

NITROGEN POLLUTION:



Sources and Consequences in the U.S. Northeast

by Charles Driscoll, David Whitall, John Aber, Elizabeth Boyer, Mark Castro, Christopher Cronan, Christine Goodale, Peter Groffman, Charles Hopkinson, Kathleen Lambert, Gregory Lawrence, and Scott Ollinger

Nitrogen pollution is a growing environmental problem in the northeastern United States. Nitrogen constitutes 78 percent of the Earth's atmosphere in the form of N_2 and is an essential nutrient used by all living things. However, N_2 is an "unreactive" form of nitrogen that plants and animals cannot access directly. For organisms to draw on this nitrogen to support their growth, the nitrogen must be "fixed"—that is, converted from the unreactive N_2 form to a reactive form such as nitrate (NO_3^-) or ammonium (NH_4^+). In an environment absent of human influence, this conversion occurs only through fixation by plant- and soil-associated bacteria and lightning strikes. Thus, under pristine conditions, there is usually not enough nitrogen to go around. Over the past 100 years, however, these conditions have changed. The Earth's growing human population has increased demand for food and energy worldwide. Meeting these demands has doubled the global rate at which reactive nitrogen is produced, greatly increasing the amount of reactive nitrogen in the environment.¹ The primary processes developed in the past century that convert unreactive nitrogen to reactive nitrogen are the manufacture of fertilizer, the combustion of fossil fuels, and the planting of nitrogen-harnessing croplands.



Bacteria living on the roots of leguminous crops such as soybeans, alfalfa, and peanuts convert unreactive nitrogen into reactive forms in a process called "nitrogen fixation."

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Excess reactive nitrogen in the environment can lead to pollution problems, including the deterioration of air quality, disruption of forest processes, acidification of lakes and streams, and degradation of coastal waters. While the global increase in reactive nitrogen from human activities supports higher crop yields and greater energy production, it also sets off a series of adverse environmental changes

known as a "nitrogen cascade."² Given the combination of beneficial and harmful effects, nitrogen pollution in the environment is often referred to as "too much of a good thing."

A group of scientists convened by the Hubbard Brook Research Foundation examined the sources and consequences of nitrogen pollution in the northeastern United States (see the box on page 10). The Northeast provides an interesting case

study in nitrogen pollution because this region

- has experienced steady population growth, which tends to increase reactive nitrogen in the environment (see Figure 1 on page 10);
- has undergone significant land-use change since farm abandonment in the late 1800s, which influences nitrogen retention and loss (see Figure 1);

The Hubbard Brook Research Foundation

In 1963, Gene E. Likens, F. Herbert Bormann, and Noyes M. Johnson joined Robert S. Pierce of the U.S. Forest Service to launch the Hubbard Brook Ecosystem Study (HBES). Their research focused on the movement of water, energy, and nutrients through small watersheds within the Hubbard Brook Experimental Forest in New Hampshire. Over the past four decades, this research has generated many important insights into the structure and function of ecosystems; notable among them is the documentation of acid rain in North America in 1972. In recent years, the long-term data from the HBES has been used to evaluate the effectiveness of pollution controls.

In 1993, the Hubbard Brook Research Foundation was formed to promote the exchange of data and information between scientists and policy makers. To facilitate this sharing process, the

Foundation created a new program called Science Links™. The program aims to synthesize, translate, and disseminate research from the HBES and other projects to inform public policy decisions. The first Science Links™ project addressed acid rain. This second initiative brings together the research and policy issues regarding nitrogen pollution. The nitrogen Science Links™ project was a 2-year effort by 12 leading scientists resulting in several major publications including, "Nitrogen Pollution: From the Sources to the Sea." These publications were accompanied by a series of policy and media briefings.

The work of Science Links™ and the Hubbard Brook Research Foundation is one of many emerging efforts to bridge the gap between ecosystem science and environmental policy. To learn more, visit the Hubbard Brook web site at www.hubbardbrook.org.

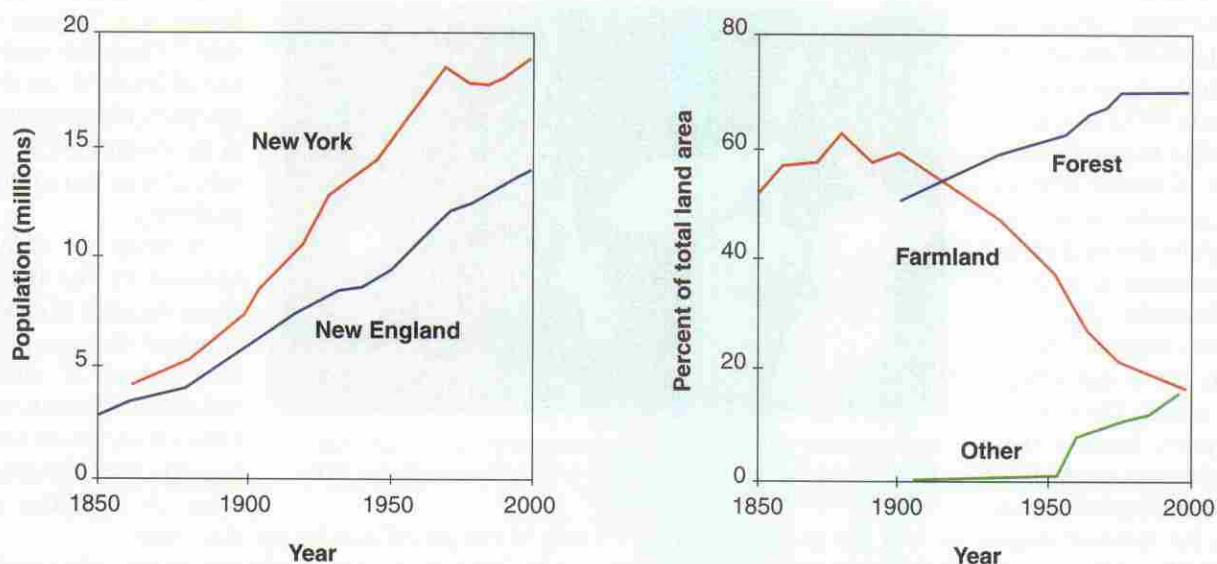
- receives large amounts of reactive nitrogen to the air, land, and water; and
- encompasses a diverse landscape ranging from sparsely populated and acid-sensitive forests with few sources of nitrogen to densely populated urban areas with multiple sources of nitrogen (see Figure 2 on page 11).

To address the issue of nitrogen pollution in the Northeast, it is important to answer three major questions: What are the anthropogenic sources of reactive nitrogen? What are the ecological effects of nitrogen pollution? And to what extent will policy options reduce nitrogen pollution and mitigate its effects?

Sources of Reactive Nitrogen in the Northeast

To determine the sources of reactive nitrogen that cause nitrogen pollution, the Hubbard Brook team analyzed eight large watersheds in the Northeast. The results show that food (most of which is

Figure 1. Northeast population and land-use trends



SOURCE: Compiled from U.S. Bureau of Census and U.S. Department of Agriculture data. Figure is adapted with permission from C. T. Driscoll et al., "Nitrogen Pollution in the Northeastern United States: Sources, Effects, and Management Options," *BioScience* 54, no. 4 (2003): 358.

imported from outside the region) accounts for the largest amount of reactive nitrogen in the region (38–75 percent).³ Airborne emissions of nitrogen oxides (NO_x) and ammonia (NH_3)—and the subsequent deposition of nitrate (NO_3) and ammonium (NH_4)—contribute 11–36 percent.⁴ Nitrogen fertilizer applied to crops, pastures, and lawns adds another 11–32 percent.⁵ Other sources of reactive nitrogen that contribute to pollution include increased production of crops that host nitrogen-fixing bacteria and nitrogen in animal feed. Together, these two sources constitute 2–16 percent of the reactive nitrogen in northeastern watersheds (see Figure 3 on page 12).⁶

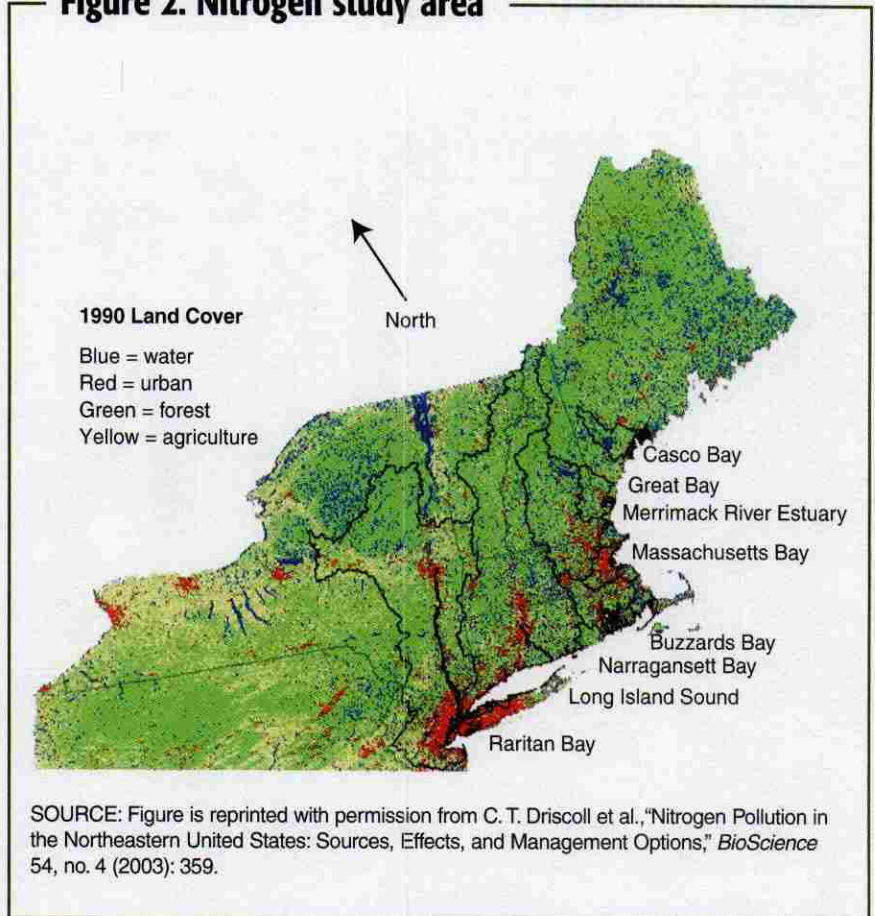
This analysis shows a wide range in the rate that reactive nitrogen is added to the watersheds. The values range from a low of 14 kilograms of nitrogen per hectare per year (kg N/ha-yr), which is equivalent to 12.5 lbs N/acre-yr, in the Saco River watershed that drains to Casco Bay, Maine, to a high of 68 kg N/ha-yr (61 lbs N/acre-yr) in the Massachusetts Bay watershed. This range in reactive nitrogen inputs results from differences in population density and land use.⁷

On a landscape scale it is also clear from this analysis that sources of reactive nitrogen vary significantly in forested headwaters compared to densely populated coastal zones. For example, in the relatively remote and unpopulated forested watersheds of the Hubbard Brook Experimental Forest in New Hampshire, nearly 100 percent of new reactive nitrogen originates from emissions by vehicles, electric utilities, and agricultural activities.⁸ By contrast, food dominates the sources of reactive nitrogen in the populated coastal zone.

Nitrogen in Food

Based on U.S. Census and Department of Agriculture statistics, nitrogen in food is the largest source of reactive nitrogen in nearly all of the eight Northeast watersheds examined. Because the Northeast has a high population and relatively low

Figure 2. Nitrogen study area



food production, imported food represents a major input of reactive nitrogen.

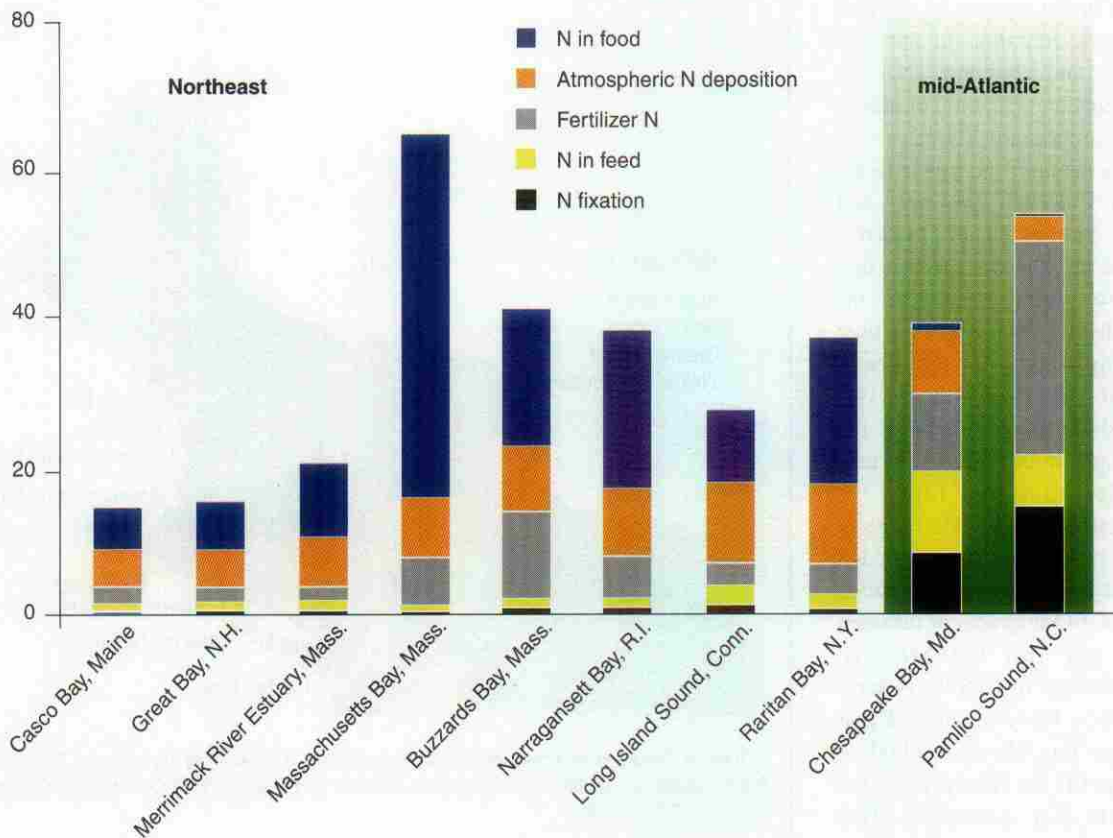
The consumption of protein, and the associated consumption of nitrogen, has been tracked by the U.S. Department of Agriculture since 1909. (There are 6.25 grams of nitrogen per gram of protein.) With the increase in population and per capita consumption of nitrogen, the total amount of nitrogen consumed in New England and New York has risen steadily since the early 1900s. The average human body needs roughly 2.0 grams of nitrogen per day to support basic metabolic functions.⁹ The typical American diet supplies approximately 13 grams of nitrogen per day.¹⁰

Food generates reactive nitrogen in the environment as a byproduct of both food production and food consumption. Food production leaves a legacy of reactive nitrogen in the regions where it is produced. It is estimated that 10

times the amount of nitrogen is used during the food production process than is ultimately consumed by humans as protein.¹¹ Much of this additional nitrogen is applied as fertilizer that can run off into groundwater, rivers, and coastal waters. Moreover, the production of animal protein by raising livestock adds substantial quantities of reactive nitrogen to the environment in the form of nitrogen-rich manure that can decrease water quality in agricultural areas.

Once food is consumed, it can contribute to pollution through the production and discharge of sewage. Humans do not use all of the nitrogen contained in food. The remaining nitrogen is lost as waste to septic systems or wastewater treatment plants. While the technology exists to remove reactive nitrogen from wastewater, investments in these upgrades have not been made at most

Figure 3. Nitrogen sources in 10 large watersheds



NOTE: The major sources of reactive nitrogen in northeastern watersheds differ significantly from sources in other regions. In the Chesapeake Bay and Pamlico Sound watersheds, nitrogen fixation in croplands is the largest source, reflecting their heavy agricultural land use, in contrast to the more urbanized land-use pattern in the Northeast.

SOURCE: Figure is reprinted with permission from C. T. Driscoll et al., "Nitrogen Pollution in the Northeastern United States: Sources, Effects, and Management Options," *BioScience* 54, no. 4 (2003): 362.

treatment plants (see the box on page 13). Because most septic systems and treatment plants do not effectively remove nitrogen from the waste, reactive nitrogen is eventually discharged into rivers and coastal waters where it contributes to water quality problems.

Deposition of Nitrogen

Nitrogen oxides and ammonia, the most prevalent nitrogen emissions in the Northeast, can be transported long distances and eventually deposited on land and water surfaces as nitrate and ammonium in precipitation (rain, snow, sleet, hail) or as gases and particles. This process is known as "nitrogen deposition."

Nitrogen deposition patterns in the Northeast are related to three factors: dis-

tance from large emission sources, latitude, and elevation. The western Adirondack Mountains of New York, for instance, experience the highest deposition rates in the region at 12 kg N/ha-yr (11 lbs N/acre-yr), reflecting their relatively close proximity to midwestern sources, the largest emitters affecting the Northeast.¹²

Using the airshed for the Long Island Sound watershed as an example, the largest sources of nitrogen emissions are transportation NO_x from passenger cars, diesel trucks, and recreation vehicles (39 percent); electric utility NO_x , especially from coal-fired plants (26 percent); and ammonia emitted from animal waste (16 percent).¹³

Long-term data from the Hubbard Brook Ecosystem Study show that the

concentration of nitrogen in precipitation has been relatively constant since measurements began there in the early 1960s, with nitrate levels around 25 microequivalents per liter and ammonium levels around 10 microequivalents per liter.¹⁴ These relatively high deposition levels persist in part because the 1990 Amendments to the Clean Air Act (CAAs) did not substantially limit nitrogen emissions.

Nitrogen in Fertilizer

Nitrogen fertilizer is used throughout the region to increase crop yields and improve lawn and turf conditions. Based on fertilizer sales data, nitrogen fertilizer is the second- or third-largest source of reactive nitrogen in each of the eight

Northeast watersheds analyzed. Of land in the Northeast likely to be fertilized, 60 percent is pasture and hay, 34 percent is row crops, 5 percent is urban recreational grasses, and 1 percent is "other." The watershed with the highest annual input of nitrogen from fertilizer per land area is the Hudson River watershed in New York. The lowest levels are found in the Great Bay watershed in New Hampshire. The sale of nitrogen fertilizer in the region increased approximately 30 percent between 1965 and 2001.¹⁵ The use of nitrogen fertilizer on residential lawns is a growing component of fertilizer use in the United States.

There is a wide range in fertilizer application rates across the region. However, more nitrogen is generally applied to the land than can be assimilated by the vegetation. Some scientists estimate that approximately 20 percent of the nitrogen in fertilizer leaches to surface or groundwater, with extreme levels reaching as high as 80 percent for row crops in sandy soils.¹⁶

Nitrogen in Animal Feed

Animal feed in the form of corn silage, oats, and hay is imported to the Northeast to feed cows, pigs, chickens, and other livestock. The watershed with the largest amount of nitrogen in animal feed per hectare is the Connecticut River watershed due to relatively high levels of livestock production.¹⁷ Nitrogen in animal feed can become a pollution source through the excretion of nitrogen-rich manure that releases gaseous ammonia into the atmosphere and leaches nitrate into local water bodies. Nitrogen in animal feed is of greatest concern on farms where intensive livestock production results in more nitrogen-rich manure than the farmer can effectively use as fertilizer and where adequate containment or treatment facilities do not exist to minimize leaching to adjacent surface waters.

Nitrogen Fixation in Croplands

Nitrogen fixation is the process by which bacteria living in association with leguminous crops such as soy-

beans, peanuts, and alfalfa, or living freely in the soil, convert unreactive forms of nitrogen (such as N_2) into reactive forms available for plant growth. The increased cultivation of crops with nitrogen-fixing bacteria adds to the total amount of reactive nitrogen in a watershed. In the Northeast, nitrogen fixation is primarily associated with increased alfalfa production for livestock feed.¹⁸ Watershed inputs of reactive nitrogen associated with nitrogen fixation in croplands is low, with the highest percentage occurring in the Hudson River watershed.

Ecological Effects of Nitrogen Pollution in the Northeast

This article examines four of the major environmental effects of nitrogen pollution in the Northeast: ground-level ozone, acid rain, forest effects, and coastal overenrichment. Nitrogen also contributes to other issues that are not considered here, such as groundwater contamination, regional haze, airborne particles, and global climate change.

Ground-Level Ozone

Ground-level ozone is formed when nitrogen oxides and volatile organic compounds (from the vapors of paint, gasoline and solvents, and natural emissions from plants) combine in the presence of high temperatures and sunlight to form ozone (O_3). In the Northeast, the generation of ground-level ozone is controlled largely by nitrogen oxide emissions. High concentrations of ground-level ozone can have adverse effects on both human health and the environment (see the box on page 14).

On warm summer days, ground-level ozone concentrations in the Northeast often exceed the U.S. Environmental Protection Agency (EPA) National Ambient Air Quality Standard for human health. The current ozone standard is 0.08 parts per million averaged over an eight-hour period. Approximately 26 million people live in areas of the Northeast where the ozone standard was exceeded up to 90 days each year from 1983 to the present.¹⁹

Ground-level ozone also presents a significant health risk for trees and other veg-

Nitrogen Removal from Sewage Treatment Plants

Many different systems and technologies exist to remove nitrogen from wastewater. Most nitrogen removal technologies use naturally occurring bacteria to convert the organic nitrogen in the waste to inert nitrogen gas (N_2) through a process known as biological nitrogen removal (BNR). When the process is complete, the nitrogen gas is converted to the unreactive form N_2 and returned to the atmosphere where it is no longer a risk to surface waters.

BNR is a three-step process. First, nitrogen is converted to ammonium under oxygen-rich conditions. This level of waste treatment is typically referred to as "secondary treatment." Through further aeration, the nitrogen is converted to nitrate in a process known as "nitrification." In the final step, the wastewater is exposed to oxygen-poor conditions where bacteria convert the nitrate to inert nitrogen gas

through "denitrification." At this point, nitrogen removal from the wastewater is complete.

Connecticut and New York have undertaken a comprehensive effort to upgrade wastewater treatment plants with biological nitrogen removal technology to reduce the total loading of nitrogen to Long Island Sound by 58.5 percent. To achieve this goal, four large wastewater treatment plants in New York City have been retrofitted with BNR technology, decreasing their baseline nitrogen loads to western Long Island Sound by 20 percent. New York City has also begun a multibillion-dollar program to rebuild the four facilities with full BNR capability by 2014. Connecticut municipalities have retrofitted or reconstructed 30 treatment plants with BNR to reduce their nitrogen loading to Long Island Sound by 35 percent—nearly meeting permit limits set for 2005.

etation in the Northeast. The two major categories of plant effects are injury to leaves and needles and physiological changes. Ozone comes into contact with plants through "stomatal conductance," or

the uptake of ozone through small pores on a leaf or stem (stomates). Ozone uptake by plants is greatest during the growing season of May–October, when the plants are growing most vigorously.

Visual symptoms of ozone stress include damage to parts of the leaf or needle, known as foliar stippling or necrotic spotting, and premature loss of foliage. Physiological changes can also occur to the plant without visible signs of injury. The most pronounced physiological effect is the reduction in the ability of the plant to convert sunlight to energy that is needed to fuel plant growth. The net effect of this change is a decrease in biomass production, or growth.

Health Effects of Atmospheric Nitrogen Emissions

by JONATHAN LEVY

Ground-level ozone, particulate matter, and nitrogen dioxide resulting from anthropogenic inputs of reactive nitrogen can lead to respiratory and cardiovascular health effects.

Nitrogen oxide emissions can contribute to the formation of secondary compounds, including ground-level ozone. Ozone reacts with molecules in the lining of the lung, contributing to adverse respiratory outcomes.¹ In epidemiological studies, short-term ozone exposure has been associated with decreased lung function, respiratory hospital admissions, and premature death. Although it is difficult to separate the effects of ozone from weather (more ozone forms on hot and humid days) and other air pollutants, studies that carefully account for these factors have documented a significant independent effect of ozone.² Along with the effects of short-term, high-intensity ozone exposure, there is also some evidence that long-term exposure to ozone can result in increased asthma development among children who exercise outdoors in high ozone areas³ and in chronic decreases in lung function.⁴

Nitrogen oxide emissions also contribute to the formation of fine particulate matter—particulate matter smaller than 2.5 microns in diameter (PM_{2.5}). Nitrogen oxides can be oxidized to form nitric acid, which can react with ambient ammonia to form ammonium nitrate particles. While there has been relatively little direct evidence to date regarding health effects of individual particulate matter constituents, PM_{2.5} as a whole has been linked with numerous respiratory and cardiovascular outcomes. For example, a study of approximately 500,000 individuals across the United States found that long-term exposure to fine particulate matter was associated with an increased risk of premature death, principally due to respiratory or car-

diovascular disease.⁵ Short-term exposure to PM_{2.5} has been associated with premature death as well as respiratory or cardiovascular hospitalizations, respiratory symptoms, and other morbidity outcomes.

Finally, nitrogen dioxide (NO₂) itself has been associated with adverse respiratory outcomes, in part because it has similar oxidative properties as ozone. Extremely high levels of NO₂, more typically found in indoor environments with combustion sources, have led to symptoms such as cough or shortness of breath. In homes with gas stoves and associated elevated levels of nitrogen dioxide over longer periods, there is an increased risk of respiratory illness in children.⁶

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2. J. I. Levy et al., "Assessing the Public Health Benefits of Reduced Ozone Concentrations," *Environmental Health Perspectives* 109 (2001): 1215–26.

3. R. McConnell et al., "Asthma in Exercising Children Exposed to Ozone: A Cohort Study," *Lancet* 359 (2002): 386–91.

4. N. Kunzli et al., "Association between Lifetime Ambient Ozone Exposure and Pulmonary Function in College Freshmen—Results of a Pilot Study," *Environmental Research* 72 (1997): 8–23.

5. C. A. Pope et al., "Lung Cancer, Cardiopulmonary Mortality, and Long-Term Exposure to Fine Particulate Air Pollution," *Journal of the American Medical Association* 287 (2002): 1132–41.

6. V. Hasselblad, D. J. Kotchmar, and D. M. Eddy, "Synthesis of Epidemiological Evidence: Nitrogen Dioxide Epidemiology Studies," *Journal of Air and Waste Management Association* 42 (1992): 662–71.

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Acid Rain

Rainfall is acidic in much of the Northeast. The average pH of rain and snowfall at the Hubbard Brook Experimental Forest in New Hampshire is 4.5, 10–15 times more acidic than unpolluted rainwater.²⁰ Recent surveys show that approximately 41 percent of lakes in the Adirondacks of New York and 15 percent in New England are chronically or periodically too acidic to support fish and other aquatic life.²¹

Nitrogen in the form of nitric acid is one of the two major constituents of acid rain (the other is sulfuric acid). As regulatory controls on sulfur dioxide emissions have decreased the amount of sulfate in rain and snow, nitrate has become an increasingly important contributor to acid rain. Moreover, nitrate is the major driver in seasonal and "episodic" acidification that results in short-term increases in the acidity of surface waters. These episodes typically occur in the spring, fall, and winter when trees and other vegetation are not actively growing and are therefore using less nitrogen.

The effects of acid rain are well documented and are described in detail in the Science Links™ report *Acid Rain Revisited*.²² To summarize, acid rain can cause fundamental changes in soils, forests, and streams. For example, acid rain has acidified soils through the leaching of nutrients such as calcium and magnesium that are important to tree growth and help buffer soils and waters against acid inputs. At the Hubbard Brook Experimental Forest, it is estimated that more than 50 percent of

the available calcium in the soil has been depleted over the past 60 years due to acid rain.²³

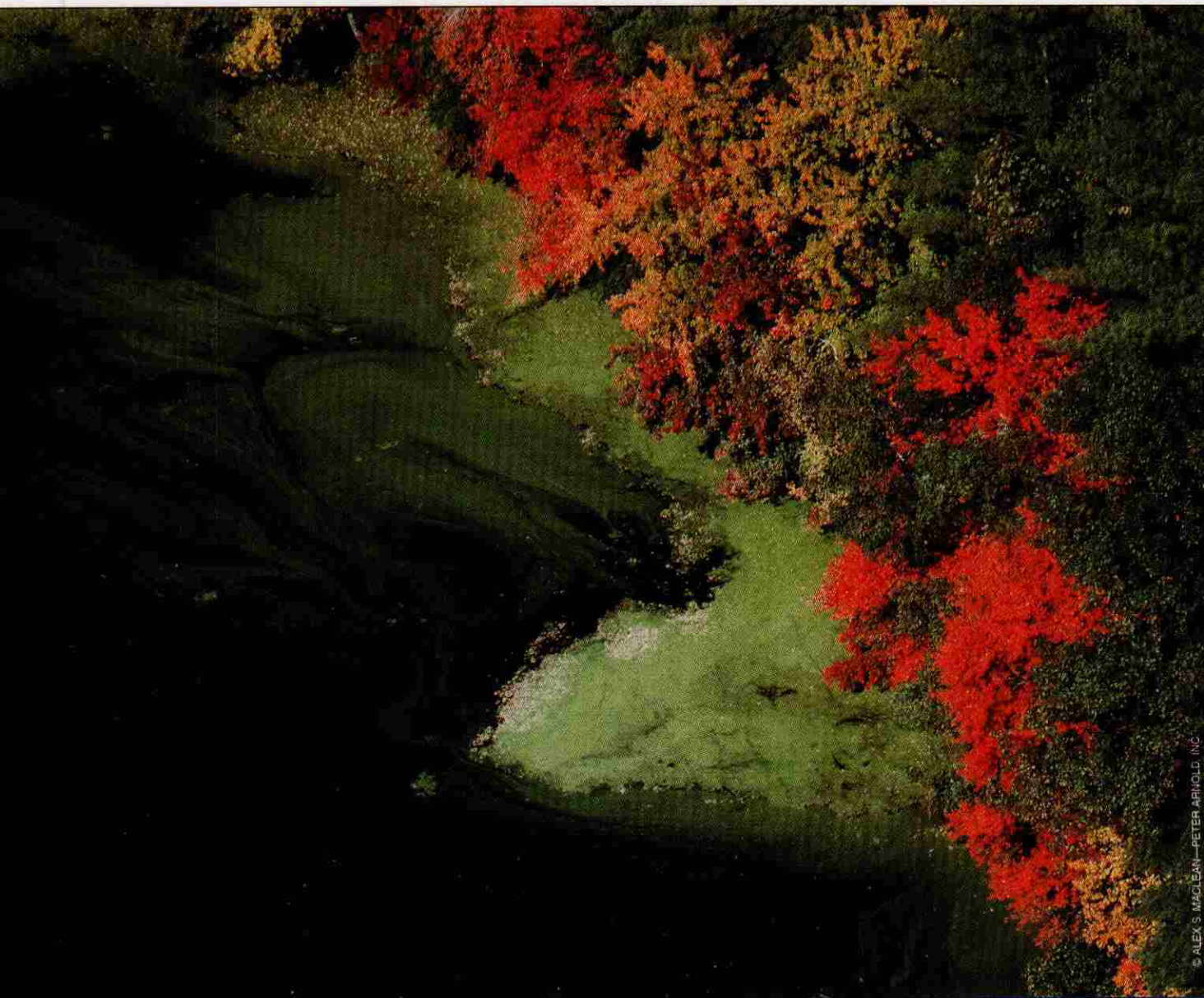
In acid-sensitive watersheds with small quantities of available calcium and magnesium in the soil, acid rain causes inorganic forms of aluminum to leach from the soil into streams. Inorganic aluminum is highly toxic to fish and other aquatic organisms, even at very low concentrations. Aluminum contributes to higher levels of fish mortality during acid episodes than

acidity does alone. Even brook trout, a relatively acid-tolerant species, cannot withstand inorganic aluminum concentrations above 3.7 micromoles per liter (100 micrograms of aluminum per liter).²⁴ This increase in aluminum can occur even in acid-sensitive watersheds where the forest retains much of the nitrogen that is deposited from the atmosphere. For example, in a Catskill, New York, watershed that retains up to 80 percent of the atmospheric deposition of nitrogen, fish popula-

tions still cannot survive due to high levels of aluminum.

Forest Effects

Research to date has shown that acid rain can affect forest health in two ways: direct impacts on foliage and reduced stress tolerance associated with soil changes. The direct impacts on foliage include the loss of important "membrane-associated" calcium from tree species like red spruce that can reduce cold tolerance and induce freezing of



Overabundance of nutrients promotes the excessive growth of algae. Decomposing algae in such quantities consume oxygen at the water's bottom, creating hypoxia, which can cause fish and shellfish to suffocate.

foliage at high elevations.²⁵ This has led to the dieback of 25–50 percent of the large canopy red spruce in the White Mountains of New Hampshire, the Green Mountains of Vermont, and the Adirondacks of New York.²⁶ The reduction in stress tolerance associated with acid rain is linked to a loss of the available calcium and magnesium in the soil that tends to make several hardwood species more susceptible to insect infestation, disease, or drought.²⁷ Signs of stress connected to acid rain have been documented in sugar maple stands on sensitive soils across the region.

In addition to acid rain effects on the forest, high levels of nitrogen deposition may change forest processes in other ways. Research from Europe and the United States has identified a process known as “nitrogen saturation” that can result from high levels of nitrogen deposition.²⁸ Nitrogen saturation occurs when nitrogen deposition exceeds the ability of the forest to retain all of the nitrogen it receives and in its later stages leads to decreased tree productivity.

Changes in forest growth due to nitrogen deposition are wide-ranging and difficult to predict. While some forests may experience increased growth in response to low levels of nitrogen deposition, other forests respond little or not at all. Research from the Harvard Forest in Petersham, Massachusetts, shows that long-term exposure to very high levels of nitrogen deposition can inhibit growth in pine.²⁹

Regionally, research indicates that forests in the Northeast currently retain

80–99 percent of the nitrogen from nitrogen deposition. However, even with high retention, forestlands show elevated levels of nitrate leaching into streams under conditions of chronic nitrogen loading. A recent study of 350 lakes and streams in the Northeast shows that spatial patterns



Nitrogen emissions from midwestern sources land in the Adirondacks in the form of nitrate and ammonium in rain, snow, sleet, and hail.

of nitrate in streamwater are related to rates of nitrogen deposition. At deposition levels above approximately 7–10 kg N/ha-yr (6–9 lbs N/acre-yr), stream nitrate concentrations increase with increasing deposition.³⁰

An analysis of forestland in the region shows that approximately 36 percent of

Northeastern forests receive 8 kg N/ha-yr (7 lbs N/acre-yr) or more and may be susceptible to elevated nitrate leaching, an early indicator of nitrogen saturation.³¹

Coastal Overenrichment

To understand the coastal effects of nitrogen pollution in the Northeast, it is necessary to consider the fate of the reactive nitrogen that has been added to the region's watersheds. Once reactive nitrogen enters a watershed in food, atmospheric deposition, or fertilizer, some of it is retained within the landscape, some of it returns to the atmosphere, and approximately 22 percent flows downstream to coastal estuaries.³² Nitrogen loading to the estuaries downstream of the eight watersheds analyzed in this study is dominated by wastewater effluent (36–81 percent) and atmospheric deposition of nitrogen (14–35 percent) (see Figure 4 on page 17).³³

Reactive nitrogen loading from wastewater treatment plants in the Northeast is linked to the high population density in the coastal zone. Densely populated urban centers along the coastal zone generate large amounts of reactive nitrogen in human waste that is discharged through septic systems and wastewater treatment plants. Unfortunately, conventional septic systems are not designed to

remove reactive nitrogen. Moreover, most wastewater treatment plants do not employ tertiary biological nitrogen removal (BNR) technologies and discharge high levels of reactive nitrogen to surface waters (see the box on page 13).

The contribution of reactive nitrogen to coastal waters from atmospheric

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deposition includes nitrogen that is deposited directly to the estuary as well as nitrogen deposited on the watershed that ultimately is transported downstream to the estuary.

Agricultural and urban runoff is also an important contributor to the loading of reactive nitrogen in some estuaries. As compared to undisturbed forests, agricultural, suburban, and urban lands produce nitrogen-rich runoff. This reactive nitrogen originates from many sources, including lawn and garden fertilizer, crop fertilizer, animal manure, urban runoff, and sewer overflows.

Coastal ecosystems are naturally very rich in plant and animal life. However,

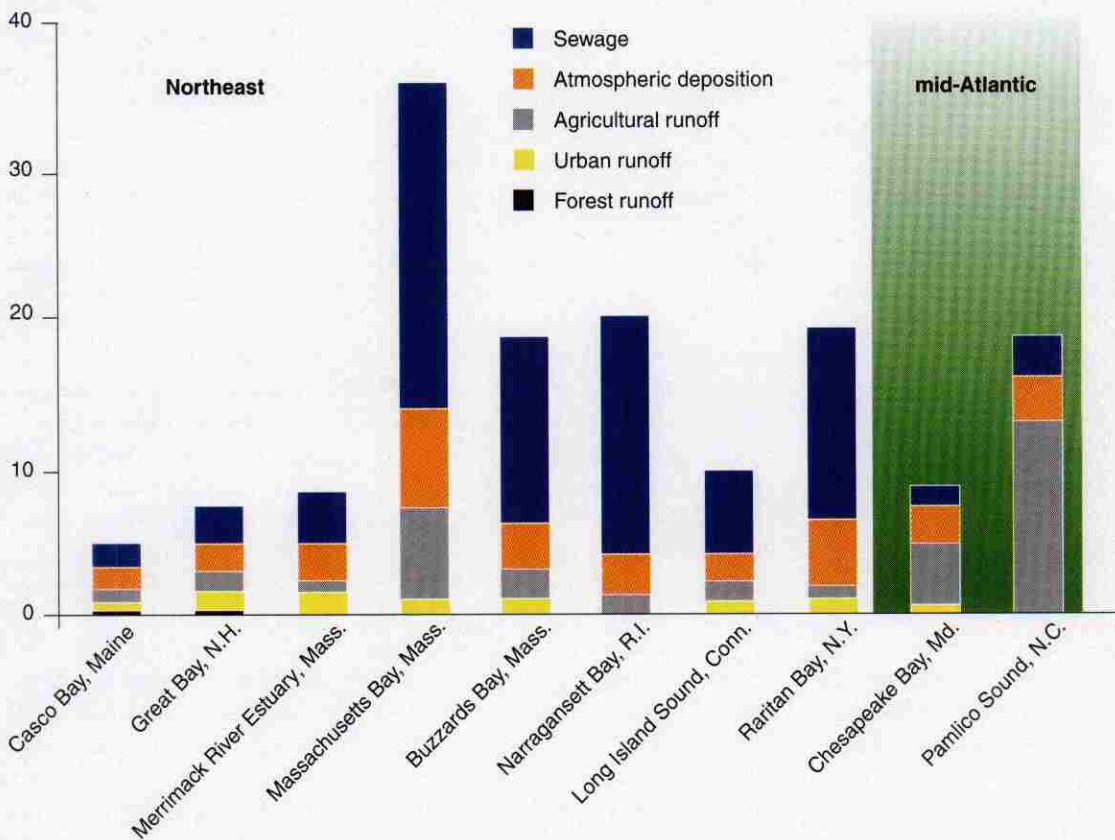
because the richness (or productivity) of saltwater ecosystems is naturally limited by the availability of reactive nitrogen, excess nitrogen can lead to a condition of overenrichment known as eutrophication. According to a study by the National Oceanic and Atmospheric Administration, of 23 estuaries examined in the Northeast, 61 percent were classified as moderately to severely degraded by nutrient overenrichment.³⁴

The overenrichment of estuaries promotes the excessive growth of algae. The increased algal growth can shade out seagrass beds and other submerged aquatic vegetation that provide critical habitat for fish and other marine organisms. Further-

more, when the algae die and decompose, oxygen in the bottom water is consumed. Low oxygen conditions, known as hypoxia, can cause fish and shellfish suffocation. Hypoxia has occurred across large areas in Long Island Sound each year for the past decade.

The effects of elevated nitrogen have been documented over several decades in the estuaries of Waquoit Bay in Massachusetts. Suburban residences on permeable soils dominate this watershed where wastewater and atmospheric deposition contribute large amounts of reactive nitrogen to the estuaries. Long-term research from this site has allowed scientists to quantify the rela-

Figure 4. Nitrogen loading to 10 major estuaries



NOTE: Nitrogen inputs are calculated for the watershed draining each estuary. The sources of reactive nitrogen to estuaries in the Northeast differ from those in the mid-Atlantic. Agricultural runoff is the major source of reactive nitrogen to Chesapeake Bay and Pamlico Sound, for instance.

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Table 1. Airborne nitrogen emissions reduction scenarios

Sector	Scenario	Percent reduction in total nitrogen emissions
Transportation	Reduction in NO _x emissions consistent with EPA Tier 2 regulations.	24
	90 percent reduction in passenger car emissions beyond EPA Tier 2 standards achieved by converting the passenger car fleet to low emission vehicles.	29
Electric utilities	75 percent reduction in NO _x emissions beyond current levels.	10
Agriculture	34 percent reduction in ammonia emissions through animal waste treatment.	2
Integrated	90 percent reduction in passenger car emissions beyond EPA Tier 2 standards, 75 percent reduction in NO _x emissions beyond current levels, and 34 percent reduction in ammonia emissions.	39

NOTE: Each scenario was also run with an additional 75 percent reduction in sulfur emissions from electric utilities beyond the emission levels required in the 1990 Clean Air Act.

tionship between the increase in total reactive nitrogen loading to the estuaries and the decreased eelgrass habitat. The results show that as nitrogen inputs to the estuaries increase, seagrass habitat decreases. From 1951 to 1992, the total seagrass coverage in Waquoit Bay has decreased substantially.³⁵

The degree of eutrophication an estuary can tolerate without adverse effects depends on the amount of reactive nitrogen it receives and its physical characteristics, such as size, depth, volume of freshwater runoff, and tidal flushing. Even with these many physical variables, the reactive nitrogen input rate is considered the major determinant of water quality degradation.

Reducing Airborne Nitrogen Pollution

The Clean Air Act is the primary federal law governing emissions of nitrogen to the air. The act sets National Ambient Air Quality Standards (NAAQS) and articulates regulatory programs to meet these standards. NAAQS to protect human health and the environment have been established for six pollutants; three are related to nitrogen emissions: nitrogen dioxide, ozone, and particulate matter. No air quality standards exist for ammonia.

Congress most recently amended the Clean Air Act in 1990 and established

goals for reducing NO_x emissions from vehicles at that time. In 1994, EPA implemented these goals by setting "Tier 1" standards for NO_x emissions based on vehicle type, ranging from 0.4 grams per mile (g/mi) for cars, to 1.0 g/mi for diesel cars, and 1.1 g/mi for light trucks weighing more than 5,750 pounds. In 1999, EPA enacted "Tier 2" of these standards, which requires U.S. manufacturers to meet an average of 0.07 g/mi for passenger vehicles beginning in model year 2004. In addition to these national standards, several states in the Northeast are considering policies that would increase the number of low emission vehicles sold.

It is estimated that the 1990 Clean Air Act Amendments (CAAA) will result in a 1.8 million metric ton reduction in NO_x emissions from electric utilities by 2010; this is beyond levels that would have occurred without this legislation. However, the CAAs did not cap total NO_x emissions from electric utilities, and it is possible that emissions could actually increase in the future as energy generation increases. Recent U.S. congressional proposals call for additional NO_x emissions reductions from electric utilities that range from 56 percent of 1990 levels to 75 percent of the projected 2010 levels. Most of these proposals include a cap on nitrogen oxide emissions.

The model PnET-BGC (Photosynthesis and EvapoTranspiration-BioGeo-Chemical) was used to evaluate the effect that current and potential future policies may have on airborne nitrogen pollution in the Northeast. PnET-BGC is a mathematical model that incorporates climate data, atmospheric emissions, and deposition together with known forest processes to predict soil and stream conditions.³⁶ The model can be used as a predictive tool to evaluate the response of forest ecosystems to changing environmental conditions, including emissions scenarios (see Table 1 on this page). The Hubbard Brook team applied the model to two well-studied watersheds under current climate conditions: the Hubbard Brook Experimental Forest in New Hampshire and the Biscuit Brook watershed in New York.

Several emissions-reduction scenarios that were measurable and regional in scope were used to evaluate the environmental effects of reductions in vehicle emissions, utility emissions, and emissions from agricultural activities.

Next, several indicators of chemical stress associated with nitrogen pollution were defined. These indicators are based on the best available estimates of the conditions that tend to cause adverse change related to nitrogen deposition and acid rain.³⁷ The PnET-BGC model

was then used to predict how these indicators are likely to change over time with each policy scenario.

The PnET-BGC model results provide insight into the relationship between emissions reductions and ecosystem recovery. According to this analysis

- The emissions reductions called for in the 1990 Clean Air Act Amendments will not reduce nitrogen deposition below the target of 8 kg N/ha-yr at the Hubbard Brook Experimental Forest or the Biscuit Brook watershed.

- Additional reductions (~30 percent) in total nitrogen emissions within the airshed of the Northeast would be needed to achieve the 8 kg N/ha-yr target in the Biscuit Brook watershed; it currently receives 11.2 kg N/ha-yr. Watersheds with higher deposition may require

greater emissions reductions to reach the 8 kg N/ha-yr target. Watersheds such as the Hubbard Brook Experimental Forest that receive lower amounts of nitrogen from atmospheric deposition, however, would reach the 8 kg N/ha-yr target with less stringent emissions reductions.

- The 1990 CAAAs will not reduce emissions and deposition of acid compounds (such as nitric acid) enough to completely mitigate adverse chemical conditions associated with acid rain at the Biscuit Brook or Hubbard Brook watersheds.

- Under the most aggressive scenario, which cuts total nitrogen emissions in the airshed by 50 percent from current levels, the targets for chemical recovery from acid rain would not be reached at Hubbard Brook within 50 years. However, substan-

tial improvements do occur, demonstrating that the emissions reductions would have beneficial effects. At Biscuit Brook, the aggressive nitrogen scenario would achieve some of the targets by 2050, including stream pH. The slow recovery from acid rain in both watersheds is related to the fact that sulfur dioxide is also a large component of acid rain.

- When cuts in sulfur dioxide emissions from electric utilities of 75 percent beyond the 1990 CAAAs are considered with the nitrogen reductions, the prediction is that the Biscuit Brook watershed would reach nearly full chemical recovery by 2050. The rate of improvement at Hubbard Brook would increase markedly under this option.

- The PnET-BGC model results suggest that sensitive forest ecosystems would



Weathering of this mausoleum sculpture in New York City is hastened by acid rain. Nitric acid and sulfate are the two major components of acid rain; as regulatory controls on sulfur dioxide reduce the amount of sulfate in rain and snow, nitric acid plays an increasing role.

require substantial reductions in nitrogen and sulfur emissions beyond the 1990 CAAAs to mitigate ecosystem stress due to acidic and reactive nitrogen inputs within 50 years.

Reductions in NO_x emissions are particularly important in reducing stream nitrate concentrations during spring, fall, and winter when stream nitrate concentrations

and acidity are highest. Another analysis using PnET-BGC shows that proposed reductions in NO_x emissions that are limited to the summer ozone season would not decrease stream nitrate concentrations much over the short term. Year-round controls would be more effective in reducing the total nitrogen load and elevated nitrate concentrations during the dormant season over the long term.³⁸

Estuary Nitrogen Reduction Scenarios

Wastewater nitrogen scenarios

- Implementation of biological nitrogen removal (BNR) at wastewater treatment plants throughout the entire watershed.
- Implementation of BNR at wastewater treatment plants within the coastal zone.
- Combined basinwide BNR and improvement in septic system treatment.
- Displacement of nitrogen to the continental shelf through offshore pumping.

Agricultural scenarios

- 34 percent reduction in nitrogen emissions from agricultural facilities through the treatment of animal waste.
- 33 percent reduction in edge-of-field nitrogen runoff from agricultural facilities through increased use of best-management practices.

Airborne nitrogen scenarios

- 75 percent reduction in NO_x emissions from electric utilities from current emissions levels by 2010.
- Reductions in vehicle emissions of NO_x consistent with EPA Tier 2 regulations.
- 90 percent reduction in vehicle emissions of NO_x beyond the levels achieved through Tier 2.

Integrated

- Basinwide BNR, 90 percent reduction in NO_x emissions from vehicles beyond the Tier 2 standard, 75 percent reduction in NO_x emissions from electric utilities, and 33 percent decrease in edge-of-field runoff from agricultural facilities.

Reducing Nitrogen Pollution to Estuaries

The U.S. Clean Water Act and Safe Drinking Water Act set water quality standards for nitrogen in surface waters and groundwater. These standards provide the basis for regulatory programs implemented by EPA. Water quality standards for nitrogen pollution include standards to protect human health, drinking water, and aquatic life. States are allowed to establish more stringent water quality standards but must enforce the federal standards at a minimum.

The federal standards establish a concentration limit for specific forms of nitrogen in surface waters. However, there is currently no water quality standard that limits the total loading of reactive nitrogen to surface waters. If excess nitrogen causes violations of other water quality standards (such as dissolved oxygen), state agencies are required to develop an EPA-approved plan to address the reactive nitrogen loading. The plan, known as a Total Maximum Daily Load (TMDL) plan, must specify the pollutant-loading levels from all contributing sources that can be allowed and still attain water quality standards. In 2001, Connecticut and New York adopted a TMDL plan to address chronic dissolved oxygen problems in Long Island Sound by reducing reactive nitrogen loading to the sound 38 percent by 2014. Most of the nitrogen reductions will come from Connecticut and New York, where a 58.5 percent reduction target has been established.

To compare the impact of several scenarios for reducing loading of reactive nitrogen to estuaries of the Northeast, the Hubbard Brook team used the model WATERSN (Watershed Assessment Tool

for Evaluating Reduction Strategies for Nitrogen). The estuaries within Long Island Sound in Connecticut and New York and Casco Bay in Maine, which have different land-use patterns, were used as case studies.

WATERSN is a nitrogen model for coastal watersheds that estimates total nitrogen loading to specific estuaries based on a numerical accounting of all watershed inputs (food, feed, fertilizer, nitrogen deposition, and nitrogen fixation in cropland) and all watershed nitrogen losses.³⁹ Individual sources of reactive nitrogen can be altered to predict the change in estuarine nitrogen loading that would result from nitrogen pollution controls.

Several nitrogen-reduction scenarios were defined based on current policy options that would decrease nitrogen inputs to the estuaries (see the box on this page). The scenarios target nitrogen reductions from each of the major sources that contribute reactive nitrogen to estuaries in the Northeast.

The WATERSN model provides the following results, which are useful in guiding nitrogen management for coastal systems:

- Differences in land use and population size have a substantial impact on the relative effectiveness of the reduction scenarios for Long Island Sound and Casco Bay. For example, in the more highly populated watershed that drains to Long Island Sound, improvements in wastewater treatment plants reduce reactive nitrogen loading to a greater extent than in the less-populated Casco Bay watershed.

- Improved wastewater treatment results in the largest reduction in reactive nitrogen loading to Long Island Sound and Casco Bay. Basinwide biological nitrogen removal (BNR) and improvements in septic systems would achieve approximately a 55 percent reduction in reactive nitrogen loading to Long Island Sound and a 40 percent reduction to Casco Bay.

- The NO_x emission reduction scenarios for utilities and vehicles would reduce reactive nitrogen loading in Casco Bay by up to 13 percent and in Long Island Sound by roughly 4 percent.

- An integrated management plan that includes nitrogen controls on both air and

water sources achieves the maximum reductions of all scenarios considered. The integrated plan would reduce reactive nitrogen loading to Casco Bay by about 45 percent and to Long Island Sound by 60 percent.

Summary

Nitrogen pollution is increasing in the Northeast and contributes to a wide array of environmental problems. As a single nitrogen molecule cascades through the environment, it contributes to air-quality degradation, acidification of soil and surface waters, disruption of forest processes, and overenrichment of coastal waters. Solving the nitrogen problem will require a multipronged approach. Computer model results show that the current Clean Air Act has not had a substantial effect on airborne nitrogen emissions and further reductions are needed to mitigate the impacts of high nitrogen deposition on sensitive ecosystems. Another computer model determined that nitrogen loading to estuaries in the Northeast is high and dominated by nitrogen discharged from wastewater treatment plants. Adding nitrogen control technology to treatment plants would significantly reduce nitrogen pollution in the region's estuaries. The results of this study show that policy efforts in the Northeast should include concentrated efforts to reduce airborne nitrogen emissions from vehicles and electric utilities and increased investment in improved wastewater treatment to address nitrogen pollution.

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