeding operations (CAFOs). EPA's Office of Research and Development aims to conduct leading-edge research and foster the sound use of science and technology in support of the Agency's mission. The Office of Research and Development is well recognized for providing a scientific basis for the development of the National Ambient Air Quality Standards for NO_x and particulate matter (PM). The Office of Research and Development's Ecosystem Services Research Program has been developed to identify and quantify the positive and negative impacts on ecosystem services resulting from changes in nitrogen loadings from major source categories. This research will support policy and management decisions in EPA's Offices of Air and Radiation and Water.

EPA has brought a great variety of risk reduction tools to bear on Nr: conventional regulation and enforcement; cap and trade approaches; measurement, monitoring and place-based approaches; control technology development and verification; communication and education; intergovernmental and international cooperation; and voluntary approaches. The variety and breadth of EPA programs addressing Nr reflect the ubiquity of Nr in the environment, the historical single-medium regulatory approach, and the lack of a "silver bullet" for reducing risks from Nr.

Need for an integrated management strategy

The EPA programs discussed above (and the programs of EPA's predecessor organizations) have been active in the management of Nr through efforts to: decrease or transform Nr in sewage; control NO_x to decrease photochemical smog and acid rain; control Nr inputs to coastal systems; control fine particulates in the atmosphere; and decrease Nr leaching and runoff from crop and animal production systems and developed

lands. As beneficial as those efforts have been, they have focused on the specific problem without consideration of the interaction of a particular system with other systems downstream or downwind. Given the reality of the nitrogen cascade, this approach may result in short-term benefits for a particular system but may only temporarily delay larger-scale impacts on other systems. Thus there is a need to integrate N management programs, to ensure that efforts to lessen the problems caused by N in one area of the environment do not result in unintended problems in other areas.

Biofuels feedstock production provides a good example of the need for comprehensive and integrated assessment and management of Nr. Increasing corn production for ethanol has raised the prospect of increased Nr losses (i.e., transfer from fertilized land to water) and degraded water quality. The alternative of cellulosic based ethanol does not necessarily mitigate the potential for this negative externality. High yields of cellulosic materials also require N and the "marginal" land assumed for such production may be more susceptible to nutrient leakage. Another good example is provided in Chapter 4 of this report (Box 2). This example considers the water impacts of Nr in the Chesapeake Bay and shows that the total reduction of damage from excess Nr may rely nearly as much on stricter enforcement of the Clean Air Act as the Clean Water Act. This challenges the traditional approach to regulation, but it is a consequence of comprehensively examining Nr guided by the nitrogen cascade.

There can be many unintended consequences associated with a focus on managing one pollutant, even an integrated focus on various forms of N. For example, as further discussed in Chapter 4 and Appendix G of this report, numerous lakes, reservoirs, rivers, estuaries (e.g., the Gulf of Mexico), and fjords worldwide exhibit N and phosphorus (P) co-limitation, either simultaneously or in seasonally-shifting patterns. Therefore, strategies are needed to reduce both P and N inputs, and not all control practices will be effective for dual nutrient reduction. Synergistic effects on nutrient loss reductions can occur where combinations of control practices produce more or less than the sum of their individual reductions (U.S. EPA SAB, 2007). An integrated strategy should take this into consideration.

Objectives of the SAB Integrated Nitrogen Committee study

The EPA Science Advisory Board formed the Integrated Nitrogen Committee to assist EPA in its understanding and management of nitrogen-related air, land, and water pollution issues. In this report, the Committee has provided findings and recommendations addressing the following objectives. Assessment of the challenges and costs to EPA of implementing the recommendations is beyond the scope of the report.

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

To address this objective, the Committee used the nitrogen cascade framework to determine the major sources of newly created Nr in the U.S. (Figure ES-1). The flows of Nr within the food, fiber, feed and bioenergy production systems and developed lands in the U.S. were examined, paying special attention to the locations within each of these systems where Nr is lost to the environment. The same process was employed for fossil fuel energy production but, since all the Nr formed and released during energy production is lost to the environment, the Committee identified the important energy producing sectors that contribute to Nr emissions.

The Committee next examined the fate of the Nr lost to the environment, estimated the amount stored in different systems (e.g., forest soils) and tracked Nr as it is transferred from one environmental system (e.g., the atmosphere) to another (e.g., terrestrial and aquatic ecosystems).

Source and fate analyses set the stage for identifying the environmental and human health problems Nr presents, and the links among them. Using the nitrogen cascade, the Committee identified the impacts Nr has on people and ecosystem functions as it moves through each system. The Committee also addressed the alternative metrics that could be used, including the number of tons of specific forms of Nr, human health indicators and the economic damage cost, to assess incommensurable impacts due to environmental changes (e.g., acid deposition) vs. impacts due to losses of ecosystem services (e.g., loss of biodiversity), and trade-offs among Nr impacts.

2. Evaluate the contribution an integrated nitrogen management strategy[6] could make to environmental protection.

An integrated management strategy should take into account the contributions of all Nr sources, and all chemical species of Nr that adversely impact both human health and environmental systems. Further, an integrated strategy should ensure that solving one problem related to Nr does not exacerbate another problem or diminish ecosystem services that support societal demands. In short, the strategy should seek to achieve desirable benefits of Nr, while limiting adverse effects.

[6] An integrated nitrogen management strategy takes a holistic approach for managing Nr. In the context of the nitrogen cascade, all Nr anthropogenic creation and destruction mechanisms and all Nr uses are recognized. The strategy should take account of synergies and trade-offs, to ensure that decreasing one problem related to nitrogen does not result in other unintended adverse environmental, economic and societal consequences. By identifying relative priorities, assessing cost effectiveness and risks, the strategy should seek to maximize the benefits of Nr, while limiting overall adverse effects.

To address this challenge, the Committee identified several actions that could be taken to better manage Nr in one environmental system and avoid unintended consequences in another. Examples of "integrative" management actions that could be taken are highlighted in that discussion.

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

As further discussed below, the Committee has identified four major goals for management actions that collectively have the potential to decrease Nr losses to the environment by about 25 percent. Decreasing Nr emissions by these actions will result in further decreases in Nr-related impacts throughout the nitrogen cascade. The Committee has suggested several ways to attain these management goals including conservation measures, additional regulatory steps, voluntary actions, application of modern technologies, and end-of-pipe approaches. These are initial but significant actions; however, others should be taken once the recommended actions are completed and assessed, and further opportunities are explored in an adaptive management approach. Thus, the last sections of this report focus on a better understanding of Nr dynamics and impacts in the U.S. that could lead to more cost efficient management, balancing human and environmental needs.

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

In this report, the Committee has provided numerous recommendations for additional Nr research to support risk reduction activities. These research recommendations are discussed in various chapters of the report and are consolidated in the summary of findings and recommendations presented in Chapter 6.

Major Findings and Recommendations

Throughout the report there are boxes containing summary statements labeled "Findings." Attached to these findings are one or more specific "Recommendations" for actions that could be taken by EPA or other management authorities. In each case, the intent is to provide the scientific foundation regarding a specific Nr-relevant environmental issue and one or more recommendations by which EPA acting alone or in cooperation with other organizations could use currently available technology to decrease the amount of Nr lost to the U.S. environment. The findings and recommendations are consolidated in Chapter 6 of this report.

Overarching recommendations

Optimizing the benefits of Nr, and minimizing its impacts, will require an integrated nitrogen management strategy that involves action not only on the part of EPA, but also coordination with other federal agencies, the states, the private sector, universities, and the public, supported by a strong public outreach program. Therefore the Committee has also provided four overarching recommendations to assist EPA in its understanding and management of nitrogen-related air, land, and water pollution issues:

Overarching Recommendation 1: The Committee recommends an integrated approach to the management of Nr. This approach draws upon a combination of implementation mechanisms. Each mechanism must be appropriate to the nature of the problem at hand, be supported by critical research on decreasing the risks of excess Nr, and reflect an integrated policy that recognizes the complexities and tradeoffs associated with the nitrogen cascade. Management efforts at one point in the cascade may be more efficient and cost effective than control or intervention at another point. This is why understanding the nature and dynamics of the N cascade is critically important.

Overarching Recommendation 2: The framing of the reactive nitrogen cascade provides a means for tracking nitrogen as it changes form and passes through multiple ecosystems and media. This complexity requires the use of innovative management systems and regulatory structures to address the environmental and human health implications of the most damaging forms and quantities of Nr. It is difficult to create de novo fully effective regulations for such a complex system so we recommend utilizing adaptive management to continuously improve the effectiveness and lower the cost of implementation policies. This in turn will require a monitoring system that will provide feedback on the effectiveness of specific actions taken to lower fluxes and concentrations of Nr.

Overarching Recommendation 3: An intra-Agency Nr management task force within EPA is recommended to build on existing Nr research and management capabilities within the Agency. This task force should be aimed at increasing scientific understanding of: (1) Nr impacts on terrestrial and aquatic ecosystems, human health, and climate; (2) Nr-relevant monitoring requirements; and (3) the most efficient and cost-effective means by which to decrease various adverse impacts of Nr loads as they cascade through the environment.

Overarching Recommendation 4: Successful Nr management will require changes in the way EPA interacts with other agencies. Coordinated federal programs could better address Nr concerns and help ensure clear responsibilities for monitoring, modeling, researching and managing Nr in the environment. Thus, the Committee recommends that EPA convene an inter-agency Nr management task force. It is recommended that the members of this inter-agency task force include at least the following federal agencies: U.S. Department of Agriculture,

U.S. Department of Energy, U.S. Department of Housing and Urban Development, U.S. Department of Transportation, National Oceanic and Atmospheric Administration, U.S. Geological Survey, U.S. Forest Service, and Federal Emergency Management Agency. The EPA Office of International and Tribal Affairs should work closely with the Department of State to ensure that EPA is aware of international efforts to control Nr and is developing national strategies that are compatible with international initiatives. Similar recommendations for coordination and joint action among and between agencies at both state and federal levels have been made in the National Research Council's recent reports on the Mississippi Basin (NRC, 2008b, 2009). These intra- and inter-agency Nr management task forces should take a systems approach to research, monitoring, and evaluation to inform public policy related to Nr management, and implement a systems approach to Nr management, as recommended by the Committee.

Summary of specific recommendations by study objective

The Committee's findings and recommendations corresponding to each of the four study objectives are summarized briefly below.

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

The Committee finds that uncertainty associated with rapid expansion of biofuels, losses of Nr from grasslands, forests, and urban areas, and the rate and extent of denitrification have created the need to measure, model, and report all forms of Nr consistently and accurately. Addressing this need will decrease uncertainty in the understanding of the fate of Nr that is introduced into the environment and lead to a better understanding of the impacts of excess Nr on the health of people and ecosystems. This should be accomplished through a coordinated effort among cognizant federal and state agencies, and universities.

In addition, the Committee recommends that EPA routinely and consistently account for the presence of Nr in the environment in forms appropriate to the medium in which they occur (air, land, and water) and that accounting documents be produced and published periodically (for example, in a fashion similar to National Atmospheric Deposition Program summary reports). The Committee understands that such an undertaking will require substantial resources, and encourages the Agency to develop and strengthen partnerships with appropriate federal and state agencies, and private sector organizations, with parallel interests in advancing the necessary underlying science of Nr creation, transport and transformation, impacts, and management.

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

The Committee finds that effective management of Nr in the environment must recognize the existence of tradeoffs across a number of impact categories involving the cycling of nitrogen and other elements. In addition, an integrated multi-media approach to monitoring Nr is needed.

In that regard, the Committee recommends that:

1. EPA should develop a uniform assessment and management framework that considers the effects of Nr loading over a range of scales reflecting ecosystem, watershed, and regional levels. The framework should include all inputs related to atmospheric and riverine delivery of Nr to estuaries, their comprehensive effects on marine eutrophication dynamics, and their potential for management.
2. EPA should examine the full range of traditional and ecosystem response categories, including economic and ecosystem services, as a basis for expressing Nr impacts in the environment, and for building better understanding and support for integrated management efforts.

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

The Committee finds that a number of risk management actions should be considered to reduce Nr loading and transfer to the environment. These include farm-level improvements in manure management, actions to reduce atmospheric emissions of Nr, and interventions to control Nr in water management programs. As an example, the Committee recommends that EPA should reexamine the criteria pollutant "oxides of nitrogen" and the indicator species NO_2 and consider supplementing this with NH_x and NO_y as indicators of chemically reactive nitrogen (Nr without N_2O).

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

The Committee finds that research is needed in a number of areas to support Nr risk reduction activities. These areas include research to advance the understanding of: the quantity and fate of Nr applied to major crops; how to accelerate crop yields while increasing N fertilizer uptake efficiency; agricultural emissions of forms of Nr; atmospheric deposition of Nr; and the potential for amplification of Nr-related climate impacts.

Four recommended management actions

Consistent with the overarching and specific recommendations noted above, the Committee identified four management actions that could be undertaken in the near term by applying existing proven science and technology and determined how those actions could contribute to the reduction of excess Nr in the environment.

1. The Committee estimates that if EPA were to expand its NO_x control efforts for emissions of mobile sources and power plants, a **2.0 Tg N/yr** decrease in the generation of reactive nitrogen could be achieved. Such changes can be effected by applying existing, proven technology. Emissions from many point sources are controlled with low-NO_x burners or NO_x reduction. Such equipment should also be installed on industrial boilers and the remaining, uncontrolled power plants. NO_x controls for modern on-road vehicles are effective and these technologies should be applied to off-road vehicles, locomotives, ships and other devices with internal combustion engines.
2. The Committee estimates that excess flows of Nr into streams, rivers, and coastal systems can be decreased by approximately 20% (approximately **1 Tg N/yr**) through improved landscape management and without undue disruption to agricultural production. This would include activities such as using large-scale wetland creation and restoration to provide needed ecosystem services of Nr retention and conversion as well as matching cropping systems and intensity of Nr use to land characteristics. Improved tile-drainage systems and riparian buffers on cropland, and implementing stormwater and non-point source management practices (e.g., EPA permitting and funding programs) are important components. In addition, the Committee estimates that crop N-uptake efficiencies can be increased by up to 25% over current practices through a combination of knowledge-based practices and advances in fertilizer technology (such as controlled release and inhibition of nitrification). Crop output can be increased while decreasing total Nr by up to 20% of applied artificial Nr, amounting to ~**2.4 Tg N/yr** below current amounts of Nr additions to the environment. These are appropriate actions that could be taken with today's available technologies and further progress is possible.
3. The Committee estimates that livestock-derived NH_3 emissions can be decreased by 30% (a decrease of **0.5 Tg N/yr**) by a combination of BMPs and engineered solutions. This is expected to decrease $PM_{2.5}$ by approximately 0.3 micrograms per cubic meter (2.5%), and improve health of ecosystems by achieving progress towards critical load recommendations. Additionally we estimate that NH_3 emissions derived from fertilizer applications can be decreased by 20% (decrease by approximately **0.2 Tg N/yr**), through BMPs that focus on improvements related to application rate, timing, and placement.
4. The Committee recommends that a high priority be assigned to increasing funding for nutrient management. We estimate that adequate financial support for sewage treatment infrastructure upgrades to remove nutrients could decrease Nr emissions by between **0.5 and 0.8 Tg N/yr**. Additional Nr management from eligible stormwater and nonpoint sources could be accomplished through increased support.

Implementing these suggestions will decrease the amount of Nr introduced into the United States by about 25%, which will similarly decrease the amount of Nr lost to the atmosphere, soils and waters. The Committee believes that these represent realistic and attainable near-term outcomes, however further reductions are undoubtedly needed for many N-sensitive ecosystems and to ensure that health-related standards are maintained.

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Reactive Nitrogen in the United States

AN ANALYSIS OF INPUTS, FLOWS, CONSEQUENCES, AND MANAGEMENT OPTIONS