Selected Recommendations and Findings from the Integrated Nitrogen Committee

EPA Science Advisory Board

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Introduction

Reactive nitrogen (Nr) encompasses biologically active, chemically reactive, and radiatively active nitrogen compounds. At the global scale, human activities now create more Nr than natural terrestrial ecosystems produce or can assimilate. As a result, Nr is now accumulating in the environment.

Natural and human activities can release Nr to the environment in many different chemical forms. As it moves through the environment, Nr can cause both beneficial and adverse effects. The nitrogen cascade describes the movement of Nr through the environment and the resulting effects. Natural processes or control measures can change one form into another that may have different effects.

Some problems from excess Nr (associated with sewage, fossil fuel combustion, crop/animal production, etc.) are well recognized and addressed. EPA has taken an impact-by-impact approach to regulation Nr, which, with few exceptions, addresses specific forms of nitrogen in a single system (aquatic, atmospheric, or terrestrial). The principal regulatory authorities pertaining to nitrogen are the Clean Water Act (CWA) and the Clean Air Act (CAA). Because such approaches rarely consider more than a small part of the nitrogen system, they can merely delay larger scale and sometimes unanticipated impacts. They seldom prevent them. The deliberate integration of Nr research, management, and control strategies across media and issues can help maximize the beneficial uses of Nr, while minimizing adverse environmental impacts.

The Science Advisory Board (SAB) advises the Administrator of the Environmental Protection Agency (EPA) whose mission is to protect human health and the environment. The SAB's INC objectives 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.

Nr Inputs to US

It is critical to understand the relationship between inputs of newly created reactive nitrogen vs. how much of the Nr is transferred to other compartments, as well as the effects excess Nr has on humans and the ecosystem if effective control strategies are to be developed. The largest sources of Nr created by human action in the USA are fossil fuel combustion and food production. The Nr that comes from fossil fuel combustion is chiefly in the form of NOx emissions into the atmosphere; this introduces about 5.5 Tg N per year into the environment (combustion of wood and other forms of biomass generally occurs at temperatures too low to convert N_2 to Nr). Food and turf production add about 10.9 Tg N per year from fertilizer use and another 7.7 Tg N per year due to cultivation-induced biological fixation. Industrial activities introduce an additional 4.2 Tg N per year into the US. Imports of commodities contribute another 0.2 Tg N per year (a teragram (Tg) is one million metric tons). These fluxes of Nr, and the Nr sources, sinks and transfers within the air, land and water compartments are presented in Table 1.

In the United States, human activity results in about 29 Tg N per year being added to the environment from all sources. In comparison, natural ecosystems add about 6.4 Tg N per year. Human activities control the introduction of Nr into the US (Figure 1).

Consequences, Impacts and Metrics for Nr

The best and most important consequence of Nr is food production in the US and global food security. There are, however, numerous negative consequences from anthropogenic Nr, including photochemical smog, atmospheric particulate loading, ecosystem fertilization, acidification, and/or eutrophication, greenhouse effect and stratospheric ozone depletion. But mitigating risk from these factors is difficult because one reactive N-containing molecule can contribute to all of these effects as a consequence of the nitrogen cascade (Figure 2). Nitrogen is a dynamic element easily transformed from one species to another and is transported rapidly through and between ecosystem reservoirs. These characteristics make it an especially challenging element to control.

Because nitrogen is both a critical resource and also a contributor to a number of environmental problems, it is imperative to understand how to reduce the risks to society while also providing the materials, food and energy required by society.

Various approaches can be used to prevent, eliminate, reduce, or otherwise manage risk. Understanding the environmental impacts of Nr can inform decisions on how best to manage nitrogen risks. There are two main approaches to this problem – traditional impacts and ecosystem services.

Traditional impacts include global warming, eutrophication, ecotoxicity, human health (cancer and non-cancer), acidification, smog formation, and ozone depletion, among others. Sometimes these impacts can be expressed in collective metrics. Collective metrics have 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. Such metrics also encourage 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 there defined 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.

The ecosystem services approach complements traditional impact characterizations by assessing causative contaminant emissions. It considers how a specific service provided by one or more ecosystems or the corresponding causative functions (e.g. categories such as climate change, nutrient cycling, and food production) is impaired. The attractiveness of this approach lies in its recognition that the health of humans and the environment are inextricably linked. Less clear, in some cases, are ways in which to measure and monitor these impacts.

Both ways of expressing nitrogen impacts have value. Traditional categories (i.e., effects based) provide a readily adaptable framework for regulation. Function-based categories (i.e., services based) provide a richer context for the complex connections among Nr inputs and transformations. Further, their impacts on human well-being and dollar-based impacts can identify those effects that have the greatest damage costs to society. Using multiple metrics may provide a clearer picture of priorities for action, identify effective control points for reducing Nr impacts, and provide insights into more effective regulatory strategy.

Tradeoffs Among Nr Risk Reduction Options are Complex

Once the foreseeable impacts are understood and the suite of benefits associated with various risk reduction options described, then managers can consider trade-offs. Risk reduction integration provides an intellectual framework that allows managers to make informed decisions about which benefits may need to be relinquished for other benefits when not all the desired benefits can be achieved. For example, limiting nitrogen fertilizer application to reduce risks from Nr applied to agro-ecosystems risks reduced yields and higher commodity prices, which in turn may result in expansion of crop production area at the expense of natural wetlands, grasslands, and forests.

Measurement of Nitrogen in the Environment

What you measure determines both what you do and how you gauge success or failure. Most regulations set limits or specify control technologies for specific forms of nitrogen without regard to the ways in which nitrogen is transformed once introduced into the environment. Normally regulations also require some form of monitoring to document compliance. Monitoring of these specific forms of nitrogen is not enough. There is a need to measure, compute, and report the total amount of Nr, in appropriate units, present in impacted systems in appropriate units because one form of Nr can be quickly converted to other forms.

The impacts of reactive nitrogen often can be expressed as the dollar costs of damages, the cost of remediation or substitution, or 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. Similarly if human mortality and morbidity are the metrics used, priorities for Nr releases could be very different.

Integrated Risk Reduction Strategies for Nr

Typically, quantitative risk assessment; technical feasibility; economic, social and legal factors; and additional benefits of the various control strategies contribute to the development of a suite of risk reduction strategies from which managers select an approach.

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, 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. lower fertilizer application rates, controls on NO_x 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 reduced 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, control of urban runoff, 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.

Management of Nr in the Environment

Generally speaking, US environmental policy employs four mechanisms for the management of contaminants in the environment:

- Command-and-Control—in which permitted limitations on emissions, as promulgated under various statutes, are issued. Violations may result in the assessment of penalties.
- 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.
- Voluntary programs in which desired ends are achieved using private or government-initiated agreements or through outreach and education.

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. Control 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 so critically important.

Major Findings and Recommendations

The following are some of the Committee's major draft recommendations.

1. There is a pressing need to encourage an adaptive, precision-conservation approach to terrestrial nutrient management, crop production, animal management, and agricultural and urban runoff. It is possible to reduce excess flows of Nr into streams, rivers, and coastal systems by approximately 20% **(~1** Tg N per year.**)** through improved landscape management without undue disruption to agricultural production and human lifestyles and economies. This would include activities such as using wetland management (e.g., USDA Wetlands Protection Program), improved tile-drainage systems and riparian buffers on crop land, and implementing storm water and non-point source management practices (e.g., EPA permitting and funding programs).

   It is also possible to increase crop N-uptake efficiencies by up to 25% over current levels through a combination of knowledge-based practices and advances in fertilizer technology (such as controlled release). The net reduction would be somewhat less as some duplication of efforts is represented in reducing excess Nr flows and increasing N-uptake efficiencies. However, the critical conclusion is that crop output can be increased while reducing total Nr by up to 20% of applied artificial Nr, amounting to ~**2.4** Tg N per year below current levels of Nr additions to the environment. These are appropriate targets with today's available technologies; further progress is possible.

2. The Clean Air Act (1970) and its Amendment (1990), have resulted in NOx emissions that are <50% of what they would have been without the controls. While this is an admirable accomplishment, there is still a way to go, as NOx emissions are still an order of magnitude greater than at the beginning of the 20th century and, as a consequence, there are still negative impacts on both people and ecosystems.

   We recommend that the EPA expand its NOx control efforts from the current reductions of emissions of passenger cars and power plants to include other important unregulated mobile and stationary sources. Notable NOx emitters include heavy-duty on-road and all off-road mobile sources (including rail and marine), as well as currently uncontrolled electricity generation and industrial processes. Well-regulated electricity generating units and light duty vehicles currently eliminate ~90% of the NOx they would otherwise emit. Instituting 90% reductions for the major, currently uncontrolled sources would reduce annual emissions by about **2** Tg N per year. This may be sufficient to bring most of the US into compliance with the current O_3 NAAQS, but may still leave several ecosystems with more Nr than the critical load.

It is vitally important that the implementation of these controls not result in additional emissions of N_2O and NH_3 to the atmosphere, which would just change one N-related problem to another.

3. In spite of gains made over the last several decades in lowering the amount of NOx emitted from stationary and mobile combustion sources, the total amount of Nr released into the atmosphere has remained relatively constant. This is related largely to the essentially unregulated release of ammonia from livestock operations (mostly due to increasing poultry and swine production), which have expanded significantly. Ammonia emissions from livestock production have increased ~30% since 1970. We suggest a goal of decreasing livestock-derived ammonia emissions to approximately 80% of 1990 emissions, a decrease of **0.5** Tg N per year (by a combination of Best Management Practices and engineered solutions). This will reduce PM2.5 by ~0.3 $\mu g/m^3$ (2.5%) and improve health of ecosystems by achieving progress towards critical load recommendations. Additionally we recommend decreasing ammonia emissions derived from fertilizer applications by 20% (decrease by ~**0.2** Tg N per year.).

4. National loadings of Nr to the environment from public and private wastewater point sources are relatively modest in comparison with other releases to the environment, but can be important local sources with associated impacts. In most cases Nr ultimately finds its way into municipal and private sewers and treatment systems where, irrespective of its initial chemical form, it is partially or completely nitrified. Subsequent engineered complete denitrification processes (including tertiary wastewater treatment, engineered or restored wetlands, and algae production for biofuels) can convert the nitrate to only N_2. Federal and State assistance programs directed at construction of treatment plants are an important Nr control policy in the US. The committee recommends that a high priority be assigned to nutrient management through a targeted construction grants program under the CWA. The committee believes that **0.5 to 0.8** Tg N per year can be saved from Nr inputs to the environment.

5. Acreage devoted to corn production has increased about 10% for corn based ethanol production, with nearly one-third of the crop being devoted to bioethanol production. Current policy calls for bioethanol to expand to 15 billion gallons for corn-based ethanol and 36 billion gallons of bioethanol from all sources by 2022. We expect fertilizer nitrogen to increase by at least 10% **(0.5** Tg N per year**),** initially to meet biofuel feedstock crop demand. Strategies to increase N-uptake efficiencies and strategies to reduce N losses must be implemented across corn and other N intensive biofuel crops.

   N_2O in the atmosphere is also increasing. For additional production of liquid biofuels beyond the grandfathered amount in the 2007 Energy Independence and Security Act (EISA), EPA has the power to exercise some controls on N_2O emissions through the life cycle greenhouse gas accounting requirements.

   In the absence of Nr controls and a failure to implement best practices, current biofuels policies will make it extremely difficult to reduce Nr releases to soils, water and air. Integrated management strategies will be required. In this regard, we endorse Section 204 of EISA which requires that after 3 years and then every 3 years thereafter, the EPA

Administrator, the Secretary of Agriculture, and the Secretary of Energy shall report to Congress on the impact of the Clean Air Act requirements related to environmental issues, resource conservation issues, and the growth and use of cultivated invasive and noxious plants. (http://www.ethanol.org/pdf/contentmgmt/Full_Text_of_HR6.pdf)

6. The current air pollution indicator for oxides of nitrogen, NOx, is an inadequate measure of reactive nitrogen in the atmospheric environment. We recommend that the inorganic reduced nitrogen (ammonia plus ammonium) and total oxidized nitrogen (NOy) be monitored as indicators of total chemically reactive nitrogen. The basis for the recommendation is that inorganic reduced nitrogen has environmental impacts equivalent to the current criteria air pollutants.

7. There is an urgent need to improve and maintain foundational data required to track sources of Nr and Nr loads in the environment. Specific data needs include: the rationalized and geospatially defined fertilizer use data; improved estimates of nitrogen fertilizer efficiency and its variation based on estimates from production-scale fields for the major crops and cropping systems; and improved monitoring and estimates of wet/dry Nr deposition and its transformation and transport on land and in water.

8. What is managed depends on what is measured, and because Nr undergoes multiple chemical transformations as it cascades through multiple media and ecosystems, impacts and intervention points are difficult to determine. There are many metrics for evaluating and prioritizing Nr impacts. The most widely used traditionally measure has been mass of nitrogen by chemical species, but one can also measure damage costs of impacts, or replacement and mitigation costs or human health measures. The use of multiple metrics may provide a fuller picture of the impacts of reactive nitrogen and improve the setting of priorities.

The actions recommended above would decrease the amount of Nr entering the environment by ~7 Tg N/yr, or about 25% of the anthropogenic Nr created each year in the US. Other actions could be taken, and all actions need to take into consideration an over-arching finding of the committee—as the amount of reactive nitrogen released to the environment grows, more effective integration of strategies that work across media, address multiple problems and avoids unintended adverse consequences is necessary to reduce costs and create more enduring solutions.

The Committee's recommended actions have real economic costs. Trade-offs will be made both within and between recommendations. For example, treating nitrate with engineered wetlands, that provide additional benefits, such as the production of algae for biofuels, may prove to be more cost effective than traditional tertiary treatment. Similarly, where reducing ammonia emissions from animal feeding operations can be paired with the recovery of methane for fuel then overall costs should be lower and greenhouse gas emissions will also be reduced.

The Committee's recommendations represent realistic intermediate targets based on current demands and technologies. There are and will be opportunities to go beyond these recommendations. Developing these opportunities will be critical given the growing demand from population and economic growth for food- and fiber-production and energy use.

Concluding Statement

Fossil fuel combustion and food production have significantly increased the introduction of Nr into the US environment and, while there are tremendous benefits, there are also tremendous damages to the health of both ecosystems and people. Optimizing the benefits of Nr while minimizing its problems will require an integrated nitrogen management strategy that not only involves EPA, but also other federal agencies (e.g., USDA, DOE, NOAA), state agency managers, the private sector and a strong public outreach program.

Table 1. Reactive nitrogen fluxes for the USA, Tg N in 2002*		
Nr inputs to Atmospheric compartment		
N_2O-N emissions		0.8
agriculture - Soil management	0.5	
*fossil fuel combustion - transportation N_2O	0.1	
Miscellaneous	0.1	
NHx-N emissions		3.1
agriculture: livestock NH_3-N	1.6	
agriculture: fertilizer NH_3-N	0.9	
miscellaneous	0.6	
NOx-N emissions		6.2
*fossil fuel combustion - transportation NOx	3.5	
*fossil fuel combustion - utility & industry NOx	1.9	
miscellaneous	0.9	
Nr inputs to Terrestrial compartment		
atmospheric N deposition	6.9	
*N fixation in cultivated croplands	7.7	
*N fixation in non-cultivated vegetation	6.4	
*N import in commodities	0.2	
*N fertilizer use on farms & non-farms	10.9	
*non-fertilizer uses	4.2	
manure N production	6.0	
human waste N	1.3	
Nr inputs to Aquatic compartment		
surface water N flux		4.8

*these fluxes represent injection of new Nr into the USA

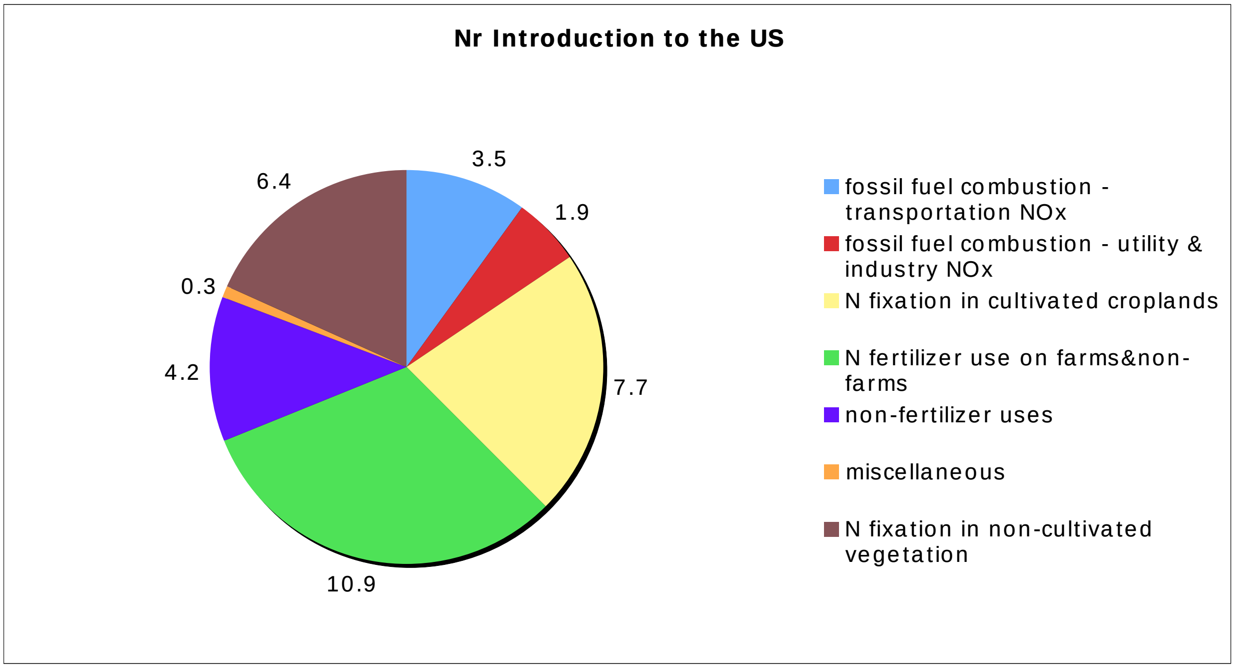

Figure 1: New Nr introduced into the US, 2002, Tg N.

Note that the numbers from the table do not all match up with the figure because some recycled Nr is included in the table (livestock, manure, and human sewage).

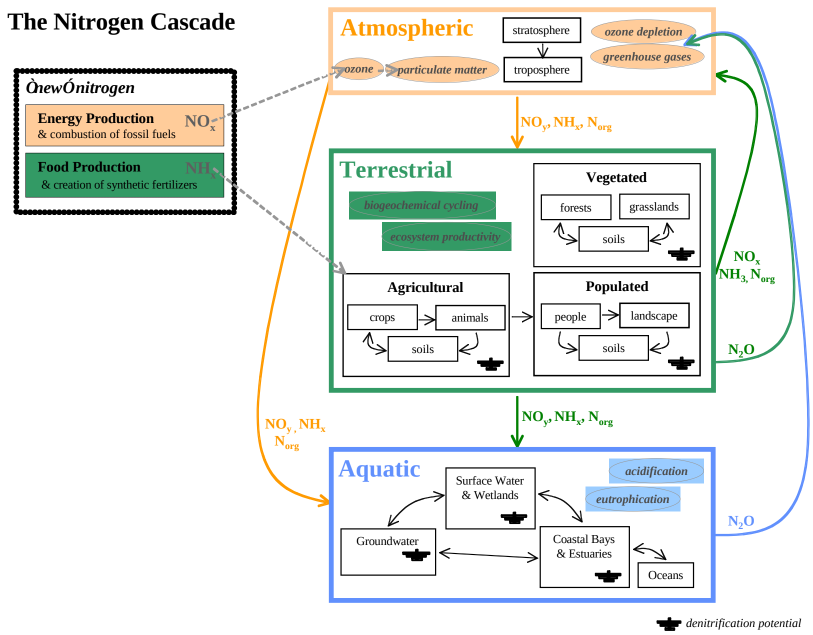

Figure 2: The Nitrogen Cascade: The popular concept of the nitrogen cascade highlights that once a new Nr molecule is created, it can, in sequence, travel throughout the environment contributing to major environmental problems (Galloway et al., 2003). This adaptation of the cascade was developed by the 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, urban runoff). 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.