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Reactive Nitrogen in the Environment

Too Much or Too Little of a Good Thing

United Nations Environment Programme

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Table of Contents

Executive summary

Nitrogen is an essential, fundamental building block for life. It is the most plentiful element in the earth's atmosphere, yet in its molecular form (N_2), it is unusable by the vast majority of living organisms. It must be transformed, or fixed, into other forms, collectively known as reactive nitrogen (See Glossary), before it can be used by most plants and animals. Without an adequate supply of nitrogen, crops do not thrive and fail to reach their maximum production potential. In many ecosystems, nitrogen is the limiting element for growth. However, when present in excess, reactive nitrogen causes a range of negative environmental effects, poses risks to human health and consequently can have negative economic and social consequences. This non-technical review seeks to convey an understanding of the effects of reactive nitrogen in the environment, focusing mainly on those caused by excesses of reactive nitrogen. It also examines experience with some policies developed to address those effects, and offers recommendations to advance understanding and policy responses to them.

Natural production of reactive nitrogen includes nitrogen fixation by legumes, blue-green algae and a few other organisms and by lightning. Although substantial amounts of nitrogen are fixed through these naturally occurring processes, those rates are not sufficient to meet the food demands of an increasing world population. Because of this, scientists and technologists have found ways to increase its availability by artificially fixing nitrogen and producing synthetic fertilizers. Application of reactive nitrogen, in the form of synthetic fertilizers, plays a central role in modern crop production. These applications have a two-fold consequence: (1) the fertilizers enable increased crop production, supporting a larger human population; (2) at the same time this increases unintended releases of reactive nitrogen to the broader environment through agricultural runoff and additional sewage. These are important factors in the redistribution of reactive nitrogen, especially as it is introduced into groundwater, rivers and estuaries, causing overgrowth of algae in coastal zones, a process known as eutrophication.

Another major source of reactive nitrogen is associated with the growing use of fossil fuels for energy. Combustion of fossil fuels leads to the creation of nitrogen oxides (NO_X) in the atmosphere, and these emissions have increased dramatically since the beginning of the industrial revolution. In the last 150 years, the annual inputs of reactive nitrogen primarily from these agricultural, industrial and transportation sources to the earth's atmosphere, soils, and water bodies have increased by more than a factor of ten and now exceed the annual rate of production of reactive nitrogen from natural sources.

While the overall amount of reactive nitrogen production has increased, it is not evenly distributed around the world. In some areas, primarily industrialized nations, there is an excess of reactive nitrogen. It is accumulating in the air, the soil and the water, moving between each and causing subsequent environmental, human health and related economic problems. In areas where there is too little nitrogen, primarily in the developing world, agriculture cannot meet the basic challenge of producing enough food to sustain the population, nor fulfill its potential contribution to economic development. Insufficient nitrogen and other agricultural nutrient inputs can also lead to land degradation, soil erosion, desertification and their attendant long-term environmental and economic consequences.

A single nitrogen-containing molecule can have a series of impacts on the environment because reactive nitrogen can so easily move among the different media of air, soil and water. In the air, it can contribute to higher levels of ozone in the lower atmosphere, causing respiratory ailments and damaging vegetation. From the atmosphere, it generally falls to the surface in atmospheric deposition, generating a series of effects — corrosion of buildings, bridges and other human-made structures, acidification of soils and water bodies, and inadvertent fertilization of trees and grasslands, creating unnatural growth rates, nutrient imbalances, and decreasing or altering biodiversity. Leaching out of the soils, reactive nitrogen can make groundwater and surface water unfit for human consumption. Reactive nitrogen also promotes eutrophication in coastal ecosystems, which can negatively impact fish stocks and biodiversity. Eventually, most reactive nitrogen is denitrified back to molecular nitrogen, but a portion is converted to nitrous oxide which contributes to both the greenhouse effect and to stratospheric ozone depletion.

The complex environmental, human health and economic issues surrounding reactive nitrogen (whether in excess or in deficiency) require monitoring, research and assessment of their effects, as well as broader information sharing to inform the design of specific policy responses at local, national and regional levels. Experience shows that well designed policy instruments can play a major role in rectifying reactive nitrogen imbalances and their resulting effects. However, developing effective policies is not a simple matter because the effects of reactive nitrogen are not limited to a single medium — air or soil or water — and a policy to remedy one issue may inadvertently aggravate another. Thus, a comprehensive and coherent understanding of the issue, and of the status of related policy initiatives, is an initial requirement for any action, regardless of scale. It is incumbent upon all the stakeholders — including scientists, policymakers and private sector leaders — both to broadly understand and to specifically address this range of concerns to work towards solutions.

The most successful policy initiatives that have been implemented reflect the integrated nature of the actions needed to address air, water and soil pollution resulting from the excessive release of reactive nitrogen.

- In Europe, progressive action has been taken regarding reactive nitrogen and its role in air and water pollution. The Convention on Long-Range Transboundary Air Pollution and its Protocols provide a strong example of a policy that has evolved over time, strengthening environmental protection in light of increased information. Guidelines implemented under the auspices of the Helsinki Commission in 1974 encompass a range of pollutants and have been strengthened as more is known about the causes and impacts of eutrophication in the Baltic Sea.

- In North America, the ongoing restoration of the Chesapeake Bay through an intragovernmental, interagency approach highlights how a regional governance framework for managing reactive nitrogen can achieve coordination and the necessary joint actions among governmental agencies at different levels with overlapping jurisdictions.

In both these examples progress has been made, but in neither example have the objectives of reducing levels of reactive nitrogen to acceptable levels been achieved. Continued diligence and perhaps novel modifications of these efforts will be required to fully achieve these goals over the long term. Additional examples of evolving policy initiatives further illustrate the challenges of implementing regulatory measures.

- In Latin America and the Caribbean, the Cartagena Convention and its Land-Based Sources Protocol, which has not yet entered into force, illustrates what happens when there is a conflict between stated policy goals to reduce pollution and perceived economic or other development objectives. A clearer appreciation of the costs (environmental, economic and health) of excess reactive nitrogen releases, and capacity building to support analysis and implementation of the agreed policy measures are required.

- In Asia, specifically China, heightened levels of water pollution due to rapid industrialization, a fast-growing population, and increased agriculture are resulting in compromised drinking water quality, with resulting increases in waterborne illnesses and other diseases. Recent governmental actions have included some higher standards for sewage treatment, coupled with the construction of some additional treatment plants. However, much remains to be done to address the various sources of reactive nitrogen, including sewage, energy production and agricultural runoff, that are contributing to the recent deterioration of drinking water quality and to the increase in eutrophication of estuarine and coastal zones.

Efforts in regions characterized by a deficiency of reactive nitrogen are also crucial, both because policies must assist in alleviating the gap between the supplies available and those needed to improve crop production and because those policies must avoid creating the environmental and human health problems inherent in situations where excess exists.

- In Africa, where more reactive nitrogen is being removed through harvest or lost through ineffective management than is replaced, efforts are underway to address the various factors contributing to deficiency, namely through improved infrastructure, increased availability of fertilizers, incentives for their use and smallholder microfinancing.

The effective management of reactive nitrogen in the environment is progressing, though still hampered by a lack of awareness regarding the full extent of its economic, environmental, human health and social implications and by insufficient coordination among involved parties, be they political entities, industries or other stakeholders. More broadly, a lack of technical capacity and economic or informational resources hampers effective policy making and action on this issue. Well developed and meaningful assessment tools are important for beginning a discussion about the challenges presented by reactive nitrogen.

Successfully resolving the challenges created by the excesses of reactive nitrogen requires an integrated approach across policy sectors. This integration must be guided by further assessment, monitoring and analysis of the behaviour and impacts of reactive nitrogen in the environment through soil, air and water, and by experience already gained in developing and implementing policies to reduce the impacts of reactive nitrogen.

Global-scale cooperation in communication regarding problems and solutions, regional cooperation in developing and implementing policy or other legislative instruments, cooperation between the public and the private sector and with the scientific community, and a willingness to explore tools and strategies at all levels are required. The transboundary movement of gases and particles that contain nitrogen as well as materials including fertilizer, animal feed concentrates, and grains that contain nitrogen may warrant international and, in some cases, global approaches. Commonly experienced national or regional issues, including marine hypoxic zones, also warrant information sharing and some coordination of responses at the international level. UNEP's Global Programme of Action (GPA) for the Protection of the Marine Environment from land-based Activities Coordination Office could provide a platform for such exchange of information and experiences, as recommended at the 2nd Intergovernmental Review of the GPA, held in Beijing in October 2006. UNEP-DTIE could continue to work with the scientific and policy-making communities on this issue, as well as key private sector and civil society stakeholders, to support the development of appropriate responses to excess reactive nitrogen in the environment.

Introduction

This non-technical report summarizes the present scientific understanding of the major issues surrounding reactive nitrogen, and discusses the overarching environmental, human health and economic issues created by both excesses and deficiencies. The report provides case studies of effective policy implementation and reviews emerging policies to show how negative impacts associated with reactive nitrogen may be successfully addressed locally, nationally and regionally, given similar challenges, shared experiences and effective solutions.

THE INTERNATIONAL NITROGEN INITIATIVE (INI)

The INI has established five regional centers — in Africa, Asia, Europe, Latin America and North America — to further emphasize the global nature of the challenges of nitrogen and to enable regionally appropriate and flexible responses through cooperation and collaboration. The objective of the INI is to minimize the adverse environmental and human health impacts of nitrogen while continuing to optimize its role in sustaining food production (see www.initrogen.org).

A specific outcome of the 2004 INI conference was the signing of the Nanjing Declaration. This document, signed by conference participants and presented to UNEP, formally cited the commonalities that exist between the goals of successful reactive nitrogen management and other global initiatives including the Millennium Development Goals and the World Summit on Sustainable Development. It further issued a call to action to governments and to UNEP regarding the urgency with which these concerns should be addressed, with an emphasis on nitrogen management. A fourth INI conference will take place in Brazil in October 2007, and will include not only scientists with expertise in nitrogen and its challenges, but also participants from the policy, development and engineering communities. The meeting will build an agenda for how to better manage reactive nitrogen in the environment, and will develop specific goals to reach by 2025, set in the context of the United Nations Millennium Development Goals.

This report has been prepared jointly by the United Nations Environment Programme (UNEP) Division on Technology, Industry and Economics (DTIE) and the Woods Hole Research Center (WHRC), with significant contributions from the International Nitrogen Initiative (INI). The report also follows up on a feature article in the GEO2003 Yearbook which appeared in response to UNEP's mandate to bring emerging environmental threats to the attention of decision-makers. The current report also responds to UNEP's mission to provide leadership and encourage partnership in caring for the environment by inspiring, informing and enabling nations and peoples to improve their quality of life without compromising that of future generations. It also fulfils WHRC's mission to conduct research, identify policies and support educational activities that advance the well-being of humans and of the environment.

The report also follows on a series of international interdisciplinary conferences on nitrogen: these have been held in the Netherlands in 1998; in the United States in 2001; and in China in 2004. A specific recommendation made at the 2001 conference led, in 2003, to the establishment of a programme jointly sponsored by the Scientific Committee on Problems of the Environment (SCOPE) and the International Geosphere-Biosphere Programme (IGBP) to specifically address reactive nitrogen. This programme, the International Nitrogen Initiative (INI), has established regional centres and defined three activities to address reactive nitrogen in the environment: (1) assessment; (2) development and identification of effective policy measures; and (3) implementation of solutions.

In March 2006, UNEP-DTIE and the WHRC co-sponsored a workshop, with financial support from the government of the Netherlands, which gathered representatives of the scientific and policy communities to more fully explore the distribution and effects of reactive nitrogen. The main objectives of the meeting were to identify gaps in understanding the effects of reactive nitrogen in the environment, strategize on how to fill those gaps and contribute to effective and coordinated responses to impacts of reactive nitrogen. This non-technical review builds upon those discussions to raise awareness of policy-makers of the environmental, human health and economic effects of excess reactive nitrogen in the environment, as well as the problems associated with deficiencies of reactive nitrogen in the agricultural production of many developing countries. The primary aim is to foster more collaboration between the scientific and policy-making communities, as well as private sector and civil society stakeholders, in developing effective responses to reactive nitrogen excesses and deficiencies.

The main body of the review is supplemented by two annexes to further readers' understanding of the issues and potential responses. Annex A provides a roster of policies, both currently being implemented and pending, as well as international bodies that address issues of reactive nitrogen. Annex B provides references and information sources for further reading on the topic.

Understanding the role of reactive nitrogen in the environment

An introduction to nitrogen in the environment begins with a paradox: nitrogen — existing in its inert state as N_2 — is the most abundant element in the earth's atmosphere but, in this form, is almost wholly unusable by the vast majority of living organisms. Thus, this element, essential for life, must be transformed into a variety of other forms, together called "reactive nitrogen", in order to be biologically functional. Human intervention has dramatically altered the nitrogen cycle by increasing the rate of transformation of N_2 into reactive nitrogen. Where too much has been introduced by humans, its positive outcomes can be outweighed by negative ones, ultimately threatening the very ecosystems it initially supports. Where there is not enough reactive nitrogen, soil fertility declines, serious land degradation may occur, and agricultural productivity is reduced. As a consequence, populations that rely directly on these agricultural systems cannot produce enough food to survive.

The creation of reactive nitrogen occurs both through natural processes and through human interventions. Under natural conditions, breaking the triple bond that binds two nitrogen atoms together as N_2 requires either lightning or the activity of microbes able to carry out the process known as biological nitrogen fixation (BNF). These microbes are generally bacteria often residing in a symbiotic relationship with certain legumes, including soybeans, and many native plants in the legume family. In the oceans, BNF is carried out primarily by cyanobacteria, commonly known as blue-green algae.

Prior to the mid-19th century, the supply of reactive nitrogen to agricultural soils, either through BNF, animal manure, or rotation of crops and fallow, supported human populations. However, by the end of the 1800s, with a growing human population, it became apparent that these sources of reactive nitrogen could not adequately support the needed expansion of agriculture. In the early 1900s, as the pressure for increased food production combined with the rising demand for nitrate to manufacture munitions due to the outbreak of World War I, a method was created in Germany by Fritz Haber and later improved and adapted to an industrial scale by Carl Bosch. Now known as the Haber-Bosch process, this method was the first to use high pressure to generate a chemical reaction that produced reactive forms of nitrogen, thus allowing for the mass production of fertilizer by synthesizing ammonia from nitrogen and hydrogen gases. Nearly 100 years after its invention, the Haber-Bosch process remains the most economical anthropogenic means of fixing nitrogen and is responsible for sustaining nearly 40 percent of the current world population due to its ability to increase agricultural yields.

As the 20th century progressed, the annual rate of reactive nitrogen being produced continued to grow. Although most human-created reactive nitrogen is associated with the use of nitrogen fertilizers in the production of food, energy production through fossil fuel combustion also contributes significantly to the release of reactive nitrogen

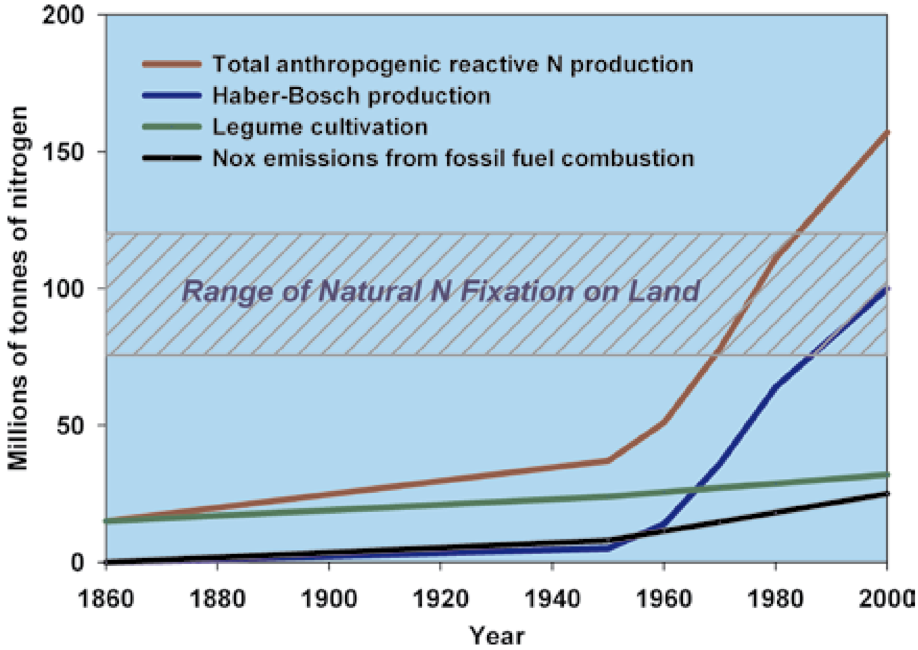


FIGURE 1 *Historical trends of reactive nitrogen formed annually by human activity, including cultivation of N-fixing legume crops, the Haber-Bosch process of synthetic production (primarily to manufacture N fertilizers), and emissions of nitrogen oxides from combustion of fossil fuels. A million metric tonnes is 10^{12} grams. For comparison, also shown is the "natural range" of N fixation (about 100 million tonnes of N per year) that occurs in native terrestrial ecosystems, primarily by bacteria in symbiotic associations with plants. Based on data in Galloway et al., 2004 and Smil, 2001.*

(See Figure 1). Nitrogen oxides, collectively abbreviated as NO_X, are a by-product of fossil fuel combustion. NO_X is one of the reactants that forms ozone in the troposphere (the lower atmosphere). Ozone is a major pollutant in urban and rural areas and affects human health and terrestrial ecosystems. Furthermore, NO_X can contribute to acidification and eutrophication when it and other forms of reactive nitrogen fall onto land and water bodies in rain- and snow-fall and as deposition of nitrogen-containing gases and aerosols. (See Figure 2). This deposition of atmospheric nitrogen can affect the biodiversity and health of the aquatic and terrestrial ecosystems. The nitrogen-containing gases and aerosols can also affect human respiratory health.

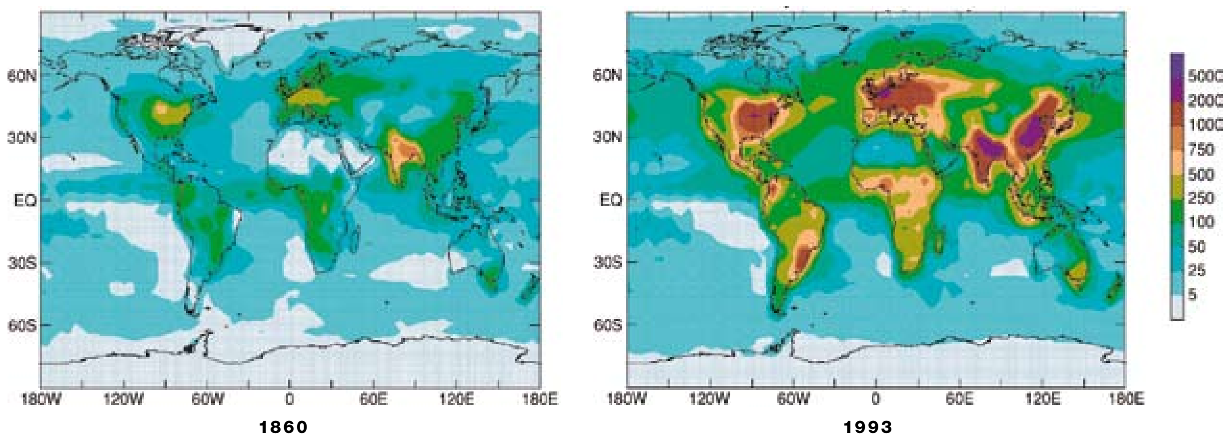


FIGURE 2 *Comparison of atmospheric deposition of total inorganic nitrogen across the globe estimated for 1860 and 1993. Units for the values shown in the colour legend are milligrams nitrogen per metre squared per year. Adapted from Galloway et al., 2004.*

Although carbon dioxide is the most prominent of the greenhouse gases, and the one most widely publicized as a contributor to climate change, nitrous oxide (N_2O), which is a particular form of nitrogen oxide produced primarily by bacteria in nitrogen-rich soils and water bodies, also plays a part in this growing global concern. The average lifetime of nitrous oxide in the atmosphere is over 100 years, making its long-term climatic effects among the most persistent of the greenhouse gases. It is also among the most potent greenhouse gases, so that, when integrated over a century, the global warming potential of nitrous oxide is nearly 300 times that of an equal mass of carbon dioxide. The global atmospheric N_2O concentration is now 18 percent higher than in pre-industrial times, and it has continued to increase at a rate of about 0.3% per year since 1980. More than a third of all N_2O emissions are anthropogenic and are primarily due to agriculture.

The ever-growing human population and its increased generation of sewage and industrial wastes have also increased reactive nitrogen inputs to the environment. In developing countries, the majority of wastewater is released untreated directly into waterways. Fewer than 35 percent of cities in developing countries have any form of sewage treatment. Where sewage treatment facilities do exist, they often provide only primary treatment, which does little to remove nitrogen. Even in the developed world, most sewage treatment facilities do not include the tertiary treatment step that removes most of the reactive nitrogen. Because populations are often expanding rapidly, many communities are ill-equipped to implement effective sewage treatment processes. In some localities, wastewater is the largest source of release of reactive nitrogen into the environment.

While human sewage is a major source of reactive nitrogen in the environment, many times more reactive nitrogen is introduced to the environment through the multiple steps of food production prior to human consumption. Currently, the annual rate of introduction of reactive nitrogen into the environment due to agricultural production is more than ten times the rate of what existed at the close of the 1800s. In the last 50 years, the total annual production of anthropogenic reactive nitrogen has surpassed the total fixed annually through natural processes. In fact, more than half of the synthetic nitrogen fertilizer ever produced has been made since 1985. Furthermore, the expansion of area devoted to legume crops, such as soybeans, has markedly increased the rate of BNF, which has further augmented the amount of reactive nitrogen in the environment. In addition to growth of agricultural productivity during the 20th century, international trade in agricultural commodities, including the nitrogen that they contain, has increased steadily. Thus, beyond the international transport of nitrogen through the atmosphere and rivers, its presence in internationally traded fertilizer, feedstock grains and food meant for human consumption also increases the global flux of nitrogen. (See Figure 3.)

The amount of nitrogen used in food production can be upwards of ten times the amount of nitrogen actually consumed by humans, leaving the unused portions to be taken up by soils, waterways and the atmosphere (See Figure 4). Some of these inefficiencies of nitrogen use in agriculture may be unavoidable, but advances in agricultural technologies have significantly improved fertilizer use efficiency in the past and can improve it further in the future. Economic incentives and other factors affecting agricultural practices are also important. For example, calculations of optimal fertilization rates are seldom perfect, and farmers often prefer to err on the side of over-application of nitrogen, especially where fertilizer costs are less than the potential revenue losses due to lower crop yields if crop demands for nitrogen are not fully met. While this may make good economic sense for the farmer, any overestimation of the crop need for nitrogen is likely to result in significant losses of that nitrogen to the surrounding environment, with the attendant environmental, economic and human health consequences for society.

To illustrate the many pathways of nitrogen losses in agriculture, we use the example of pork production in the USA, following nitrogen from its application to a field, its uptake by a feed crop, its harvest, its uptake by the animal, and then the conversion of the animal to a carcass, a product, and ultimately a consumed pork product (Figure 4). Less than 20 percent of the fertilizer nitrogen applied to the farmer's field is actually consumed by humans as meat, whereas over 80 percent is lost to the environment, much of it into the air as ammonia and nitrogen oxides and into rivers, groundwater and estuaries as nitrate. The flows of nitrogen for industrial swine

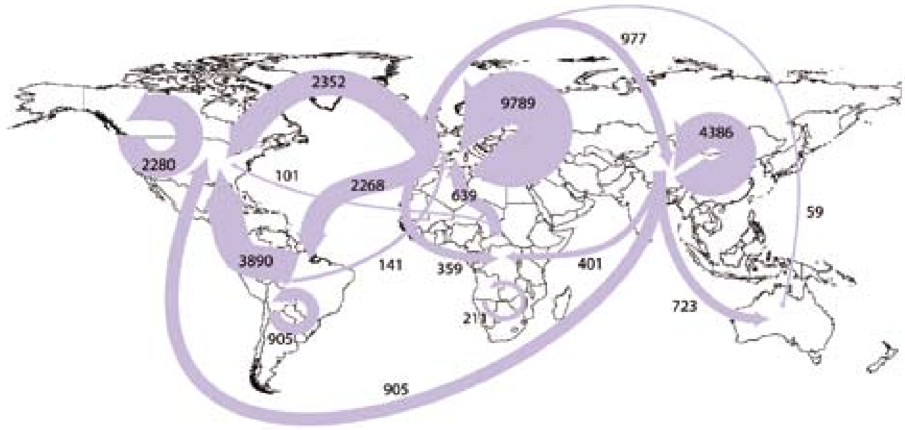


FIG 3A *Nitrogen contained in internationally traded fertilizer, by continent.*

2004 data in thousands of tons of N; minimum requirement for drawing a line is 50,000 tons N.
Total international N trade in fertilizer, 2004 = 30.7 million tons N.

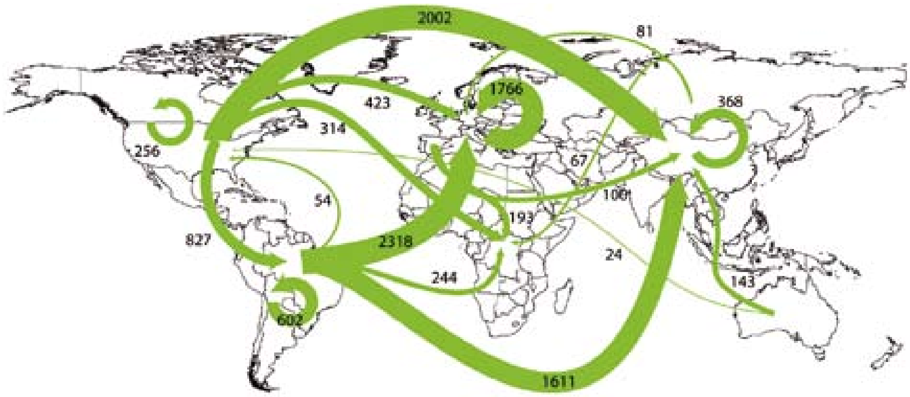


FIG 3B *Nitrogen contained in internationally traded crops, by continent.*

2004 data in thousands of tons of N; minimum requirement for drawing a line is 20,000 tons N.
Total international N trade in crops, 2004 = 11.5 million tons N.

FIG 3C *Nitrogen contained in internationally traded meat, by continent.*

2004 data in thousands of tons of N; minimum requirement for drawing a line is 10,000 tons N.
Total international N trade in meat, 2004 = 780 thousand tons.

FIGURE 3 *Diagrams of flow of nitrogen through international trade of (a) fertilizer, (b) grain for food and feed and (c) meat. Commerce is now a major vector of transboundary transport of nitrogen across the globe. From Burke, M. (Stanford University, personal communication).*

production are similar to what would be expected for poultry meat production. Dairy and beef cattle production systems can benefit from some nitrogen use efficiencies when they consume by-products of cropping systems and whole-plant material (forages) that cannot be consumed directly by humans, although the conversion of the nitrogen in feed to beef and to dairy products is relatively inefficient. In the case of corn ethanol production for energy, which is increasing rapidly in the USA and elsewhere, a large fraction of the corn crop nitrogen ends up in the by-product of fermentation, called distiller's grain. Some of this by-product is used as feed for cattle, provided that the transport of the distiller's grain to the feedlots is economically viable. Plant-derived foods consumed directly by humans vary greatly in the amount

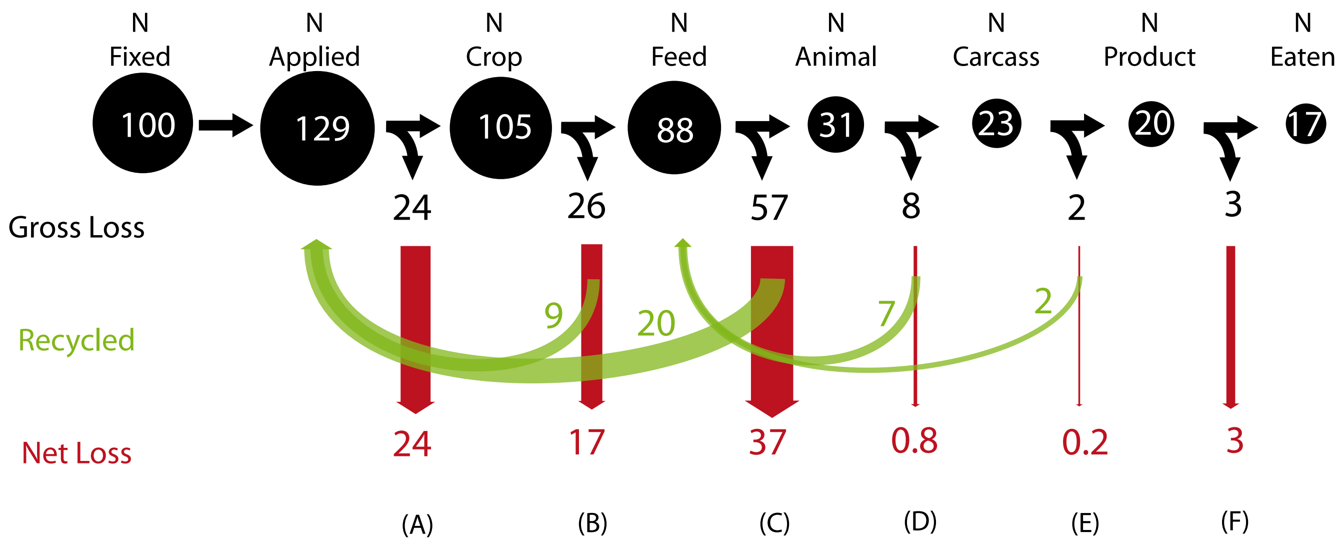


FIGURE 4 *Diagram of nitrogen losses that occur between the application of N fertilizer on a farmer's field until the food is consumed by a person for a typical industrial swine production system. Nitrogen for swine production derives from application of fertilizer for cereal grain (e.g. corn) or nitrogen fixation for soybeans. These crops take up N already in the soil as well as using N from fertilizer or fixation. When crops are harvested, the roots remain to decompose and supply N for subsequent crops, and often crop stover (vegetative mass) is returned to the field. In a given year, a typical crop may acquire less than half its N from fertilizer or fixation, with the remainder coming from the soil and biological processes from years before. At each step in the process of using grain to feed swine, some of the product, including its nitrogen content, is lost (red arrows). Only 35% of the N fed to hogs is captured in animal growth, with the remaining 65% excreted to manure. Manure is generally applied to crops but used at reduced efficiency compared with chemical fertilizer. Organic N in manure is mobilized for crop growth over time, but the timing is difficult to predict, adding to uncertainty that is met with additional N application. Harvested animals provide meat for human consumption and byproducts that are used for pet foods or other animal feeds. For purposes of these calculations, these were assumed to be recycled for swine production. Recycled crop residues, manure, and meat byproducts are represented by green arrows. Despite some recycling, over 80% of the fertilizer N applied to a farmer's field devoted to animal feed production is eventually lost to the environment (red arrows), partly to the air as ammonia and nitrogen oxides and partly to rivers, groundwater and estuaries as nitrate. Less than 20% is consumed by humans as meat. From Galloway et al., in press.*

of nitrogen lost to the environment in their production. Humans consume cereal and legume grains that can be produced with little nitrogen loss to the environment, but some industrial vegetable and fruit production systems use high levels of fertilizer application relative to the nitrogen in harvested and consumed food.

Changes in nitrogen loading are not limited to land. Globally, many coastal wetlands have been diminished or have even disappeared. This has reduced the capacity for denitrification, which is a bacterial process commonly occurring in wetlands, that converts reactive nitrogen back to unreactive molecular N_2 gas. The reduced capacity for denitrification in wetlands has resulted in higher loads of reactive nitrogen making it to the estuaries. Additionally, the enormous increase of aquaculture for food production, especially in Asia, results in an increased release of nitrogen directly into coastal waters. Water quality issues also often are related to the availability of water. Competing demands for water by communities, industry and agriculture can lead to shortfalls in viable water supplies. When water is in short supply it is often easily polluted, which includes the accumulation of high concentrations of reactive nitrogen.

This review focuses mostly on the effects of excessive reactive nitrogen in the environment. However, it is critical to emphasize that some regions in the world are grappling with an entirely different set of challenges resulting from a deficiency of reactive nitrogen. Parts of Africa, Latin America and Asia, for example, lack local sources of crop nutrients (BNF, manures, etc.) and lack the resources to either produce or import enough fertilizer to promote agriculture that can sustain their populations. This shortage is due to the costs associated with either producing or transporting fertilizer to that region of the world as well as the lack of infrastructure within the countries to distribute the resources to those areas most in need. The socioeconomic challenges this creates and some of the responses required are set out in a case study of the situation in sub-Saharan Africa in a later section of this report.

Impacts of excess reactive nitrogen in the environment

Impacts of excess reactive nitrogen on environmental quality and ecosystem services

Once in a reactive form, nitrogen is transported easily between air, water and soils in what is known as the nitrogen cascade (See Figure 5). Because it can move so easily from the atmosphere, into soils and onto other surfaces, into waterways, and back again, a single nitrogen-containing molecule can have a series of impacts on the environment. In the air, it can contribute to higher levels of ozone in the lower atmosphere, causing respiratory ailments and damaging vegetation. From the atmosphere, it generally falls to the surface in acid deposition, generating a series of effects — corrosion of buildings, bridges and other human-made structures, acidification of soils, and inadvertent fertilization of trees and grasslands, creating unnatural growth rates, nutrient imbalances, and ultimately decreasing ecosystem health and biodiversity. Leaching out of the soil, reactive nitrogen can pollute groundwater and surface water, rendering it unfit for human consumption. Reactive nitrogen also promotes eutrophication in coastal ecosystems, ultimately reducing biodiversity due to a lack of oxygen needed for the survival of many species of aquatic plants and animals. The cascade is interrupted only when reactive nitrogen is stored in inaccessible places or converted back to N_2 gas through denitrification. Even where

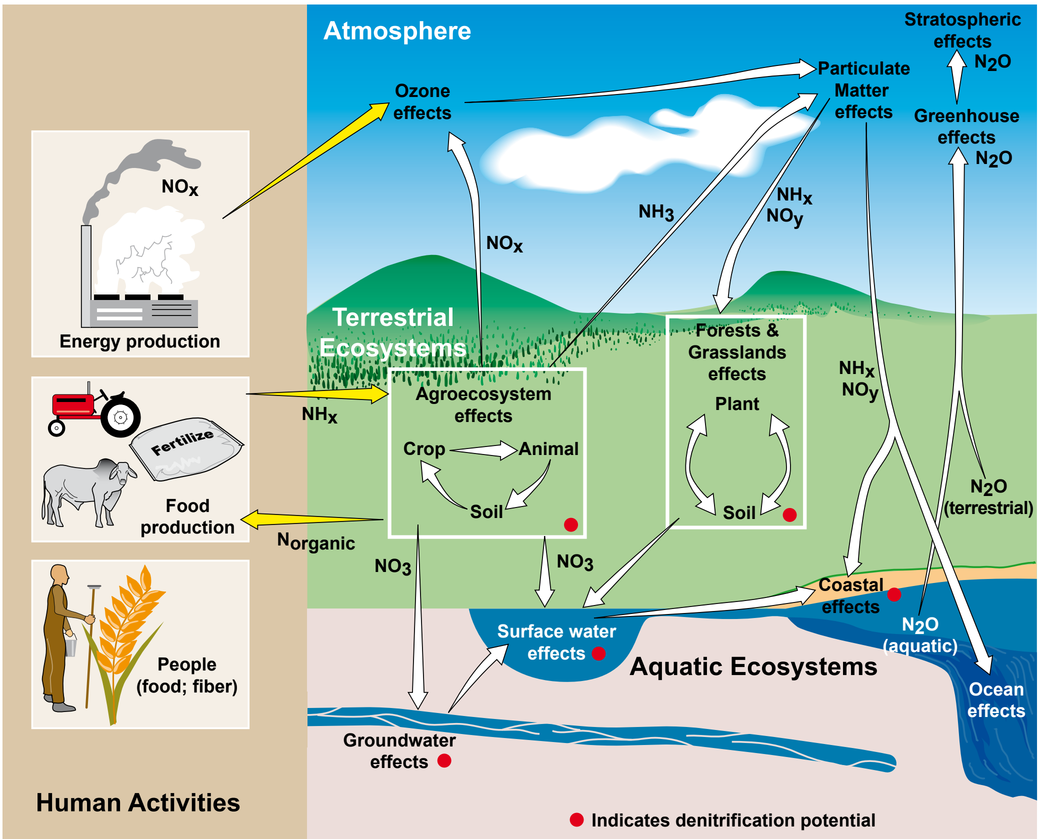


FIGURE 5 *Cartoon illustration of how reactive nitrogen (Nr) emanating from energy and food production cycles among atmospheric, terrestrial and aquatic components of the biosphere affects environmental quality in each location. Red dots indicate locations where denitrifying bacteria may convert nitrogen back to un-reactive dinitrogen gas. Adapted from Galloway et al. 2003.*

denitrification occurs, not all the reactive nitrogen is always converted to unreactive N_2. Instead a portion is often converted by denitrifying bacteria to the intermediate product, nitrous oxide, which contributes to both the greenhouse effect and to stratospheric ozone depletion.

Impacts of excess reactive nitrogen on human health

In excess, reactive nitrogen can become problematic for human health. One of the first links between reactive nitrogen and human health was found with high levels of nitrate in drinking water in the 1940s. Infants whose formula was mixed with water containing high concentrations of nitrate had a high risk of developing methemoglobinemia, commonly referred to as "blue-baby syndrome." In this condition, the nitrate in the drinking water is converted to nitrite in the digestive system, depriving the body of oxygen, which causes blue discoloration and, if unchecked, leads to digestive and respiratory failures. Concerns over this condition led many countries and the World Health Organization (WHO) to adopt standards for acceptable levels of nitrate in drinking water. The standard of 10 mg nitrate-N per litre (which is equivalent to about 45 mg nitrate per litre) was based on observations of nitrate levels in drinking water below which no cases of methemoglobinemia had been found. While this standard is met in most public water supplies in industrialized countries, it is often exceeded in developing counties and in many private wells throughout the world.

Some researchers have argued that this standard may be overly restrictive, because recent research on the links between nitrate in drinking water and methemoglobinemia has yielded equivocal results. Some studies show positive relationships, some negative, and some no effect of nitrate concentration in the incidence of methemoglobinemia.

On the other hand, recent research has shown that nitrate ingested with drinking water can be converted within the body to N-nitroso-compounds (NOC), which are potent animal carcinogens. Elevated risks for colon cancer and neural tube defects have been associated with drinking water nitrate concentrations below the current regulatory limit.

However, the dose-response relationship between nitrate in drinking water and either methemoglobinemia or NOC-induced cancer is complicated by several factors. First, nitrate is also ingested with some types of food and medicines. Second, vitamin C and other natural nitrosation inhibitors present in some fruits and vegetables appear to provide some protection against the harmful effects of nitrate ingested with food and water. On the other hand, a third factor is that some types of diets, such as those with high intake of red meat, seem to increase further the risk of some forms of cancer associated with nitrate intake. Fourth, other cofactors, such as diarrhea and respiratory diseases may interact with nitrate concentrations as risk factors. Therefore, it has become clear that studies on the effects of nitrate on human health must control for a number of factors, including diet and other disease co-factors in order to gain a better understanding of these phenomena.

EUTROPHICATION

Other nutrients, such as phosphorus (mostly from fertilizers, sewage and detergents), also contribute to eutrophication, and often need to be addressed in concert with concerns over nitrogen. A good rule of thumb is that phosphorus pollution often leads to eutrophication of fresh water, whereas nitrogen pollution often leads to eutrophication of estuaries and other marine environments. In many cases, however, nitrogen and phosphorus pollution can interact, so that integrated nutrient management regimes are needed for addressing the environmental consequences of either pollutant and for optimal use of each in agricultural systems.

Indeed a 2004 symposium sponsored by the International Society for Environmental Epidemiology concluded that "the role of drinking-water nitrate exposure as a risk factor for specific cancers, reproductive outcomes, and other chronic health effects must be studied more thoroughly before changes to the regulatory level for nitrate in drinking water can be considered." The report noted that the current drinking water standard, established several decades ago, was based on an apparent threshold concentration below which no methemoglobinemia had been observed, and therefore does not include the more contemporary approach of applying a safety factor, which is now employed for establishing most regulations. Consistent with the precautionary approach, this group of experts recommends more study before nitrate drinking level regulations are either relaxed or strengthened.

Beyond the health concerns related to excessive reactive nitrogen in water, those linked to excessive reactive nitrogen in the air are best known in regards to ozone in the lowest level of the atmosphere, the troposphere. Here, reactive nitrogen, in the form of NO_X, is an air pollutant that promotes the creation of ozone and smog, which, interacting with the lining of the lungs, can trigger respiratory conditions ranging from asthma to even death after chronic exposure. Additionally, airborne reactive nitrogen and its reaction products can aggravate a number of cardiopulmonary diseases. As with the effects of reactive nitrogen in water pollution, there is also growing evidence of a connection between reactive nitrogen in air and several types of cancer.

Economic considerations of excess reactive nitrogen in the environment

Stakeholders often confront the challenge of including cost-benefit analysis in making policy recommendations, as competing interests can and do necessitate trade-offs between environmental sustainability and development pressures, private sector aspirations and other public policy objectives. The benefits of creating and using reactive nitrogen for food production and the benefits of using fossil fuel in industry and transportation are usually easier to quantify in economic terms than are the costs and benefits of reducing the associated environmental pollution, including releases of reactive nitrogen. Many of these costs and benefits related to the environment are external to the mainstream market economy. The attention of economists has recently been turning increasingly towards evaluating the costs of reducing these nitrogen releases into the environment and monetizing the benefits of doing so. To help evaluate the economic costs and benefits of limiting nitrogen emissions where there are excesses, an economic framework called the economic nitrogen cascade has been developed to parallel the chemical nitrogen cascade. This provides a tool for evaluating and comparing the costs of damages associated with each impact, the costs of implementing strategies to avoid those impacts, the projected monetary benefits when those impacts are mitigated, and the opportunity costs (lost benefits) resulting from any curtailed economic activity. The economic nitrogen cascade will be illustrated in the case study below on the Chesapeake Bay.

When assigning a monetary value to the impacts on humans and ecosystems, the two most useful measurements are damage costs and mitigation costs. Within these assignments, varying amounts of data and types of valuations are available. For example, much more is known about the costs associated with NO_X reductions from fossil fuel combustion than with ammonia reductions from agricultural systems. Consideration should be given to costs that are borne privately and to those that are borne publicly. Mitigation costs are relative to the baseline established, and can only be calculated if the difference between levels of reactive nitrogen in the environment following implementation of a policy and levels projected in the absence of such a policy can be determined. For example, the United States Environment Protection Agency estimated the net benefits of the Clean Air Act Amendments of 1990 at $690 billion for the period 1990-2010. Of this, $610 billion came from reduced mortality risks, $49 billion from reduced morbidity, and the rest from ecological and welfare effects. Specific costs related to health impacts, through factors like hospital admissions, lost workdays and lower productivity, are more directly evident than costs associated with damage resulting in loss of ecosystem services. For example, a study conducted by the Ontario Medical Association (Canada) found that air pollution, due to excess reactive nitrogen and other pollutants, costs Ontario citizens more than $1 billion per year in hospital admissions, emergency room visits and lost work days. Less tangibly, the breadth of ecosystem services encompasses both recreational uses and commercial uses, and within that spectrum there are some losses that are more quantifiable than others. Establishing a common vocabulary for discussions and methodology for cost assignments is crucial to successfully incorporating this approach into an understanding of the effects of any pollutant, including excessive reactive nitrogen.

To evaluate the economic costs of nitrogen pollution or the gains by its mitigation requires a thorough assessment and the establishment of a monitoring programme to assign and quantify emissions. Any resulting guidelines must recognize the varying sources and amounts of pollution. For example, though the majority of nitrogen excess results from the inefficient use of synthetic fertilizer in agriculture, it is difficult to monitor emissions from these outlets (known as non-point sources) because they are dispersed in numerous locations. It is usually more feasible to account for the nitrogen released from more concentrated localized sources, such as power plant facilities, known as point sources. Non-point sources of nitrogen present a special challenge for monitoring and control efforts. It may be more feasible to monitor adherence to best management practices that are designed to reduce nitrogen releases rather than measure the nitrogen itself.

The economic implications of adopting best practices in development and management scenarios are made clear when approached by means of the economic nitrogen cascade. Because reactive nitrogen in the atmosphere has multiple effects as it cascades from air to soil to water, it is likely that the most cost-effective corrections often lie in addressing air emissions that have multiple downwind and downstream impacts. The economic nitrogen cascade is useful in understanding potential cost-effective options and offers a construct for making the sometimes economically intangible results of excessive nitrogen in the environment more tangible.

The following section gives specific examples to further the discussion surrounding these key issues and provides a context for a fuller understanding of how reactive nitrogen in the environment may be successfully addressed locally, nationally, regionally, and where appropriate, at a global level.

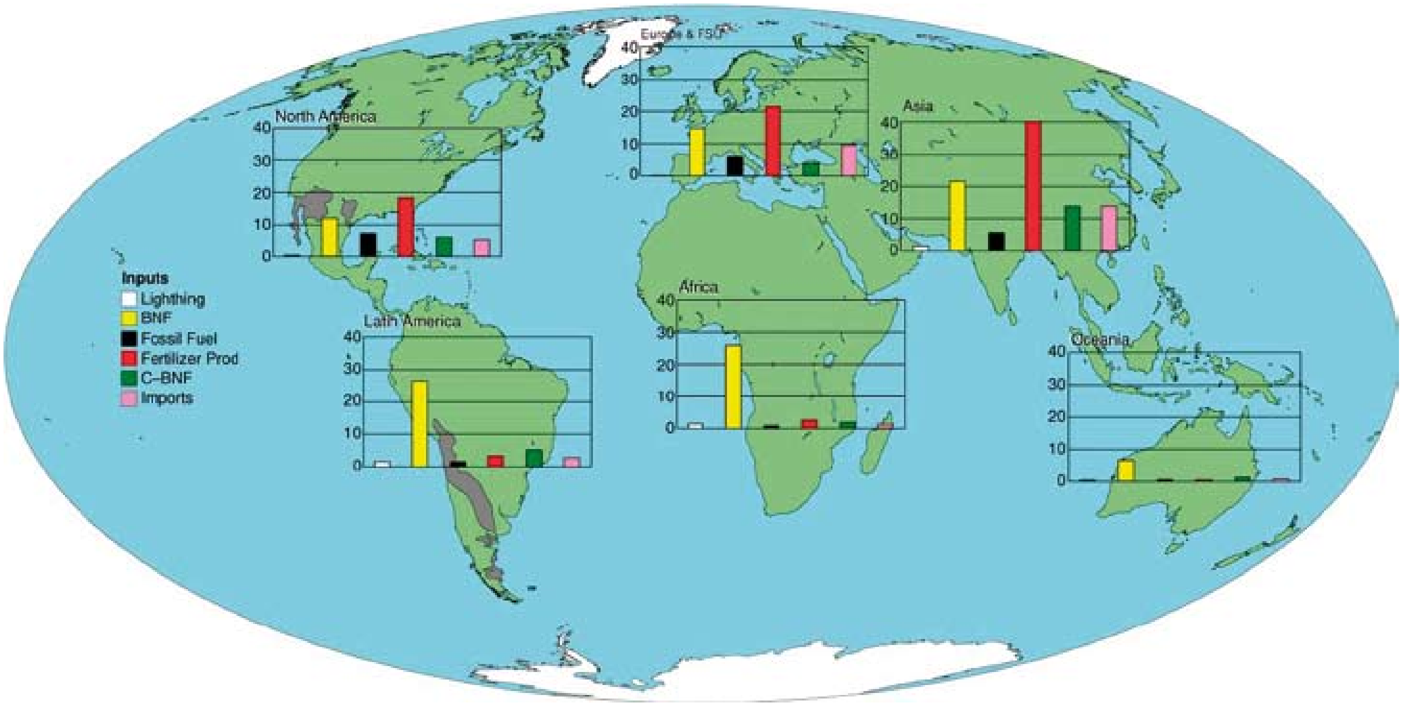
Addressing effects of reactive nitrogen in the environment

Addressing the problems that reactive nitrogen creates, whether present in excess or in deficiency, requires integrated action at local, national and regional levels. But because the effects of reactive nitrogen are not limited to simply air or soil or water, a policy to remedy one issue may inadvertently aggravate another. Thus, a comprehensive and coherent understanding of the issue, and of the status of related policy initiatives, is a pre-requisite for any effective action, regardless of scale.

Nitrous oxide is the only form of reactive nitrogen that has unambiguously global implications through its effects on climate change. It is one of the gases that is included in national inventories of greenhouse gases under the Kyoto Protocol of the United Nations Framework Convention on Climate Change. The Kyoto Protocol aims to achieve a stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Emissions of nitrous oxide along with carbon dioxide, hydrofluorocarbons, methane, perfluorocarbons, and sulphur hexafluoride, are expected to be limited or reduced in six key sectors (energy, industrial processes, solvents and other products, agriculture, land-use change and forestry and waste) during a relatively narrow time horizon (2008 to 2012) by the Parties included in Annex I to the United Nations Framework Convention on Climate Change (UNFCCC). However a global, long-term goal for stabilizing greenhouse gas concentrations in the atmosphere, along with the reductions in emissions necessary to achieve this stabilization, has yet to be agreed upon.

Other forms of transboundary air pollution, such as ammonia and NO_X emissions and resulting deposition, are also of major concern, as are water pollution issues in both waterways and the regional seas. The inefficient and sometimes excessive use of nitrogen fertilizers creates large-scale pollution of water, soil and air. These problems of excess reactive nitrogen are commonly encountered in industrialized regions (See Figure 6.). Developing regions often face a combination of both excess and deficiency challenges. In Asia, the growing use of coal and other fossil fuels results in continuing inputs of NO_X to the atmosphere. In Latin America, urban areas struggle with high levels of water pollution due to sewage release, while more rural areas grapple with agricultural runoff and the impacts that follow. Africa, however, contends almost exclusively with the crises resulting from nitrogen deficiencies, as population growth and agricultural demands exceed the land's ability to provide. But even here there are highly localized areas that have sewage disposal problems in urban areas or that have experienced high use of synthetic fertilizer, causing in turn many of the problems experienced elsewhere.

Impacts of excessive nitrogen inputs to coastal areas are being addressed, among others, under the GPA and through various regional seas conventions and related protocols. A large number of local and national Global Environment Facility (GEF), World Bank, International Financing Institutions and donor-supported projects have initiated concerted action among stakeholders to mitigate these unwanted negative impacts.



The following five case studies explore specific instances of the challenges resulting from excessive and deficient amounts of reactive nitrogen. While unique in terms of location and, to some extent, circumstance, each provides a starting point for understanding the broad and diverse nature of the problem and the requirements for both accurately assessing the problem and developing locally, nationally, and regionally appropriate policy responses where necessary. Furthermore, while the examples single out the role of nitrogen, it is important to note that other components and issues, including phosphorus, water availability, and economic considerations affect the nature and scale of problems associated with reactive nitrogen in the environment.

FIGURE 6 *Regional estimates for creation of reactive nitrogen by lightning, biological nitrogen fixation (BNF) in native ecosystems, fossil fuel combustion, fertilizer production, biological nitrogen fixation by crops (C-BNF) and imports of fertilizer, animal feed and human food from other regions. Adapted from Galloway et al. 2004.*

CASE STUDY

Nitrogen excesses in Latin America and the Caribbean

The challenges of reactive nitrogen in Latin America and the Caribbean are caused by two primary activities. The pressures of development and expanding agriculture have increased inputs of reactive nitrogen and much of this is released to the atmosphere through the practice of biomass burning. Further, excessive reactive nitrogen figures prominently in the problem of water pollution associated with large and growing urban areas. For example, in the megalopolis of 18 million people living in and around São Paulo, Brazil, less than 10 percent of the human sewage is treated. While these problems associated with reactive nitrogen in wastewater will generally require solutions at the local level, the case studies set out below examine reactive nitrogen emissions that have wider regional effects. The second case also shows how policy coordination between countries within one region has begun in response to these wider pollution effects.

Biomass burning in Brazil

Between 1990 and 2000, deforestation in Latin America and Central America averaged approximately 47,000 km^2 per year. Most of the deforestation is taking place in the Amazon region, especially the Brazilian Amazon, where forest is converted into cattle pastures, large soybean fields, and small family farms, often requiring that forest biomass is burned during the dry season. Some pastures are also burned every four to five years as a management method to 'clean the pasture' and eliminate the growth of shrubs and small trees. In southeastern Brazil, fire is also used during the dry season to facilitate the manual harvesting of sugar cane. In Central America and in the Andean countries, fuel wood is the major type of biomass burning.

During burning of tropical rainforests as they are cleared, burning of cattle pastures and agricultural fields to clear weeds, and the burning phase of sugar cane harvesting, biomass-associated nitrogen is volatilized and a large fraction is emitted into the atmosphere in the form of gaseous ammonia, NO_X and particulate aerosols. As a result, aerosols and trace gases emitted from large sugar-cane fires, for example, have significant effects on the composition and acidity of rainwater over large areas of southern Brazil. Rainfall acidity detected in this region is often similar to levels found in more industrialized regions. The rain acidity may also have deleterious effect on nutrient-poor tropical soils of Latin America, leading to the leaching of several nutrients like calcium, magnesium and potassium.

Additionally, in southeastern Brazil, a strong correlation between the biomass burning season and the increase of respiratory diseases has been shown. As biomass burning is one of the major sources of reactive nitrogen to the atmosphere, several other regions in Latin American and Central America could be undergoing similar changes in their pattern of nitrogen deposition, with similar effects on human health. It is very difficult to separate out the human health impacts of biomass burning that are due directly to gaseous nitrogen emissions and those that are caused by particulates. Many of the particulates also contain nitrogen, but their direct effects on human health are related more to particle abundance and size rather than their nitrogen content per se. In any case, policy measures related to biomass burning are likely to mitigate several harmful pollutants, including the release of reactive nitrogen into the air.

In September 2002, due to the concern with public health and air pollution, the Government of the State of São Paulo established a law stipulating that for areas larger than 150 hectares and with soil slopes lower than 12 percent, sugar cane burning must be halted on half of each property by 2011, and on the entire property by 2021. For areas smaller than 150 hectares and/or with soil slopes steeper than 12 percent, these deadlines have been delayed until 2026 and 2031, respectively. Thus it appears that while the problem has been recognized, local economic interests are contributing to a delay in the implementation of the policy response.

Coastal and marine pollution

The Caribbean Environmental Programme, which grew from the 1981 agreement known as the Caribbean Action Plan, addresses coastal and marine pollution in the wider Caribbean Region. The action plan led to the 1983 Cartagena Convention and Protocols, which comprehensively address the protection and development of the region's marine environment. One protocol, the Land Based Sources of Pollution Protocol (LBS Protocol), specifically addresses the marine pollution attributable to land-based activities. The LBS Protocol recognizes that water pollution has implications far beyond the area where it is emitted, and that the consequences of excessive nutrient pollution extend widely throughout the region. The Protocol sets regional effluent limits on sewage and requires specific plans to address agricultural pollution sources. In fact, two technical annexes of the Protocol deal with the major point and non-point sources: sewage in Annex 3 and agricultural non-point sources in Annex 4. These are the two major sources of nutrient input to the marine environment in the Caribbean.

While nutrient input was considered a very high priority during the negotiation of this Protocol, it proved impossible during the protocol negotiations to agree on an effluent standard or guideline for nutrients. In that regard the Protocol is silent, although it is stated that all governments should implement plans to reduce the input of nutrients into the marine environment. Although some signatories have individual guidelines in place on these objectives, the Protocol emphasizes the need to address these issues on a regional level. At the time of the drafting and negotiation of the Protocol, it was estimated that nearly 85 percent of the marine pollution originated in a land-based activity. A 1994 assessment in this region reconfirmed that the largest source of nitrogen for the marine environment comes from non-point sources, namely runoff from agriculture in rural areas. Of the known point source contributions, domestic wastewater was cited as the largest contributor. As of the 1994 survey, more than 90 percent of the wastewater produced was either collected in septic tanks or directly released into the environment. Of the 10 percent that was treated, very little went through tertiary treatment that would remove reactive N, meaning that substantial amounts of reactive nitrogen are being introduced into the marine environment in this region of the world. This pollution may be detrimental to environmental and human health, as well as having implications for the economic viability of the fishing and tourism industries.

It remains difficult to assess the extent to which nutrient enhancements are directly causing negative impacts on the marine ecosystem. Projects are planned to augment regional and national efforts of laboratories in this regard and to identify both national and regional pollution hotspots. Prior to the Protocol's entry into force, other measures have been initiated, though with varying degrees of success. Pilot programmes to institute national and local plans for sewage collection and treatment plants are under development in Jamaica, Venezuela and Saint Lucia. The Assessment and Management of Environmental Pollution Sub-Programme of the CEP published a report of best agricultural management practices to minimize excessive nutrient runoff, and small grants are available to assist communities that are implementing them. However, these incentives have not been widely used and are not substantial enough to effect major change.

CASE STUDY

Nitrogen excesses in Europe

In Europe, reactive nitrogen has been recognized as an important environmental issue, especially in regards to the air transport of NO_X , nitrate pollution of drinking water, and regulations regarding ammonia. Several protocols have been signed in the last several decades addressing specific problems. Currently, the European Commission is investigating the relation between the different protocols and the need for more integration, for example between the UNECE Convention on Long-Range Transboundary Air Pollution described below, and the EU Water Directive, which is not addressed here.

The Convention on Long-Range Transboundary Air Pollution

Since the early 1970s, governments and other parties addressing national, regional and global environmental issues have recognized the complexities presented by airborne reactive nitrogen in its various forms. As a component in ozone, smog and other airborne pollutants, reactive nitrogen can travel long distances, damaging ecosystems far from where it originated. Because air pollution is not limited by any political boundary, various policies have been created to improve air quality in as broad a reach as the pollution travels. One of the most comprehensive policies addressing the airborne challenges of excessive reactive nitrogen is the Convention on Long-Range Transboundary Air Pollution, adopted in Geneva in 1979 under the auspices of the United Nations Economic Commission for Europe. The Convention, commonly referred to as CLRTAP, entered into force in 1983.

CLRTAP is a good example of an instrument that has successfully augmented environmental protection at a regional level over time, even through periods of political instability. With 50 parties to the Convention, it was the first major international attempt at addressing air pollution. Its constructs provide a basis for discussion and cooperation, integrating science and policy and, in doing so, account for the many facets of transboundary air pollution. Within the Convention, a specific body for monitoring and modeling pollutant amounts and impacts was initiated in 1974 and adopted in 1977 as a special programme under the UNECE. Known as the Cooperative Programme for Monitoring and Evaluation of the Long-Range Transmission of Air Pollutants in Europe (EMEP), it fosters international cooperation on transboundary air pollution problems through collection of data, measurements of air quality, and modeling of transport and deposition of air pollution. Collaboration with governmental agencies, nongovernmental organizations, scientists and other stakeholders has made this an effective regulation both in controlling the problem and in reporting progress made.

The Sofia Protocol

The Convention, which has subsequently been modified and enlarged by eight protocols, has its initial roots in the environmental impacts generated by sulphur emissions. The first of the Convention's protocols, known as the Protocol of Sofia, did address nitrogen issues. Adopted in 1988 and entering into force in 1991, it obtained the commitment of 29 countries to stabilize NO_X emissions at 1987 levels

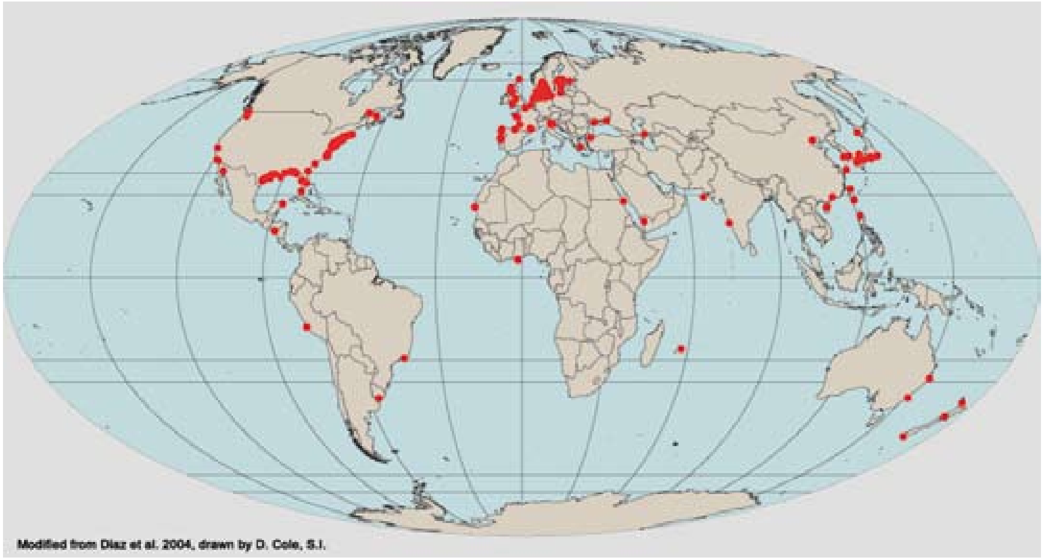


FIGURE 7 *Global map of 199 coastal oxygen depletion zones related to anthropogenic eutrophication. Updated from Diaz et al., 2004, by personal communication from R. Diaz, 2007.*

for major stationary sources and new mobile sources. It set concrete goals, with specific intermediate steps for achieving the broad aims contained in the Convention. Importantly, this Protocol recognized the desirability of addressing both environmental and economic concerns among the Parties, a balance which has assisted countries in adhering to their commitments. Overall, the initiative has been quite successful, and even greater reductions are expected as technology advances through subsequent protocols. The Convention's continuing relevance is assured due to ongoing updates and modifications, given new data on environmental and economic trends as well as an understanding of what previous protocols have either improved or overlooked. Additionally, CLRTAP provides a framework within which countries develop their own measures to meet agreed targets. This has proved to be an effective model, with some countries emerging as leaders in applying policies for effective implementation.

The Gothenberg Protocol

The most recent of the Convention's protocols is the Gothenberg Protocol to Abate Acidification, Eutrophication and Ground-level Ozone. It was adopted in November 1999 and entered into force in May 2005 with 18 countries as Parties to the Protocol. Primary stakeholders include the LRTAP Executive Body, the European Commission Directorate General of Environment, member governments, and policymakers as well as corporate interests encompassing the electric power producers, petroleum refiners and processors, automakers, manufacturers, and other industries that emit pollutants covered by this Protocol. Furthermore, the Gothenberg Protocol has served as a basis for the EU National Emission Ceiling Directive, which requires the Member States to take measures to reach the targets. Although the provisions of the Protocol also encompass sulphur and other volatile organic compounds, the Protocol emphasizes the role of nitrogen oxides and ammonia in excessive acidification, eutrophication and the formation of ground level ozone. This multi-pollutant, multi-effect scope captures some of the complex nature of the transboundary air pollution problem on local, regional and even hemispheric scales. Comprehensive emissions limits are set for each signing country, with an achievement deadline of 2010. Under full implementation, and in comparison with the selected 1990 baseline, the anticipated reductions are 41 percent for NOX and 17 percent for ammonia, all of which are stricter targets than imposed under the Sofia Protocol. This formalizes a trend of emission reductions already underway in Europe. However, a study undertaken in 2005 by the National Emission Ceiling Review predicted that only four parties of the signing states would meet the targets set by the Gothenburg Protocol for all addressed pollutants.

Though the Protocol has entered into force so recently, many of the parties have moved rapidly to establish plans leading to target achievement. Of the signatories, Germany has a strong record of incorporating its pollution control policies within its economic and policy structures. For example, in order to assist in meeting NO_X emission reductions, community-wide management practices have been supplemented with additional guidelines and incentives for the power, industrial and transportation sectors. These efforts have resulted in an overall reduction of 50 percent since 1990, though atmospheric concentrations near major transportation infrastructures still often exceed legal limits. Further efforts towards cleaner motor vehicles, in particular diesel engines, as well as cleaner transportation of goods via rail and water, versus roads, are being implemented. Numerous economic incentives toward the economic development and market penetration of cleaner diesel vehicles and/or alternative fuels have been introduced by the federal government in the past decade in order to curtail this growth in emissions.

In terms of ammonia emissions, the Protocol requires that signatories address it in relationship to its role in the impacts of reactive nitrogen, though it does so without any specific recommended measures. Recommendations include whole-cycle nitrogen management, livestock-feeding strategies, low-emission manure spreading techniques and storage systems, low-emission animal housing systems, and possibilities for limiting ammonia emissions from the use of some of the more inefficient fertilizer application practices. As discussed in the previous section of this report, controls on these agricultural emissions are among the most difficult to set and enforce, due to the dispersed non-point nature of sources and monitoring capabilities. Unlike its fellow signatories, the Netherlands and Denmark are the only countries that have specifically detailed national policies that have brought ammonia emissions into compliance with the terms of the Protocol.

Notably, within the Protocol's preamble, a link is cited between human health effects and air pollution emissions, a first for any amendment to the original Convention. This is an endorsement of the increasing awareness among stakeholders regarding the connection between excessive reactive nitrogen and ramifications extending beyond its already significant consequences on ecosystems. A September 2005 proposal by the European Commission echoes these concerns, highlighting the role of ozone in compromising human health. Health goals set forth in the proposal — and particularly to cut the annual number of premature deaths attributable to air pollution by nearly 40 percent compared to 2000 levels — complement the objectives of the EU Sustainable Development Strategy. In addition, the proposal highlights the cost savings of implementing the plan, citing specific averted costs of fewer deaths, less work time lost, and reduced hospital visits as well as the acknowledged, though less tangible and valorised benefits associated with preserving ecosystems. A 2006 study by the European Commission cited the annual value of ecosystem services in the EU — water and air purification, climate regulation, flooding mitigation, soil formation, pollination and other functions — at nearly 26 trillion Euros, a figure more than twice the value of the commercially produced and traded services that the formal, global economy currently generates annually. The Millennium Ecosystem Assessment highlighted the decline of ecosystem services, not only in Europe but globally. The inclusion of this topic in the preamble of the Protocol echoes similar concerns and points to the need for a solution. This broad perspective also assembles the range of arguments that can be made for effectively and comprehensively addressing the challenge of excess reactive nitrogen.

Further action from the signatories to CLRTAP and its Protocols is expected to come from increased dialogue with other entities addressing the nitrogen issue. Among these entities are the Malé Declaration on Control and Prevention of Air Pollution and its Likely Transboundary Effect for South Asia, the Acid Deposition Monitoring Network in East Asia, and the International Union of Air Pollution Prevention and Environmental Protection Associations. Notably, the Association of South East Asian Nations (ASEAN), in conjunction with UNEP, recently adopted the Agreement on Haze Pollution, the first international treaty addressing transboundary air pollution outside Europe. The successes of CLRTAP were a model for the creation and refinement of this policy and will likely have future ramifications for similar policies in other regions.

Eutrophication in the Baltic Sea

Since the 1800s, the Baltic Sea has changed from a nutrient-poor oligotrophic clear-water sea into a nutrient-rich eutrophic marine environment due to excessive inputs of both nitrogen and phosphorus. In recognition of this threat, the Convention on the Protection of the Marine Environment of the Baltic Sea, which is being implemented under the auspices of the Helsinki Commission (HELCOM), was signed in 1974 by the then seven coastal Baltic states. It entered into force in 1980 and since then, HELCOM as the responsible intergovernmental body, has adopted several recommendations to reduce pollution by nutrients in all sectors, including industry, municipal wastewater treatment and agriculture. HELCOM has also been working to achieve the 50 percent reduction targets for nutrient emissions and discharges set in the 1988/1998 Ministerial Declarations. These targets are now gradually being incorporated in an overarching objective for the sea to reach a good ecological status.

HELCOM assessments clearly show that agriculture is one of the main sources of nutrient pollution entering the Baltic Sea — more than half of the waterborne nitrogen and phosphorus loads entering the sea come from agriculture. HELCOM's current efforts are therefore mainly focusing on the identification of possible further measures to reduce loads from agriculture in the different parts of the Baltic Sea catchment area. However, other nutrient sources, such as municipalities, scattered settlements and airborne nitrogen still contribute significantly to the total inputs, and must also be considered in comprehensive strategies to reduce overall emissions of reactive nitrogen. A major study has been conducted to assess progress towards the strategic goals of the 1988 Ministerial Declaration regarding nutrient load reductions. This review shows that the progress in reducing nutrient loads from point sources such as municipal and industrial wastewater treatment plants has been good, with the 50 percent reduction target for phosphorus achieved by almost all the contracting parties.

Increased reductions in nutrient loads from point sources are likely, since the continued implementation of nitrogen and phosphorus removal measures will further curb loads from municipal plants, especially in the three Baltic States, Poland and Russia. Further implementation of "best available techniques" will also cut industrial nutrient pollution loads. Comprehensive official plans to reduce inputs of nutrients to the Baltic Sea have so far been adopted by national governments in Finland, Latvia and Sweden. Plans to reduce nutrient loads in the other contracting parties that are also EU members mainly focus on the implementation of the related EU Directives, which also contribute to the reduction of nutrient inputs into the Baltic Sea. The recent decreases in discharges have not been reflected in any improvements in the ecological status of the Baltic Sea as a whole. Therefore there still is a need for further actions. Actions to reach an improved ecological status are currently being identified and will be included in the HELCOM Baltic Sea Action Plan to be adopted at a ministerial meeting in November 2007.

Atmospheric nitrogen deposition is another of the main contributors to the high nutrient concentrations that stimulate massive algae blooms in the Baltic Sea. One of the deposition scenarios modelled for HELCOM by EMEP (the Cooperative Programme for Monitoring and Evaluation of the Long-Range Transmission of Air Pollutants in Europe) clearly indicates that atmospheric nitrogen deposition into the Baltic Sea will be higher in 2010 than in 2003. Approximately one quarter of the total nitrogen input into the Baltic Sea currently comes from airborne nitrogen deposited directly into the sea – of this 25 percent, approximately 40 percent originates from agriculture. In addition to this direct deposition, some of the nitrogen deposited into the Baltic Sea watershed reaches the sea via runoff from land. Sources of airborne nitrogen from outside the Baltic Sea watershed account for almost 40 percent of the total deposition of nitrogen within the watershed. This should be considered when evaluating possible further developments and the adequacy of measures taken to reduce airborne nitrogen pollution sources to the Baltic Sea. A study recently released by HELCOM shows that achieving the nitrogen emission targets set for 2010 by the Gothenburg Protocol to the Convention on Long-Range Transboundary Air Pollution (CLRTAP, discussed above) and the EU Directive on National Emission Ceilings for Certain Atmospheric Pollutants (NEC) may not be enough to reduce airborne nitrogen deposition to the Baltic Sea. The results of this study will contribute to the updating of programmes under the NEC Directive in EU member states in 2006, and proposals for the possible modification of the NEC Directive in 2008, as well as the revision of the Gothenburg Protocol.

CASE STUDY

Nitrogen excesses in Asia

Water pollution due to sewage, fertilizer, and manure runoff, and the burning of fossil fuels is also a growing concern in Asia. Nitrogen, while not the only component of the pollutants, is a significant presence. In China, for example, recent rapid industrialization is responsible for a nearly 28 percent increase in the amount of wastewater produced between 1981 and 1995, translating into an annual increase of nearly 2 percent per year in that period. In addition, China's agricultural economy has expanded as well. Nearly 41.2 million tonnes of fertilizer were used in 2004, a jump of nearly 8 million tonnes over the application rate in 1994 and 15 million tonnes more than applied in 1991. China is now the world's leading user of nitrogen, phosphorus and potassium fertilizers.

Estuary and river water quality

Among other effects, these combined inputs trigger algal blooms in estuaries, which take oxygen from the water at the expense of other marine life. These blooms result in hypoxic or anoxic regions (often known as dead zones), and have risen markedly since the 1970s, threatening fish stocks and people, with significant economic consequences for the fishing industry and human health. The number of zones of hypoxia along the Chinese coast line now resembles the frequency of such zones around North America and Western Europe (see Figure 7).

Poor water quality in estuaries and rivers affects not only fish and the people who eat them. River water is also used for irrigation and drinking water, where poor water quality can cause an increase in the occurrence of waterborne diseases, such as cholera, typhoid and dysentery. With a population of over 1.4 billion, nearly half are exposed daily to drinking water contaminated with sewage levels that far exceed safety limits. According to a study done by China's Ministry of Construction in 2005, more than 3.7 billion tonnes of sewage are discharged daily. With a current treatment rate of only 45 percent, more than half empties into rivers and lakes untreated. Even when treated, sewage discharge still can contain high levels of pollutants. In 1996, nearly 77 percent of industrial wastewater was treated; in contrast, only 11 percent of sewage was treated at all and less than 10 percent of that underwent the biological secondary treatment process. As in most other regions of the world, few of these treatment facilities have implemented tertiary treatment, the phase at which reactive nitrogen can be removed from sewage. Since 1970, rates of liver and stomach cancer have doubled in China, a trend that is, at least in part, thought to be due to insufficient wastewater treatment. The World Bank estimates that the impact of water pollution on human health is nearly $4 billion per year. While these costs are probably the results of several water pollutants in addition to nitrogen, it is difficult to separate the combinations of contributing factors on human health and the environment.

Two areas specifically affected are the Yangtze and Pearl River estuaries. For example, 126 animal species were living in the Yangtze in the mid-1980s. By 2002 that number had decreased to 52, due partly to pollution but also influenced by development, habitat loss, and overfishing. A 2005 report released by the

State Environmental Protection Administration found that 500,000 tonnes of ammonia (and 300,000 tonnes of phosphate) were transported from land-based activities into the sea. In fact, 82 red tides (a type of algal bloom most usually associated with nutrient excess in coastal waters) occurred in 2005. A single June red tide event in the Yangtze resulted in more than 12 million fish dying.

In response to these trends, China issued the "Discharge Standard of Pollutants for Municipal Wastewater Treatment Plants" in 2002, which included regulation of some inputs of reactive nitrogen, in addition to other pollutants. This action also led to the construction of wastewater treatment plants in inland areas. The economic implications of these more rigorous guidelines have the potential to be significant. The demand for increased water quality is creating business opportunities in China for contractors to build additional treatment facilities. In December 2005, China's cabinet, the State Council, affirmed its commitment to enhancing the nation's environmental protection efforts, including a goal of establishing a market mechanism for the wastewater treatment sector through outsourcing to professional contractors and increased pricing for processors. This has resulted in some mitigation, but not enough to stem the growing threat of hypoxic and anoxic zones in estuaries and coastal waters. In response, China has recently committed to increasing wastewater treatment processes in the coastal areas from the current 50 percent of wastewater that is treated to 70 percent by 2010. Though significant, this goal leaves 30 percent of wastewater still wholly untreated. Broadening awareness of the health effects resulting from water pollution will assist improvements in wastewater treatment. Where water-borne infectious diseases are the primary health concern, primary and secondary sewage treatment must be the highest priority to make drinking water safe from human pathogens. Where eutrophication and hypoxia in coastal embayments are growing environmental and economic concerns, the need for tertiary treatment must also be recognized to remove excess reactive nitrogen.

CASE STUDY

Nitrogen excesses in North America

Just as air pollution must be approached from a wide perspective, resolving water pollution issues resulting from excessive reactive nitrogen usually requires a regional effort. Effective policies require cooperation among industry, agriculture, nongovernmental organizations and multiple levels of government

The Chesapeake Bay Program

In North America, the Chesapeake Bay, once a vibrant and functioning ecosystem, is today a well-known example of how an over-fished, over-used, and under-protected environment can become seriously degraded through wide-scale air and water pollution. Even today, though water quality has generally been improving for the last 15 years, advances have been compromised by increasing pressures of development and population growth. Controversy surrounds the extent of its recovery, and its future health is not yet assured.

The Chesapeake Bay is the largest estuary in the United States, with a watershed that covers nearly 170,000 square kilometres. Fully understanding the challenges facing the Chesapeake Bay requires a comprehensive grasp of both the air and water pollution in the area. The Chesapeake's watershed includes the District of Columbia (DC), and parts of Delaware, Maryland, New York, Pennsylvania, and Virginia and West Virginia. The Chesapeake airshed, which is substantially larger, includes the watershed plus parts of Indiana, Kentucky, Michigan, New Jersey, North Carolina, Ohio and Tennessee.

Since the early 1980s, when concerns over the state of the estuary prompted a six-year study by the Environmental Protection Agency, the Chesapeake Bay has been the focus of environmental efforts to restore its viability. The largest contributing factor to the Bay's poor condition is excess nutrients, chief among them being reactive nitrogen. Sources of the excessive nutrients include sewage runoff, leaching septic systems, vehicle exhaust, acid deposition, and water runoff through urban and suburban developments. Agricultural runoff, though recently on the decline due to improved regulation and management practices, also remains a significant contributing factor to nitrogen pollution in the Bay.

The Chesapeake Bay Program is one of the primary coordinating bodies for addressing nutrient management in the region. The programme is a voluntary governmental partnership among the states of Maryland, Virginia, Pennsylvania, West Virginia, New York and Delaware, as well as the District of Columbia, the US Environmental Protection Agency and the Chesapeake Bay Commission. The Chesapeake Bay Commission is an independent, tri-state legislative body under whose jurisdiction fall the policy and implementation decisions regarding overall restoration efforts. Additional stakeholders include farmers, local governments, federal agencies, urban planners, conservationists, civic groups, academic and research institutions, local governments and concerned citizens. Each of these provides a crucial perspective on the range of measures needed to restore the Bay.

The first agreements to improve water quality in the Chesapeake Bay came in 1983 and in 1987. The latter set an ambitious goal of reducing nitrogen to 60 percent of 1985 levels. While improvements have been made — nitrogen levels are currently 16 percent less than those present in 1985 — over 90 percent of the area continues to be technically listed as impaired. Another agreement followed in 2000, and commits the parties involved to reducing levels by an additional 40 percent. In 2003, the Chesapeake Bay Program established quantitative guidelines for excessive nutrients, including nitrogen. The goal, initially intended to be achieved by 2010, reflects a substantial reduction over the amount emitted in 2000 and was based on projections necessary to alleviate the persistent lack of oxygen (known as hypoxia) resulting from the excessive algal growth caused by eutrophication in the Bay. However, due to the complexity of the recovery, it now seems unlikely that this goal will be met by 2010.

State reductions are set based upon the impact on water quality, and though some are administered at the state level, municipal bodies coordinate many other practices. Pennsylvania and Virginia have recently implemented novel nutrient trading schemes, in which nitrogen credits can be traded among housing, industry and agricultural sectors within each state, although inter-state trade has not yet been implemented. For example, a developer of a residential complex in Pennsylvania bought nitrogen pollution credits from a poultry farm operator, who agreed to export poultry manure out of the watershed, to be applied to nitrogen deficient lands elsewhere. If managed properly, a net reduction in reactive nitrogen release to the watershed could be achieved through trading schemes while also permitting further economic development.

In addition to the 2010 goals, the Chesapeake Bay Program is also monitoring a matrix of biotic ecosystem components — including fish, birds and grasses — as a measure of success. This approach is a shift to measuring the progress of the recovery by using species robustness as an indicator of functional ecosystem health, which recognizes the inherently interconnected aspects of a full ecosystem recovery on a comprehensive scale.

Another dimension that can be considered in evaluating the progress of the restoration of the Chesapeake Bay is the concept of an economic nitrogen cascade. Developed to parallel the chemical nitrogen cascade (as discussed earlier in this report), the economic nitrogen cascade provides stakeholders with a more tangible and compelling reference to the consequences of excess reactive nitrogen. By showing that actions, or lack thereof, have specific costs and benefits, the economic nitrogen cascade provides an additional framework to guide the design of appropriate policies.

Diagrams of both the biogeochemical and economic nitrogen cascades for the Chesapeake Bay are presented in Figures 8a and 8b, illustrating the quantities of nitrogen from each source and their damage costs as excess reactive nitrogen cascades through the various systems in the watershed. Cost estimates in boxes are the estimated costs per tonne of nitrogen emitted by each source type for each ecosystem type. In addition to the monetary damage estimates, the types of economic damage for which monetary estimates were not available are also identified. This analysis demonstrates how the damage costs of reactive nitrogen emitted into the air accumulate as they move from air to land to water, causing economic consequences in each location. While the reactive nitrogen present in water bodies has the same environmental and economic impacts there regardless of whether it originated from sewage, agricultural runoff or atmospheric deposition, the reactive nitrogen that was first emitted into the air has the overall most damaging effect because of its impacts in each medium and location. Hence, there may be greater economic advantage to society by controlling nitrogen releases into the environment as far upstream and upwind as possible in order to avoid this accumulation of impacts and damage costs. This is true, however, only from an integrative perspective of the overall effects of excess reactive nitrogen throughout the air, land and water bodies. A more narrowly defined cost-benefit analysis that pertains only to impacts on aquatic ecosystems would rank the economic damage costs of each reactive nitrogen source equally.

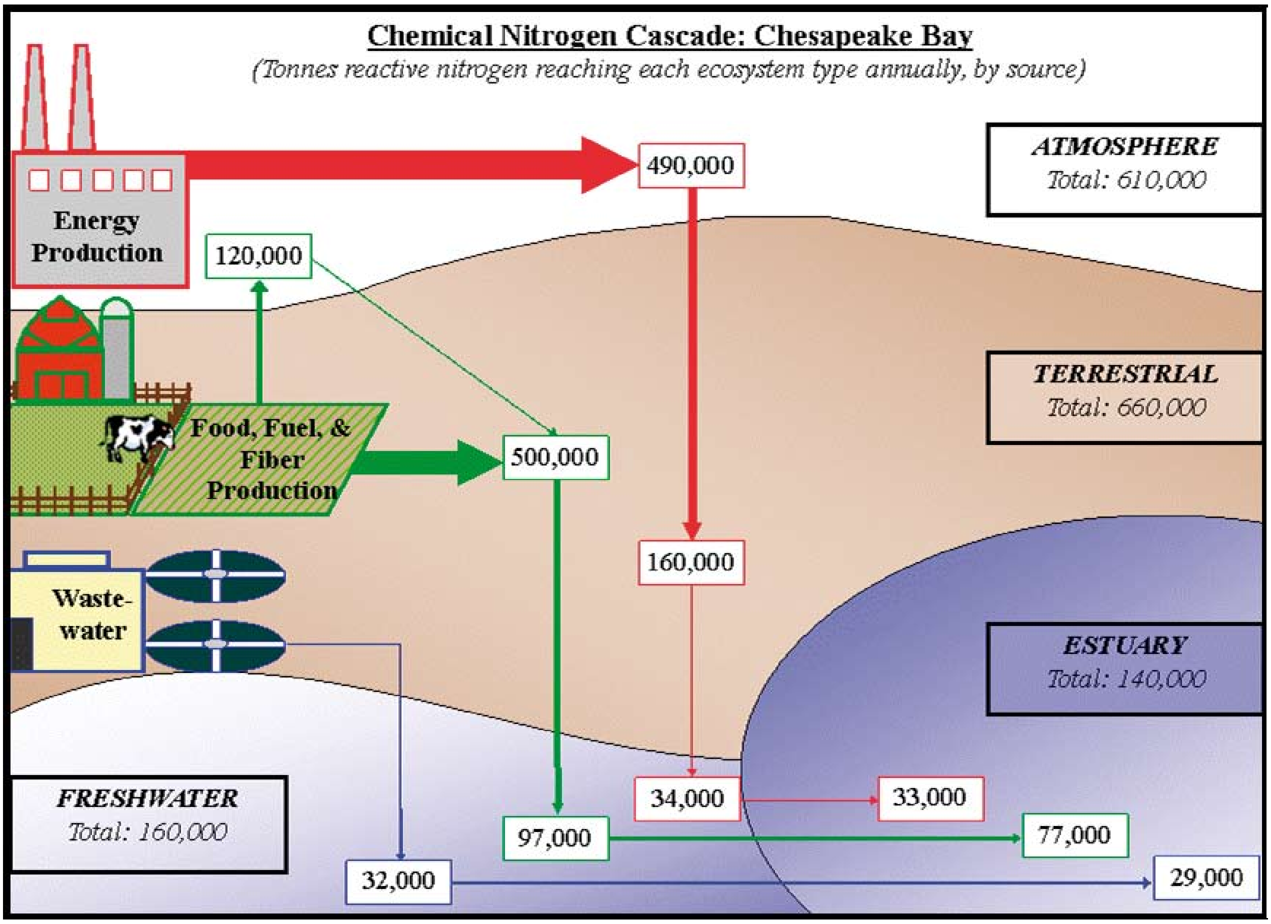


FIGURE 8A *Diagram of the biogeochemical nitrogen cascade, showing the major fluxes of reactive nitrogen among atmospheric, terrestrial, freshwater and estuarine systems in the Chesapeake Bay watershed. These inputs of reactive N to the Bay are attributed to three source types: energy production, food and fiber production, and wastewater. Arrow width varies according to flux size. Adapted from Moomaw and Birch, 2005.*

The most useful outcome of the nitrogen cascade constructions — both chemical and economic — are as frameworks to better understand the wide-ranging consequences of excessive reactive nitrogen in its various forms as it cascades through air, landscapes and waterscapes. By seeing the larger, and inter-related picture, decisions can be made in context of one another to best overcome the obstacles. While the Chesapeake Bay example provides the most comprehensive set of economic costs data available, utilizing this approach in other problem regions of the world would help inform sound decisions.

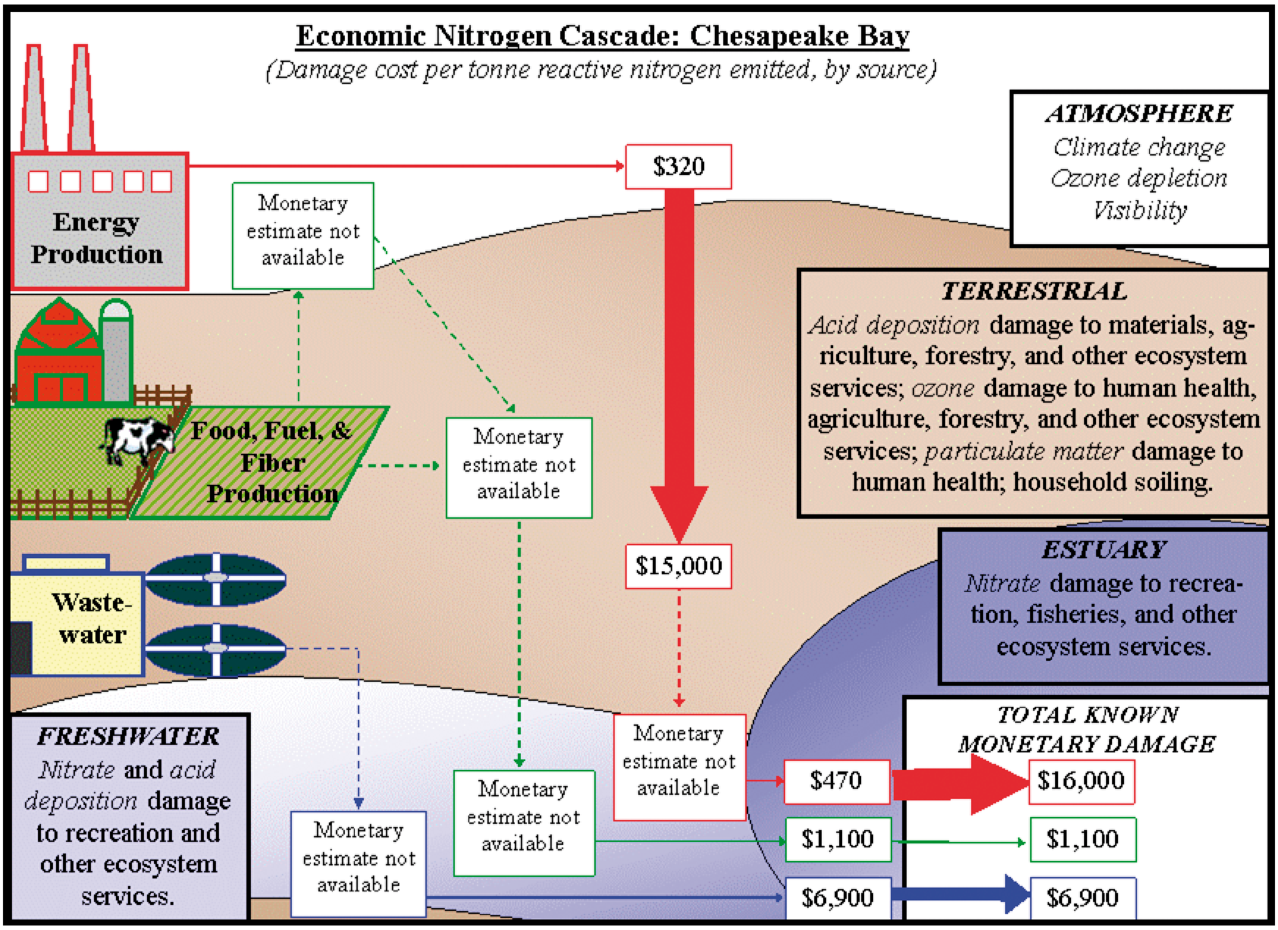


FIGURE 8B *Diagram of economic nitrogen cascade, illustrating the damage costs associated with nitrogen from each source type as it cascades through the various systems in the watershed. Cost estimates in boxes are the estimated costs per tonne of nitrogen emitted by each source type for each ecosystem type. Monetarized costs include reduced recreational and residential visibility, mortality, hospitalization and work loss caused by particulate and ozone exposure, materials damage via corrosion, loss in agricultural productivity due to ozone exposure, reduced crab fisheries and impacted recreational use. These costs are summed for each source type to provide a total economic damage estimate (in monetary terms) for each source type. In addition to the monetary damage estimates, the types of economic damage for which monetary estimates were not available are also identified, including nine such types of damage for nitrogen from energy production and seven types each for food and fibre production and wastewater. Adapted from Moomaw and Birch, 2005.*

CASE STUDY

Nitrogen deficiencies in Africa

Worldwide, nearly one billion people — 15 percent of the global population — are affected by insufficient food production. Because adequate amounts of crop nutrients are not available from other sources, synthetic fertilizers provide a crucial tool for increasing food production. Consequently, where soil fertility is poor and crop nutrients are scarce, communities experience high rates of malnutrition, which compound the effects of malaria, measles, diarrhea and other conditions, all of which contribute to increased mortality, especially among children. This imbalance in the distribution of reactive nitrogen, including the availability and affordability of synthetic fertilizers, impedes the immediate food supply and threatens the long-term ability of the land in some localities and regions to produce crops at levels required to sustain local communities.

Effective solutions to nitrogen deficiencies, and the resulting increase in food production, will have positive impacts on issues of malnutrition and poverty. These broader effects coincide with outcomes identified in the Millennium Development Goals, illustrating again that resolving the challenges associated with reactive nitrogen in the environment is inherently linked with other issues confronting the international community.

Famine in sub-Saharan Africa

Although agriculture is the primary industry in sub-Saharan Africa, this region has the lowest fertilizer application rate in the world, thus aggravating the problem of decreasing crop yields and per capita food production. To simply maintain crop production at the same levels as the late 1990s, nearly 11.7 million tonnes of all types of fertilizer (including, but not restricted to, nitrogen fertilizer) are needed per year. Current application rates are only approximately 3.6 million tonnes per year. In fact, all but three African countries have negative annual nutrient balances, meaning that more reactive nitrogen and other essential plant nutrients are being removed through harvests or being inadvertently lost from agricultural fields than are being introduced into the system through fertilizers, BNF or manure management. What nitrogen fertilizer is available is predominantly imported, as this region of the world lacks substantial quantities of the resources, including natural gas, needed for domestic production as well as the capital needed to invest in effective and efficient production facilities.

Regardless of whether the fertilizer is imported or produced domestically, the overall lack of access in sub-Saharan Africa is attributable to many factors. Because there are few suitable waterways in sub-Saharan Africa, the majority of goods must be transported over land. In general, suppliers experience difficulty in bringing their products to market, as roads are frequently in disrepair or few and far between, and some areas are disrupted by political and social instabilities. Rail systems do not reach most agricultural areas. Such challenges impact the price of fertilizer, even doubling or tripling costs over what they are in other parts of the world, an unneeded obstacle in an already poverty-stricken region.

Though home to just over 10 percent of the world's population, this region of the world accounts for barely one percent of the global use of synthetic fertilizer, and despite acute need, fertilizer suppliers realize greater profits by concentrating their resources in areas where more intensive use occurs, most often where commercial markets for farmer output has triggered infrastructure development. To further compound the problem, even once the fertilizer has arrived at a marketplace, often farmers must travel long distances to purchase it and may not have access to motorized vehicles to transport the bulky and heavy fertilizer products. When such transport is available, the cost may limit the quantity of fertilizer that can be purchased.

Due to a rapidly growing population in Africa, land use has changed and agricultural practices in many places have intensified to meet food production demands, but without the resources to manage the system sustainably. Traditionally, farmers rotated the fields that they cropped, allowing some fields to remain fallow for several years, thus gradually accumulating available nutrients that would be needed for the next cropping cycle. But because of population pressures, communities now till the same land over and over, in effect depleting usable soil nutrients, increasing the risk of soil erosion, and creating an environment unable to support those living there. Farms owned by smallholders, which are most often subsistence farms, usually have very limited fertilizer application. Net losses of nitrogen (outputs greater than inputs) are due to a variety of factors, including shallow and highly weathered soils; ineffective or absent soil conservation techniques; continuous cereal cropping without legume rotations to enhance BNF; limited water supply; and the high cost of fertilizer due, in part, to weak transportation infrastructure.

Possible remedies for the lack of reactive nitrogen in Africa include better soil management practices, including crop rotation, soil conservation and water management, agroforestry cropping systems, as well as integrated livestock management. Some of the crop rotation and agroforestry systems include leguminous plants that contribute to nitrogen fertility through biological nitrogen fixation. Providing farmers with access to education and financial assistance while at the same time reducing trade barriers, including tariffs, establishing fair prices, in part through balancing supply and demand, are essential, yet daunting, requirements. Through the use of technological advances in fertilizer production, targeted blends of nutrients in fertilizers applied in appropriate amounts can maximize crop yield while minimizing the amount of reactive nitrogen and other nutrients introduced into the environment.

As one venue for beginning to implement solutions, a summit addressing the food challenges of Africa and their inherent relationship to the lack of accessible fertilizer was held in Nigeria in June 2006 by The New Partnership for Africa's Development (NEPAD). The meeting provided a forum for government leaders, NGOs and corporate representatives, policy-makers and other stakeholders to outline effective strategies at both the national and regional levels. Integrated initiatives addressing policy and regulatory tools, combined with institutional and structural reforms as well as capacity-building efforts are expected to be implemented, backed by partnerships at regional, country and local levels and measures to address financing shortfalls. Among the first steps agreed upon at the summit were the lifting of all cross-border taxes and tariffs on fertilizer and the agreement to establish an African fertilizer financing mechanism within the African Development Bank, although these steps have yet to be fully implemented. The first progress report was given in January 2007, and this exercise will be repeated every six months — an important measure to ensure that there will be effective and coordinated follow-up to the initial political commitment.

Conclusion and recommendations

The impacts of reactive nitrogen in the environment

Reactive nitrogen, made available through either natural or anthropogenic means, is integral to sustaining the world's human population, as well as being a partially unavoidable by-product of energy use. Its role in supporting agriculture is key to human life as we know it, and regions of the world that lack sufficient reactive nitrogen, in the form of fertilizer, struggle with malnutrition, disease and poverty. While this report explores the negative consequences of excessive reactive nitrogen in fuller detail than those consequences created by a lack of reactive nitrogen, it is crucial to remember that the lack of fertilizer to support agriculture in many developing countries factors prominently in the larger issues of sustainability, famine reduction, and other human welfare priorities addressed by recent initiatives such as the Millennium Development Goals.

The growing scale of the environmental, health and economic impacts of excess reactive nitrogen in various parts of the world has led governments to develop a range of policy responses, most at national levels (e.g., national regulations on air and water quality), some at regional levels (e.g., regional, international policy instruments to set goals and mechanisms for achieving reduced emissions of air and water borne nitrogen). At the global level, the United Nations Framework Convention on Climate Change (UNFCCC) describes provisions for Parties to make available national inventories of anthropogenic emissions by sources and removals by sinks of all greenhouse gases, including N_2O, which are not controlled by the Montreal Protocol.

The extent to which policies have been implemented varies widely, with some remaining as policies only on paper. Even some of those that have been backed by significant commitments of financial, regulatory and technological resources are proving less effective than hoped in reducing overall reactive nitrogen emissions or reducing some of its key negative impacts on the environment. The absence of effective policies or failure to implement them is linked to various factors, including lack of awareness of the range and magnitude of impacts, shortage of the necessary financial and technological investments, and the absence of sufficient information to make rational decisions that balance environmental, economic and health objectives.

The following conclusions and recommendations for assessment and monitoring of reactive nitrogen impacts are offered here in support of the development of effective policy responses.

Varying impacts, scales, and responses to reactive nitrogen

Many of the impacts of excessive reactive nitrogen in the environment occur within a short distance of the emission sources. As such, authorities within one legal jurisdiction can effectively carry out many of the responses required. However the mobility of reactive nitrogen, and particularly of emissions into the atmosphere and to a lesser extent into surface waters, means that some impacts extend to the regional level, implying the need for a collective response that spans different jurisdictions. Partially successful examples, such as Europe's Convention on Long-Range Transboundary Air Pollution, illustrate how a multidisciplinary, collaborative approach, combining the expertise of the scientific and policy-making communities to achieve measurable outcomes and backed up by a system for holding parties accountable, can result in pollution remediation. The multifaceted programme to restore the Chesapeake Bay underlines the need for a multistakeholder and multijurisdictional effort to effect improvements. The Chesapeake Bay Program involves the federal, state and local governments as well as non-profit and private sector stakeholders, all within the framework of a regional governance structure. This unusual regional governance creation transcends normal governmental hierarchical structures. While this is within one sovereign nation, other regional efforts might benefit from imaginative governance structures operating across international boundaries. Even in instances where implementation is proving difficult, such as the LBS Protocol to the Cartagena Convention in Latin America and the Caribbean, a better understanding of the circumstances limiting full cooperation could lead to more effective implementation.

Comprehensive responses to problems of excess reactive nitrogen in the environment can require not only the involvement of multiple legal jurisdictions, and the range of ministries responsible for relevant sectors (e.g., energy, transport, agriculture, water and sanitation), but also strong engagement of the scientific, business and NGO communities. The need for this challenging coordination and integration of different interests, perspectives, technical skills, and ultimately investments in implementation, is well illustrated by the Chesapeake Bay Commission and ongoing implementation of the CLRTAP. Although neither of these has yet fully achieved its goals, experience gained in these contexts can help guide the development of responses in other countries and regions which are experiencing increasing negative effects of excess reactive nitrogen. For water related issues, the Global Programme of Action for the protection of the Marine Environment from Land-based Activities (GPA) might provide a platform for sharing of information and experiences, having a focus on coastal impacts of excessive nitrogen and addressing the natural linkage with integrated freshwater resources management.

Addressing the challenges created by deficiencies of reactive nitrogen also requires further analysis, enhanced information sharing, and increased collaboration among governments and international agencies. Overarching issues of famine, poverty and sustainability are omnipresent in efforts to improve human welfare in Africa where the deficiencies are greatest. Alleviating the fertilizer shortage, and thus mitigating the shortage of reactive nitrogen and other crop nutrients, will be best solved in the context of larger, more integrated initiatives focusing on sustainable agricultural and rural development.

Assessment, monitoring and designing effective multi-stakeholder responses

A prerequisite for designing and implementing effective, integrated policy responses to reactive nitrogen excess, is the need for scientific understanding of its behavior in the environment. A programme of assessment and ongoing monitoring is required, which should be led by governments, with collaboration from intergovernmental organizations, nongovernmental organizations and the private sector. Such assessments should include the economic and health impacts of reactive nitrogen in the environment. There is an increasing need for valuation models and especially figures on the ecosystem services that are affected by excessive nitrogen, on the appropriate scale, to enable decision-makers to set priorities for policy development and mitigating action. Developing this integrated approach through a series of regionally-specific assessments, which are updated as new ecological, economic and epidemiological evidence and understanding become available, has been and continues to be one of the main objectives of the International Nitrogen Initiative.

Policy instruments that emerge from the knowledge gained through assessment and monitoring must have the flexibility to evolve as seen in the case of the UNECE CLRTAP. In that instance, successive protocols enabled countries to respond to the changing impacts of reactive nitrogen and the improvements in the understanding of these impacts. Policy design must clearly take account of both environmental and economic concerns, to address the impacts of reactive nitrogen that truly matter to society, and also to develop balanced responses which reflect the different interests of various stakeholders. Capacity building and technical assistance in this regard will be required by developing countries and economies in transition. Experience with existing policy instruments and programmes and addressing reactive nitrogen excess within regions that encompass countries at more than one level of development, can provide important lessons in this regard.

Information sharing and collaboration for effective policies on reactive nitrogen

This need for information sharing regarding the effects of excess reactive nitrogen is not limited to its importance for policy collaboration but also for heightened public awareness regarding the issue and the comprehensive responses required to successfully address the challenge. Reaching a broader, more public audience requires outreach mechanisms built into assessment, monitoring and policy tools. These same mechanisms will also facilitate the engagement of the stakeholders necessary in developing balanced and sometimes multilateral policies.

Policy solutions for addressing excess reactive nitrogen are required at all levels, from local to global. At the most individual level, farmers should be encouraged, via a combination of education and information outreach, economic incentives, and command and control regulations, to implement sound tillage and soil management practices. Urban areas of all sizes must appropriately treat the wastewater released to control emissions into waterways. Even more broadly, states and countries should collaborate on transboundary pollution issues, both water and air, which in turn can lead to international efforts that recognize the regional and global implications of reactive nitrogen.

There may also be a case for developing new mechanisms at the international level to assist in the management of forms of reactive nitrogen that have widespread distributions, such as those responsible for the growing number of hypoxia zones in coastal areas throughout the world. This suggestion is considered controversial by some, because the causes and impacts of each case of hypoxia, although repeated in many areas on nearly a global scale, could be addressed through local and regional scale policies and mitigation efforts. Nevertheless, international cooperation on these issues could involve sharing useful expertise and experiences from various regions, as well as providing a global forum in which progress at local, national and regional scales can be reported. Similarly, because agricultural practices that result in leaching of reactive nitrogen to coastal zones may also affect emissions of nitrous oxide from soils, it would make sense to coordinate these efforts with those of the UNFCCC and the Kyoto Protocol or future climate change commitment periods and/or agreements.

This non-technical report conveys the crucial issues surrounding reactive nitrogen as it impacts the environment, human health and economies from local to global scales. Bringing the challenges of reactive nitrogen more fully into focus for the global community will assist all stakeholders in implementing coherent and effective policies that can resolve problems of both nitrogen excess and deficiency. It is hoped that this review will start to build a clearer picture of how assessments and policies on reactive nitrogen at different levels can be examined, understood and ultimately guide development of a more coherent and effective package of responses to address negative environmental and related social and economic effects where they occur.

RECOMMENDATIONS:

Improved local, regional, and in some cases global assessments are needed of the environmental, economic and human health impacts of excesses and deficiencies of reactive nitrogen. These assessments should be comprehensive, integrating environmental, health and economic analyses. Improved monitoring of forms of nitrogen pollution moving through air, water and soil, as well as nitrogen in commercially traded commodities, is also needed for many regions of the world. Deeper analysis, more investment in monitoring, enhanced sharing of information, and more collaboration at different levels of government and between the public and private sectors are required to develop effective responses to both excesses and deficiencies of reactive nitrogen.

Although better assessments and monitoring programmes are needed, enough is known about excesses and deficiencies of reactive nitrogen in many regions to develop appropriate policy instruments to address many of these problems. A number of the policy efforts that have already been developed provide important examples of successes and failures. All such policy instruments should have the flexibility to evolve as better assessments and as results from monitoring programmes become available.

Policy responses to excess reactive nitrogen must integrate the causes and effects that span several common regulatory domains. For example, policies intended to ameliorate the problem for water quality might exacerbate the problem for air quality. Likewise, upwind emissions may affect water quality far downwind and downstream. Because reactive nitrogen is actively traded in commodities and is readily mobile through air, water and soil, policy integration is needed, both geographically and across agencies that deal with air, water, soil, agriculture and commerce.

The mobility of reactive nitrogen through air, water and traded commodities (human food, animal feed, fertilizer) means that some of the impacts of excessive reactive nitrogen extend to regional levels, implying the need for collective responses that span different political jurisdictions. Hence, policy responses to excesses and deficiencies of reactive nitrogen may be required at many scales, from local to global. Where appropriate policy responses are local or regional in scope, exchange of information across regions should be encouraged to foster learning from successes and failures.

Efforts are needed to improve awareness, both among the general public and among policy makers, of the scope and pervasiveness of the growing environmental, human health and economic impacts of too much or too little reactive nitrogen.

Glossary

Acid deposition also known as acid rain. The process by which various acidic compounds, including nitrogen oxides, precipitate out of the atmosphere and onto surfaces.

Acidification the process of making soils and water bodies more acid through the inputs of acidifying chemicals, which include some forms of fertilizer and the sulfuric and nitric acids present in atmospheric deposition. This change in acidity can alter lake habitats and the growth of terrestrial vegetation.

Airshed the upwind source area of air-borne pollutants that influence the atmospheric deposition received in a defined geographical area.

Anoxia the absence of dissolved oxygen in a body of water.

Anthropogenic (the condition of being) caused by human activity.

Biological nitrogen fixation (BNF) the transformation of gaseous nitrogen into usable, or reactive, forms of nitrogen, by microbes often existing in a symbiotic relationship with leguminous plants.

Denitrification the transformation of reactive nitrogen back to inert gaseous nitrogen in the atmosphere, carried out primarily by bacteria in soils and water bodies.

Eutrophic the condition of being rich in nutrients, usually applied to aquatic ecosystems, but sometimes also applied to terrestrial ecosystems. An ecosystem may be eutrophic naturally if there is a natural source of mineral nutrients, or it may have become eutrophic through anthropogenic inputs of nutrients in a process called eutrophication. Aquatic ecosystems that are eutrophic usually have abundant algae and other growth that makes the water appear opaque.

Eutrophication the process of increasing nutrient inputs to a body of water from anthropogenic sources, resulting in overgrowth of organisms, particularly algae, and a subsequent depletion of oxygen, leading to hypoxic or anoxic conditions.

Greenhouse gases gases in the atmosphere that trap heat re-radiating from the earth's surface thus contribute to the warming of the earth. The main greenhouse gases are water vapour, carbon dioxide, methane, nitrous oxide, ozone and several chlorofluorocarbons. The chlorofluorocarbons are entirely anthropogenic, while the other gases originate from both natural and anthropogenic sources.

Hypoxia a deficiency of oxygen in a body of water, which may shift or limit the diversity of plants and animals that are able to survive under low oxygen status.

Methemoglobinemia commonly referred to as “blue-baby syndrome,” this condition has been found in babies whose formula was made with drinking water that contained high concentrations of nitrate. The nitrate is converted to nitrite in the digestive system, which then deprives the body of oxygen, causing a blue discoloration of the body. If unchecked, methemoglobinemia leads to digestive and respiratory failures.

Nitrogen cascade a sequence of effects when excessive reactive nitrogen, in its many forms, moves among the air, soils and water, accumulating a series of primarily negative environmental consequences for ecosystems and human health.

Nitrogen cycle the chemical path of molecular nitrogen, transformed through fixation into forms of reactive nitrogen, including that which supports the earth’s biota, and back to its molecular state through denitrification. The natural balance of the nitrogen cycle has been altered through human activity and the creation of artificial processes to produce more reactive nitrogen to support increased levels of agriculture.

Nitrogen fixation the process through which gaseous nitrogen is transformed into usable, or reactive, nitrogen through either natural or anthropogenic means.

N-nitroso-compounds (NOC) cancer-causing compounds that can be formed within the bodies of animals, including humans, following ingestion of nitrate in drinking water or in food.

Oligotrophic the condition of being poor in nutrients, usually applied to aquatic ecosystems but sometimes also applied to terrestrial ecosystems. Oligotrophic is the opposite of eutrophic. Oligotrophic aquatic ecosystems are usually pristine and are characterized by clear water.

Reactive nitrogen (Nr) includes all biologically, chemically, and radiatively active nitrogen compounds in the atmosphere and biosphere. It includes forms of nitrogen, such as ammonia (NH_3) and ammonium (NH_4^+), nitric oxide (NO), nitrogen dioxide (NO_2), nitric acid (HNO_3), nitrous oxide (N_2O), and nitrate (NO_3^-), and organic compounds such as urea, amines, proteins and nucleic acids.

Valorise (also called monetise) to establish and maintain the price of a service or a commodity that is not normally traded and priced in the marketplace.

Watershed the specific area of land that drains into a river or other defined body of water.

ANNEX A

Roster of policies and relevant institutions

African Fertilizer Summit: (June 2006)
http://www.africafertilizersummit.org/

Agreement on the Action Plan for the Environmentally Sound Management of the Common Zambezi River System, 1987
http://www.fao.org/docrep/W7414B/w7414b0j.htm

Agreement on the Cooperation for the Sustainable Development of the Mekong River Basin, 1995
http://www.mrcmekong.org/

ASEAN Agreement on Haze Pollution, 2002
http://www.aseansec.org/8914.htm

Caribbean Environment Program
http://www.cep.unep.org/

Chesapeake Bay Program
http://www.chesapeakebay.net/

Cartagena Convention, 1983
http://www.cep.unep.org/

Convention on Cooperation for the Protection and Sustainable Use of the Danube River, 1998
http://www.icpdr.org/icpdr-pages/drpc.htm

Convention on Long-Range Transboundary Air Pollution, 1979
http://www.unece.org/env/lrtap/
http://www.emep.int/

European Commission Water Framework Directive, 2000
http://www.defra.gov.uk/environment/water/wfd/index.htm

Framework Convention for the Protection of the Marine Environment of the Caspian Sea, 2003
http://www.caspianenvironment.org/newsite/index.htm

Global Programme of Action for the Protection of the Marine Environment, est. 1995
http://www.gpa.unep.org

Helsinki Commission (Commission on Security and Cooperation in Europe)
http://www.helcom.fi (includes figures on nitrogen and
other nutrient inputs into the Baltic Sea)

International Nitrogen Initiative
http://www.initrogen.org/

Fourth International Nitrogen Conference (Bahia, Brazil, 1-5 October, 2007):
http://www.nitrogen2007.com

Johannesburg Declaration on Sustainable Development, 2002
http://www.un.org/esa/sustdev/documents/WSSD_POI_PD/English/POI_PD.htm

Millennium Development Goals, 2000
http://www.un.org/millenniumgoals/

Nanjing Declaration, 2004
http://www.initrogen.org/nanjing_declaration.0.html

Nile Basin Initiative, launched in 1999
http://www.nilebasin.org/

Protocol on Shared Watercourse Systems in the Southern African Development Community (SADC) Region, 1995
http://www.waterpolicy.com/SADCprotocol.PDF

Regional Seas Programme (UNEP)
http://www.unep.org/regionalseas/

Treaty for Amazonian Cooperation, 1978
http://www.otca.org.br/

United Nations Environment Programme
http://www.unep.org

Woods Hole Research Center, Massachusetts, USA
http://www.whrc.org/policy/global_nitrogen.htm

ANNEX B

References and further reading

Cassman K.G., Dobermann A.D. and Walters D. 2002. "Agroecosystems, nitrogen management and economics." *Ambio* 31: 132-140.

Chao, A. , Thun, M. J., Connell, C. J., McCullough, M. L., Jacobs, E. J., Flanders, W. D., Rodriquez, C., Sinha, R. and Calle, E. E. "Meat Consumption and Risk of Colorectal Cancer." *Journal of the American Medical Association*. January 12, 2005; 293: 172 - 182.

Diaz, R.J., Nestlerode, J. and Diaz, M.L.. 2004. "A global perspective on the effects of eutrophication and hypoxia on aquatic biota." *Proceedings of the 7th International Symposium on Fish Physiology, Toxicology, and Water Quality, Tallinn, Estonia*. May 12-15, 2003. G.L Rupp and M.D. White (eds). U.S. Environmental Protection Agency, Ecosystems Research Division, Athens, Georgia, USA. EPA 600/R-04/049, pp 1-33.

Driscoll, C.T. and Lambert, K.F. 2003. "Nitrogen Pollution: from the Sources to the Sea." Hubbard Brook Research Foundation. Science Links Publication. Vol. 1, no. 2.

Filoso S., Martinelli L.A., Howard R.W., Boyer E.W., Denetener, F. 2006. "Human activities changing the nitrogen cycle in Brazil." *Biogeochemistry* 79: 61-89.

Food and Agriculture Organization. "Integrated Nutrient Management: A Glossary of Terms." Jointly published by the Food and Agriculture Organization of the United Nations, Rome and Fertiliser Development and Consultation Organization, New Delhi, 2004.

Galloway, J. "The Global Nitrogen Cycle: How Is It Changing?" *Global Change Newsletter*. 64: December 2005.

Galloway, J. N., Aber, J.D., Erisman, J.W., Seitzinger, S.P., Howarth, R.W., Cowling, E.B. and Cosby, B.J.. 2003. "The nitrogen cascade." *BioScience* 53:341-356.

Galloway, J., Dentener, F.J., Capone, D.G., Boyer, E.W., Howarth, R.W., Seitzinger, S.P., Aser, G.P., Cleveland, C., Green, P., Holland, E., Karl, D.M., Michaels, A.F., Porter, J.H. Townsend, A. and Vorosmarty, C. 2004. "Nitrogen cycles: past, present and future." *Biogeochemistry*. 70: 153-156.

J. Galloway, F. Dentener, M. Burke, E. Dumont, L. Bouwman, R. Kohn, H. Mooney, S. Seitzinger and C. Kroeze. "*The impact of animal production systems on the nitrogen cycle*." Livestock in a Changing Landscape, Integrated Analysis and Global Consultation, *in review*.

GEO Yearbook 2003. 2004. United Nations Environment Programme. Earthscan Publications Ltd., London.

Ginsburg, E.O. and Cowling E.B. 2003. "Future directions in air-quality science, policy, and education." *Environment International*: 29: 125-135.

Howarth, R. and Ramakrishna, K. 2005. “Nutrient Management.” pp. 295-311. *Ecosystems and Human Well-Being: Policy Responses*. Millennium Assessment, Island Press, Washington, DC.

IFA Task Force on Reactive Nitrogen . January 2007. *Sustainable Management of the Nitrogen Cycle in Agriculture and Mitigation of Reactive Nitrogen Side Effects*. IFA, Paris.

L’hirondel, J. L., Avery, A. A. and Addiscott, T. August 2006. “Dietary Nitrate: Where Is the Risk?” *Environmental Health Perspectives*. 114: 458-459.

Martinelli L.A., Howarth R. W., Cuevas, E., Filoso, S., Austin, A., Donoso, L., Huszar, V., Keeney, D., Lara, L. L., Llerena, C., McIssac, G., Medina, E., Ortiz-Zayas, J., Scavia, D., Schinlder, D. W., Sota, D. and Townsend, A. 2006. “Sources of reactive nitrogen affecting ecosystems in Latin America and the Caribbean: current trends and future perspectives.” *Biogeochemistry* 79: 3-24.

Matson, P.A., Lohse, K. and Hall, S. 2002. “The globalization of nitrogen deposition: consequences for terrestrial ecosystems.” *Ambio*. 31(2): 113-119.

Moomaw, W.R. and Birch, M.B.L. 2005. “Cascading costs: An economic nitrogen cycle.” *Science in China*, Ser. C Life Sciences, Vol. 48: 678-696.

Mosier, A.R., Syers, J.K. and Freney, J.R., editors. 2004. *Agriculture and the nitrogen cycle: assessing the impacts of fertilizer use on food production and the environment*. SCOPE. Vol. 65, Island Press, Washington, DC.

National Research Council Ad Hoc Committee on Air Emissions from Animal Feeding Operations, Committee on Animal Nutrition. 2003. *Air Emissions from Animal Feeding Operations*. National Academy Press, Washington DC.

National Research Council Committee on the Causes and Management of Eutrophication, Ocean Studies Board, Water Science and Technology Board. 2000. *Clean Coastal Waters: Understanding and Reducing the Effects of Nutrient Pollution*. National Academy Press, Washington, DC.

National Research Council Subcommittee on Swine Nutrition, Committee on Animal Nutrition.1988. *Nutrient Requirements of Swine*. 9th Revised Edition, National Academy Press, Washington, DC.

Pagiola, S., von Ritter, K. and Bishop, J. 2004. “Assessing the Economic Value of Ecosystem Conservation.” *The World Bank: Environment Department*: Paper 101.

Poulton, C., Kydd, Jonathan and Dorward, Andrew. 2006. “Increasing Fertilizer Use in Africa: What Have We Learned?” *The World Bank: Agriculture and Rural Development* Paper 25.

Prather, M., Ehhalt, D., Dentener, F., Derwent, R., Dlugokencky, E. Holland, E., Isaksen, I, Katima,J., Kirchhoff, P., Matson, P., Midgley, P. and Wang, M. 2001. “Atmospheric Chemistry and Greenhouse Gases.” pp. 240-287 In J. T.Houghton, Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell, and C. A. Johnson, editors. *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, United Kingdom and New York, NY.

Rabalais, N.N. 2002. "Nitrogen in aquatic ecosystems." *Ambio* 31:102-112.

Reid, W.V. 2000. "Ecosystem Data to Guide Hard Choices." *Issues in Science and Technology*: 37-44.

Smil, V. 1999. "Nitrogen in crop production: an account of global flows." *Global Biogeochemistry Cycles* 13: 647-662.

Smil, V. 2000. *Feeding the World: A Challenge for the Twenty-first Century*. MIT Press, Cambridge, MA.

Smil, V. 2001. *Enriching the Earth*. MIT Press, Cambridge, MA.

Tandon, H.L.S. and Roy, R.N. 2004. "Integrated Nutrient Management-A Glossary of Terms." United Nations Food and Agriculture Organization.
http://www.fao.org/ag/agl/agll/ipns/index_en.jsp

Townsend A.R., Howarth, R.W., Bazzaz, F.A., Booth, M.S., Cleveland, C.C., Collinge, S.K., Dobson, A.P., Epstein, P.R., Holland, E.A., Keeney, D.R., Mallin, M.A., Rogers, C.A., Wayne, P. and Wolfe, A. 2003. "Human health effect of a changing global nitrogen cycle." *Frontiers in Ecology and the Environment*. 1:240-246.

UNESCO & SCOPE. 2007. *Human Alteration of the Nitrogen Cycle: Threats, Benefits and Opportunities*. April 2007 – No. 4. UNESCO-SCOPE, Paris.

United States Department of Commerce, International Trade Administration. 2005. Water Supply and Wastewater Treatment Market in China.
http://www.ita.doc.gov/media/Publications/blurbs/chinawater2005_blurb.html

Ward M.H., de Kok T.M., Levallois P., Bender J., Gulis G., Nolan B.T. and VanDerslice J. August 2006. "Dietary Nitrate: Ward et al. Respond" *Environmental Health Perspectives*. 114: 459-461.

Ward M.H., de Kok T.M., Levallois P., Bender J., Gulis G., Nolan B.T. and VanDerslice J. 2005. "Workgroup Report: Drinking-Water Nitrate and Health – Recent Findings and Research Needs." *Environmental Health Perspectives*: 113: 1607-1614.

Woiwode, N. 2006. "Managing the Nitrogen Cascade: Analysis of the International Management of Reactive Nitrogen." Masters Thesis, Nicholas School of the Environment, Duke University, Durham, NC, USA.

Wu C., Maurer C., Wang Y., Zue S. and Davis D.L. 1999. "Water Pollution and Human Health in China." *Environmental Health Perspectives*: 107(4): 251-256.

Zheng X., Fu C, Xu X, Yan X, Huang Y, Han S, Hu F and Chen G. 2002. "The Asian Nitrogen Cycle Case Study." *Ambio* 31:79-87.

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This review examines the impacts of reactive nitrogen on the environment, human health and economies from local to global scales. About 40% of the human population depends upon food production made possible by synthetic nitrogen fertilizers. Combustion of fossil fuels adds more reactive nitrogen to air, water and soil. This distortion of the global nitrogen cycle, while raising agricultural yields, causes degradation of water and air quality, biodiversity, ecosystem services and human health. Meanwhile, reactive nitrogen deficiencies on farmland in many developing countries continue to create economic and health hardships, and accelerate land degradation.

This review is intended to assist all stakeholders in understanding and assessing these challenges, and sets out the sources and impacts of reactive nitrogen and current trends in use and emissions. Case studies show the need to integrate scientific understanding and strengthen existing policies addressing the various impacts of reactive nitrogen. Recommendations are made on the assessment, monitoring, information sharing and collaboration required at different geographical scales, and across disciplines and jurisdictions, to develop and implement coherent and effective policies to address nitrogen excess and deficiency.

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