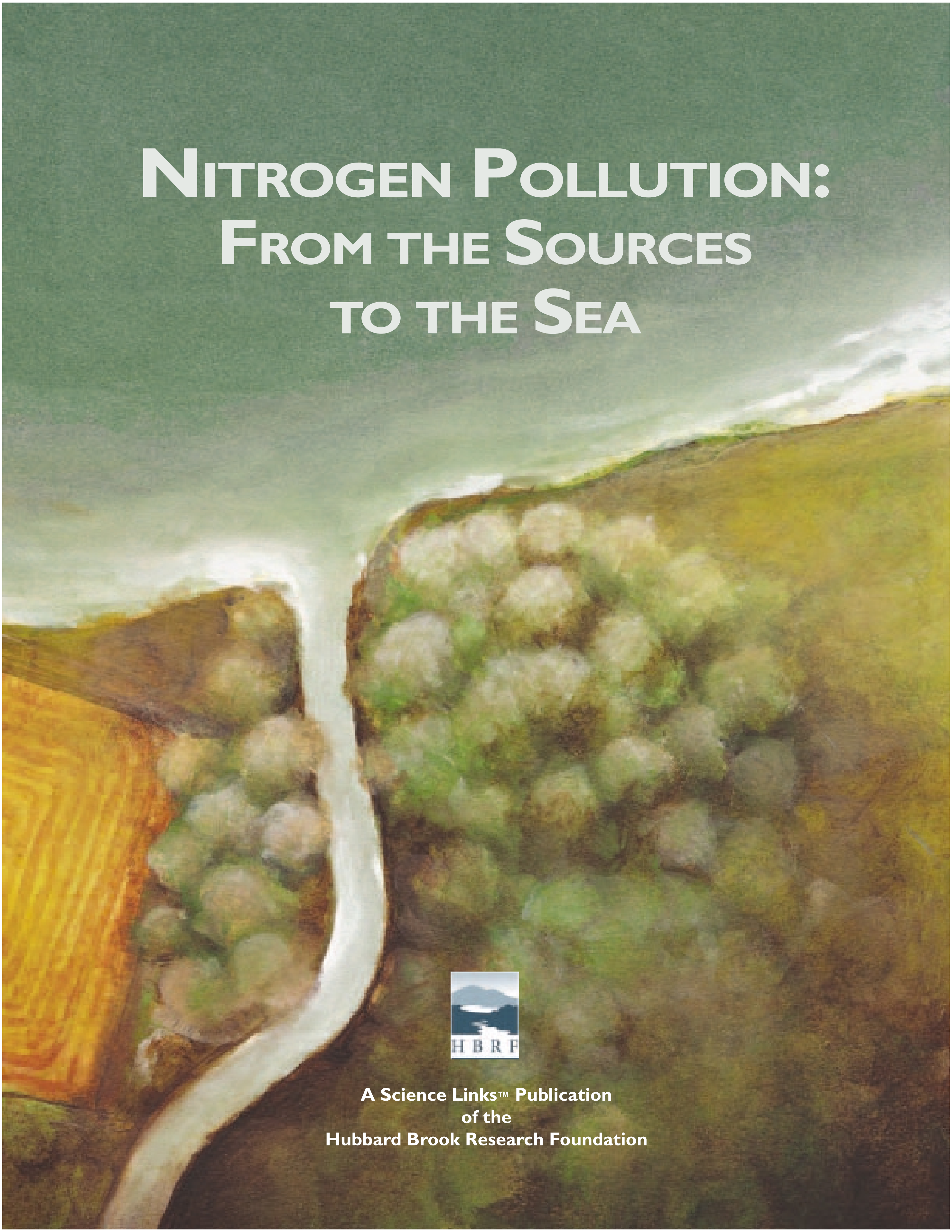
Nitrogen Pollution: From the Sources to the Sea



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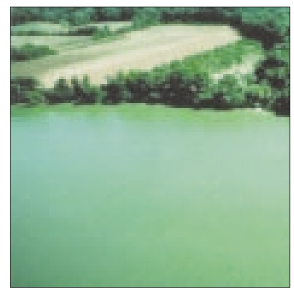
FROM THE SOURCES TO THE SEA



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Summary

Over the past century, human activity has greatly increased the amount of nitrogen pollution in the environment. Human sources of reactive nitrogen in the Northeastern U.S (the Northeast) are dominated by airborne nitrogen emissions that are deposited on the Earth, nitrogen in food and nitrogen fertilizer. Excess reactive nitrogen in the environment has given rise to a cascade of pollution problems across the Northeast. Fortunately, several policy options exist for reducing nitrogen pollution and its effects.

Nitrogen Sources

The three largest sources of reactive nitrogen to the Northeast are nitrogen in food, airborne nitrogen emissions and nitrogen fertilizer.

Food that is imported to the Northeast accounts for the largest amount of reactive nitrogen in the region (38-75 percent). Airborne emissions of nitrogen oxides and ammonia and the subsequent deposition from the atmosphere contribute 11-36 percent; and nitrogen fertilizer adds another 11-32 percent.

Nitrogen Effects

Nitrogen pollution contributes to ground-level ozone, acid rain and acidification of soil and surface waters, disruption of forest processes, coastal over-enrichment and other environmental issues.

Forests of the Northeast are experiencing elevated inputs of reactive nitrogen. While this nitrogen may initially increase forest productivity, it can eventually damage soil, reduce tree growth and produce acidic nitrate runoff to streams. Nitrate runoff from forests contributes to the acidification of streams and lakes.

Nitrogen emissions are also the primary source of ground level ozone that damages plants and compromises human health. It is estimated that forest productivity is diminished by as much as 14 percent in the region due to high levels of ozone. Approximately 26 million people in the Northeast are exposed to high ozone levels each year.

Remote forests receive most of their nitrogen pollution from nitrogen deposition, while large populated watersheds receive nitrogen from many sources. Examples include food imports for humans that result in nitrogen-rich wastewater, nitrogen emissions that are eventually deposited on the Earth's surface, and nitrogen in fertilizer that can run off into surface waters.

After entering a watershed, reactive nitrogen is transported downstream to estuaries. Fourteen major estuaries in the Northeast have been classified as "highly impacted" due to elevated nitrogen inputs. These impacts include the loss of seagrass beds, increased algal blooms, reduced biodiversity and fish kills due to oxygen depletion.

Nitrogen Management

Controls on vehicle and utility emissions of nitrogen oxides produce the largest reductions in airborne nitrogen pollution in the Northeast.

The largest sources of airborne nitrogen in the Northeast are vehicles and electric utilities. Therefore, it is not surprising that reducing emissions from these sources would result in the greatest improvement in airborne nitrogen. However, according to model results from this study, the emission reductions called for in the 1990 Clean Air Act Amendments (CAAAs) will not sufficiently reduce nitrogen deposition at the Hubbard Brook Experimental Forest in New Hampshire or the Biscuit Brook watershed in New York to mitigate elevated nitrogen runoff. Additional reductions in nitrogen emissions (~30 percent) would reduce nitrogen runoff to less harmful levels.

The 1990 CAAAs will also not reduce the deposition of acid compounds sufficient to mitigate acid rain effects in the Biscuit Brook or Hubbard Brook watersheds. However, when additional nitrogen emission reductions and a simultaneous 75 percent cut in sulfur dioxide emissions from electric utilities beyond the 1990 CAAAs are considered, it is predicted that Biscuit Brook would achieve nearly full chemical recovery by 2050 and Hubbard Brook would experience marked improvement in soil conditions and water quality.

Nitrogen removal from wastewater at a basin-wide scale is the single most effective means of reducing nitrogen loading to estuaries in the Northeast.

With respect to nitrogen loading to estuaries, model results from this study show that wastewater treatment results in the largest reduction in loading of reactive nitrogen to Long Island Sound of Connecticut and New York and Casco Bay of Maine. Nitrogen removal at wastewater treatment plants throughout the watershed and improvements in septic systems are predicted to reduce nitrogen loading by about 55 percent to Long Island Sound and 40 percent to Casco Bay.

Why assess nitrogen in the environment?

Nitrogen pollution is steadily increasing and has emerged as a pressing environmental issue of the 21st century.

Nitrogen is an essential nutrient that is used by all living things. Under pristine conditions, there is usually not enough nitrogen to go around. Over the past 100 years, however, conditions have changed. The growing human population has increased demand for food and energy worldwide. Meeting these demands has increased the amount of reactive nitrogen[1] in the environment. 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 (see Figure 1).

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

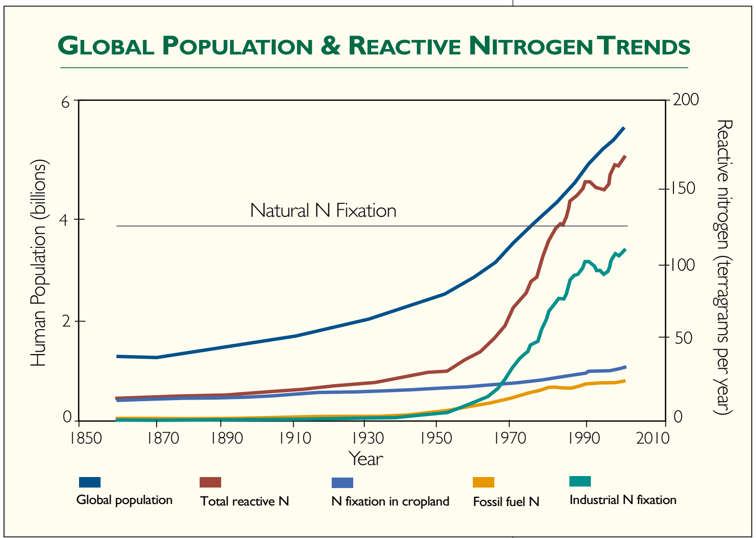

FIGURE 1: *Human activities have increased the production of reactive nitrogen. From Galloway and Cowling 2002.*

A group of scientists convened by the Hubbard Brook Research Foundation examined the sources and consequences of nitrogen pollution in the Northeastern United States (the Northeast). This report summarizes their findings. The Northeast provides an interesting case study in nitrogen pollution because this region:

1. has experienced steady population growth which tends to increase reactive nitrogen in the environment (see Figure 2a);
2. has undergone significant land use change since farm abandonment in the late 1800s, which influences nitrogen retention and loss (see Figure 2a);
3. receives large amounts of reactive nitrogen to the air, land and water; and
4. 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 2b).

This report addresses three major questions regarding nitrogen pollution in the Northeast:

1. What are the anthropogenic (i.e. human-derived) sources of reactive nitrogen?
2. What are the ecological effects of nitrogen pollution?
3. To what extent will policy options reduce nitrogen pollution and mitigate its effects?

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[1] Reactive nitrogen refers to all forms of nitrogen that are readily available to biota (largely ammonia, ammonium and nitrate). Unreactive nitrogen exists mostly as inert N_2 gas. In excess, reactive nitrogen causes nitrogen pollution.

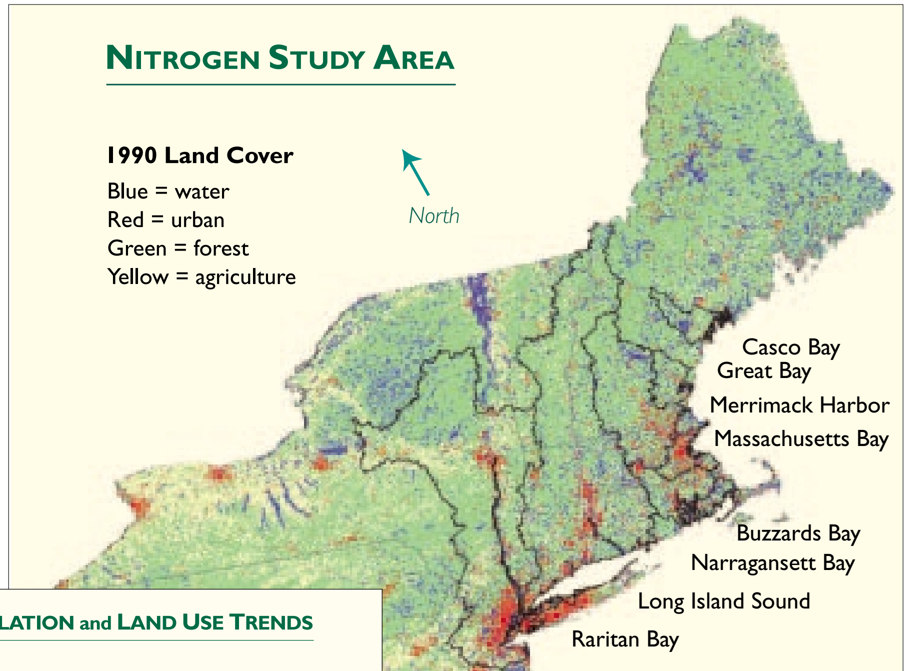


FIGURE 2a: *The study area includes eight large watersheds and two upland forested watersheds.*

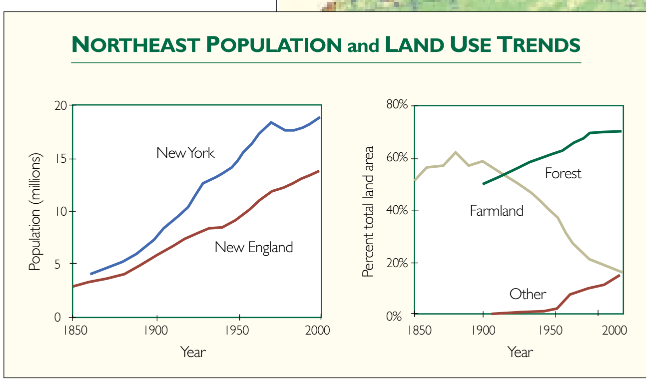


FIGURE 2b: *Land use and population trends. Data sources: U.S. Bureau of Census and U.S. Department of Agriculture.*

How does nitrogen become a pollutant?

Nitrogen becomes a pollutant when more reactive nitrogen is released into the environment than can be assimilated without degrading air, land and water resources.

Nitrogen constitutes 78 percent of the Earth's atmosphere in the basic form of N_2 (diatomic nitrogen). N_2 is an "unreactive" form of nitrogen that plants and animals cannot access directly. In order 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 ammonia (NH_3). In an environment absent of human influence, this conversion occurs only through fixation by plant- and soil-associated bacteria and lightning strikes.

Human processes have doubled the global rate at which reactive nitrogen is produced (see Figure 1). This change has led to an increase in the sources of reactive nitrogen that contribute to environmental pollution. These human-derived sources of reactive nitrogen include airborne emissions from fossil fuel combustion by vehicles and electric utilities, fertilizer production that results in runoff from farms as well as suburban and urban lands, and imported food that produces nitrogen-rich effluent leached from septic tanks and discharged from wastewater treatment plants. Figure 3 shows the sources and fate of nitrogen in both a pristine and human-altered landscape (see Figure 3 fold-out, back cover).

Additional reactive nitrogen created through human activities becomes a pollution problem when the supply of reactive nitrogen from all sources entering a watershed exceeds the basic needs of the plants, microbes and animals in that watershed, or when nitrogen emitted to the air cannot be assimilated without adverse effects on air quality.

The Cascade of Nitrogen Pollution

Air quality impacts:
~ Elevated ground-level ozone
~ Increased particles in the air
~ Reduced visibility
~ Increased acid rain and nitrogen deposition

Forest impacts:
~ Increased acidity of forest soils
~ Nitrogen saturation of forest ecosystems
~ Ozone damage to forests

Water quality impacts:
~ Elevated acidification of lakes and streams
~ Groundwater contamination
~ Over-enrichment of coastal ecosystems

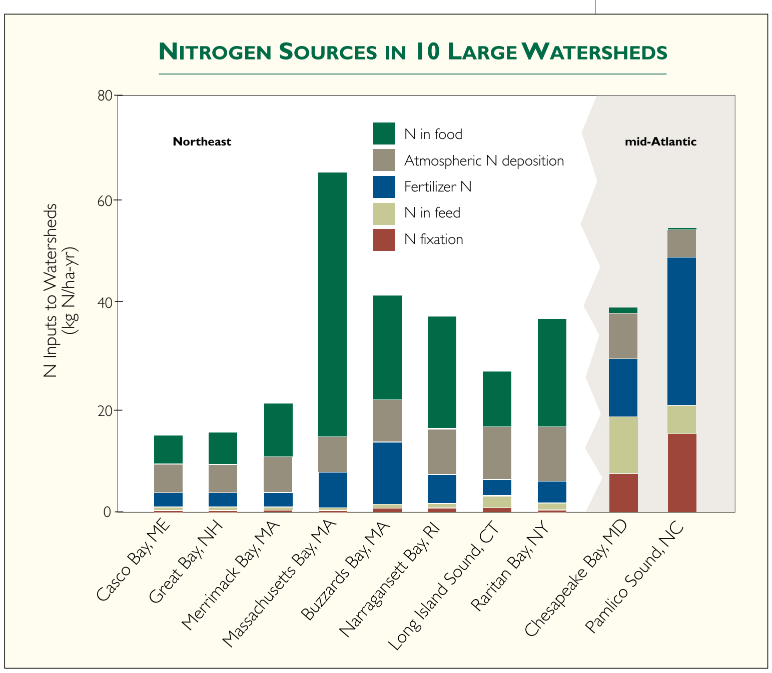
Other impacts:
~ Increased production of greenhouse gases contributing to global climate change
~ Adverse human health effects from particulate matter and ground-level ozone

What are the sources of reactive nitrogen in the Northeast?

The largest sources of reactive nitrogen in Northeast watersheds are nitrogen in food, nitrogen deposition and nitrogen fertilizer.

To determine the sources of reactive nitrogen that cause nitrogen pollution we analyzed eight large watersheds in the Northeast (see Figure 2b). The results show that food (most of which is imported from outside the region) accounts for the largest amount of reactive nitrogen in the region (38-75 percent). Airborne emissions of nitrogen oxides (NO_x) and ammonia (NH_3), and the subsequent deposition[2] of nitrate (NO_3) and ammonium (NH_4), contribute 11-36 percent. Nitrogen fertilizer

FIGURE 4: *Total reactive nitrogen inputs to several large watersheds in the Northeast and mid-Atlantic.*



Note: *nitrogen inputs are calculated for the watershed draining each estuary.*

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2 Deposition is the transfer of nitrogen from the air to the Earth's surface through rain, snow, clouds, fog, gases, or particles.

applied to crops, pastures and lawns adds another 11-32 percent (see Figure 4). 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 Northeast watersheds.

The major sources of reactive nitrogen in Northeast watersheds differ significantly from sources in other regions. For example, in Chesapeake Bay and Pamlico Sound, two largely agricultural watersheds in the Middle Atlantic region of the U.S. (the mid-Atlantic), nitrogen fixation in croplands is the largest source of reactive nitrogen (28 and 53 percent respectively), followed by fertilizer (21 and 29 percent respectively). The nitrogen sources in these mid-Atlantic watersheds reflect their heavy agricultural land use, in contrast to the more urbanized land use pattern in the Northeast. The wide variation in sources of reactive nitrogen suggests that management approaches should reflect regional differences.

This analysis of eight Northeast watersheds also 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), or 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 (e.g. forest, urban and agricultural).

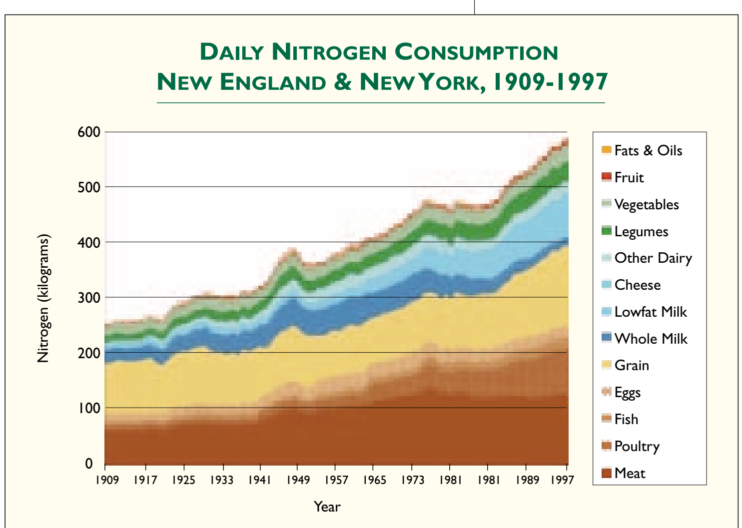
On a landscape scale it is also clear from this analysis that sources of reactive nitrogen vary significantly in forested headwaters compared to densely populated coastal zones. For example, in the relatively remote and unpopulated forested watersheds of the Hubbard Brook Experimental Forest of New Hampshire,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

The following sections explore each of the nitrogen sources in greater detail.

► *Nitrogen in food (38-75 percent)*

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 we examined. Since the Northeast has a high population and relatively low food production, imported food represents a major input of reactive nitrogen. The watershed with the highest total annual input of nitrogen from the net import of food is the Hudson River watershed that drains to Raritan Bay. This is due to the large size and population of this watershed compared to the others studied. The watershed with the highest annual input of nitrogen from food per watershed area is Massachusetts Bay (75 percent). This is attributed to the relatively high population density and limited agricultural production in this watershed.

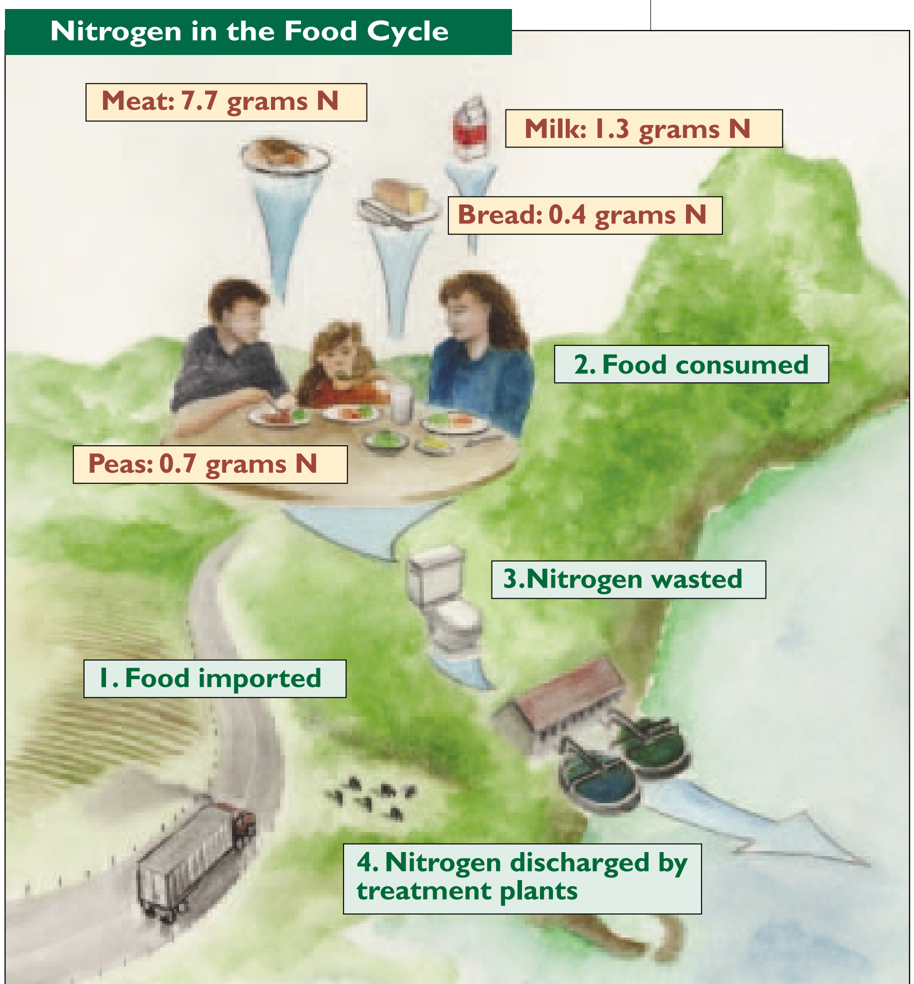
Figure 5: *Changes in nitrogen consumption by humans in New England and New York.*



The consumption of protein, and the associated consumption of nitrogen, has been tracked by the U.S. Department of Agriculture since 1909 (grams of nitrogen = grams of protein/6.25). 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 (see Figure 5). The average human body needs roughly 2.0 grams of nitrogen per day to support basic metabolic functions (Galloway and Cowling 2002). The typical American diet supplies approximately 13 grams of nitrogen per day (Boyer et al. 2002).

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 (Galloway and Cowling 2002). 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 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 utilize 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 treatment plants (see Box on page 21). Since most septic systems and treatment plants do not effectively remove nitrogen from the waste, reactive nitrogen is eventually discharged to rivers and coastal waters where it contributes to water quality problems (see Figure 6).



Note: *the nitrogen content in food groups is based on a single serving.*
Source: http://www.nal.usda.gov/fnic/cgi-bin/nut_search.pl

FIGURE 6: *Nitrogen in food is a major contributor to nitrogen loading in Northeast estuaries.*

► *Deposition of nitrogen (11-36 percent)*

The deposition of nitrogen to the Earth's surface resulting from airborne emissions is the second largest source of reactive nitrogen in the eight Northeast watersheds analyzed. The airborne emissions of reactive nitrogen are derived from the burning of fossil fuel and agricultural activities. The most prevalent nitrogen emissions are nitrogen oxides (NO_x) and ammonia (NH_3). Based on data from the U.S. Environmental Protection Agency (EPA), nitrogen oxides constitute 66-73 percent of the total nitrogen emitted in the airshed[3] of the Northeast and ammonia contributes the remaining 27-34 percent. Emissions can also include natural or human-derived organic nitrogen.

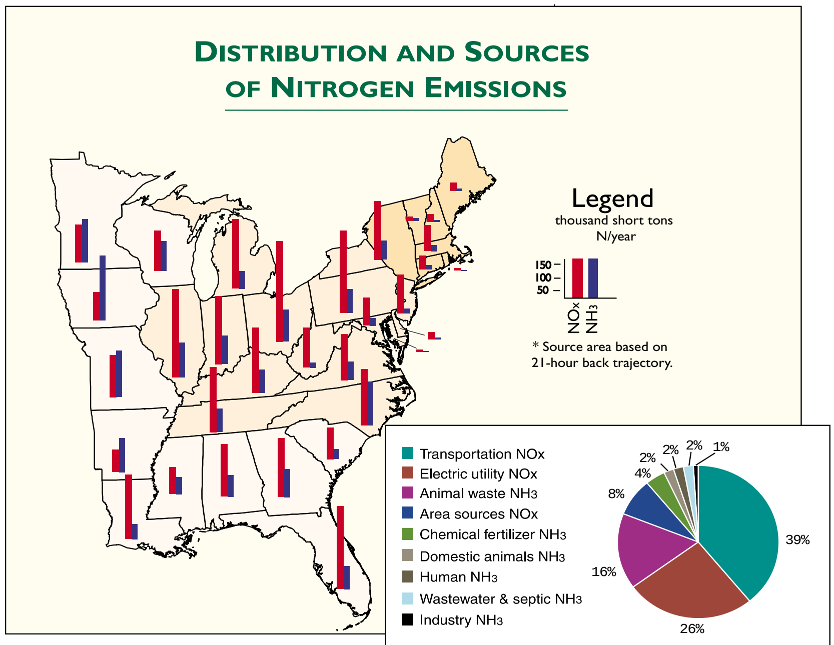


Figure 7: *Distribution and sources of nitrogen emissions to the Northeast.*

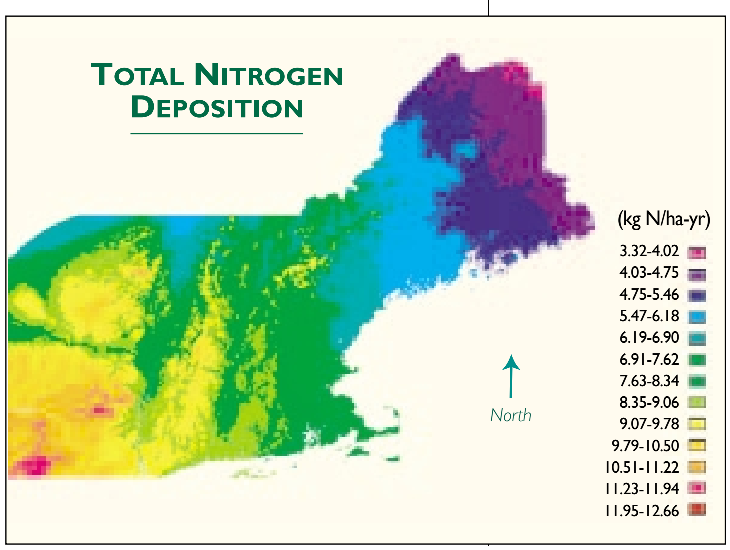
Using the airshed for the Long Island Sound watershed as an example, the largest sources of nitrogen emissions are: transportation NO_x (39 percent), electric utility NO_x (26 percent) and ammonia emitted from animal waste (16 percent). The largest emitters are located in the Midwest (see Figure 7), although local sources can be substantial and play an important role in local air quality.

Focusing on nitrogen oxide emissions alone, 54 percent of the total national NO_x emissions originate from transportation sources (e.g. passenger cars, diesel trucks and recreation vehicles), and 25 percent are emitted from electric utilities (e.g. coal-fired power plants). Of the ammonia emissions, 83 percent are associated with agricultural activities.

Both nitrogen oxides and ammonia can be transported long distances and eventually are 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."

The nitrogen deposition patterns in the Northeast are related to three factors: (1) distance from large emission sources, (2) latitude and (3) elevation. The western Adirondack Mountains of New York experience the highest deposition rates in the region at 12 kg N/ha-yr (11 lbs N/ha-yr), reflecting their relatively close proximity to Midwest sources (see Figure 8).

Figure 8: *Total nitrogen deposition. From Ollinger et al. 1993.*



[3] An airshed is the geographic area that contributes airborne emissions of nitrogen to a watershed or other locale of interest.

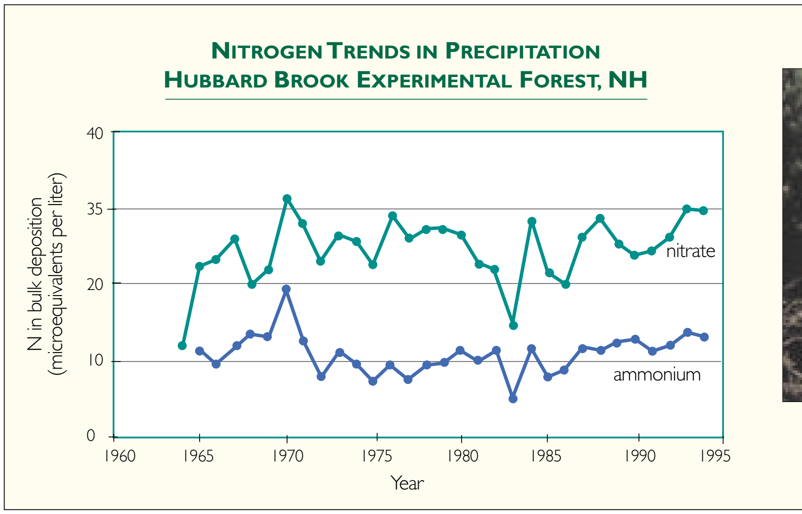


FIGURE 9: *Trends in nitrate and ammonium in precipitation. From Likens and Bormann 1995.*

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 (see Figure 9). These relatively high deposition levels persist in part because the 1990 Amendments to the Clean Air Act (CAAAs) did not substantially limit nitrogen emissions.

► *Nitrogen in fertilizer (11-32 percent)*

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. The use of nitrogen fertilizer on residential lawns is a growing component of fertilizer use in the U.S.

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 ground waters, with extreme levels reaching as high as 80 percent for row crops in sandy soils (Howarth et al. 2002).

► *Nitrogen in animal feed (1-10 percent)*

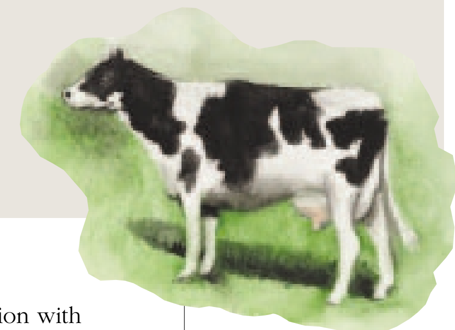
Animal feed in the form of corn silage, oats and hay is imported to the Northeast to feed cows, pigs, chickens and other livestock. The watershed with the largest amount of nitrogen in animal feed per hectare is the Connecticut River watershed due to relatively high levels of livestock production. Nitrogen 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.

Nutrient Management in Agriculture: A Case Study

Innovative nutrient management projects have been implemented on farms throughout the region. For example, the Matlink Dairy Farm uses an integrated manure management system for their 675-cow farm in Chautauqua County, New York. To address a variety of issues including odor, nutrient management and pathogen reduction, the farm recently installed an anaerobic digester with support from the New York State Energy Research and Development Authority.

The digester breaks down manure from the cows and produces biogas that the farm uses to meet its electricity needs and to sell to the grid. The farm boosts gas production from the manure by also digesting waste from nearby food facilities. The benefits of the digester project are two-fold. First, the digester effluent is stored and applied to the land in a manner that maximizes nutrient uptake by crops and reduces nitrogen runoff. Second, the digester relieves pressure on the local wastewater treatment plant that currently lacks the capacity to remove nitrogen from the waste stream.

Matlink Dairy Farm receives economic benefits from the digester project through electricity savings, tipping fees for handling food wastes, bedding material replacement, compost sales, and hot water totaling $290,000 annually. The annual savings will offset the initial capital expense of $620,000, making this investment both economically and environmentally beneficial.



► *Nitrogen fixation in croplands (1-8 percent)*

Nitrogen fixation is the process in which bacteria living in association with crops such as soybeans, peanuts and alfalfa (known as leguminous crops), 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 (Boyer et al. 2002). Watershed inputs of reactive nitrogen associated with nitrogen fixation in croplands is low, with the highest percentage occurring in the Hudson River watershed.

What are the ecological effects of nitrogen pollution in the Northeast?

Nitrogen pollution contributes to ground-level ozone, acid rain and acidification of soil and surface waters, disruption of forest processes, coastal over-enrichment and other environmental issues.

This report examines four of the major environmental effects of nitrogen pollution in the Northeast: ground-level ozone, acid rain, forest effects and coastal over-enrichment. 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.

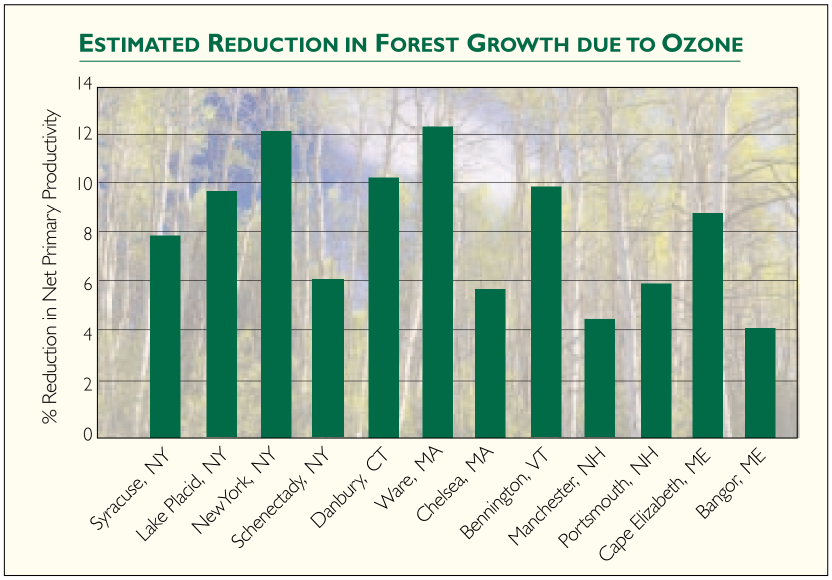
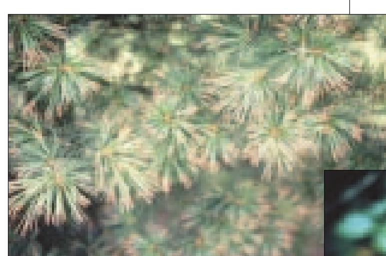


FIGURE 10: *Reductions in tree growth in the Northeast due to ozone pollution. From Ollinger et al. 1997.*

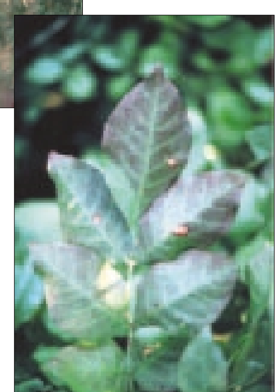
On warm summer days, ground-level ozone concentrations in the Northeast often exceed the U.S. Environmental Protection Agency (EPA) National Ambient Air Quality Standard for human health. The current ozone standard is 0.08 parts per million averaged over an eight-hour period (revised from 0.12 parts per million averaged over a one-hour period). Based on the older standard, approximately 26 million people live in areas of the Northeast where the standard was exceeded up to 70 days from 1993-1998. It is expected that even more people will be exposed to conditions that periodically violate the current more stringent standard.

Ground-level ozone also presents a significant health risk for trees and other vegetation 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 the tree (stomates). Ozone uptake by plants is greatest during the growing season of May to 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 stipling" 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 (through photosynthesis) that is needed to fuel plant growth. The net effect of this change is a decrease in tree biomass production, or growth (see Figure 10).



Tip necrosis injury on white pine.



Purple stipling on ash leaf due to ambient ozone. Acadia National Park, ME.

► *Acid rain*

Rainfall is acidic in much of the Northeast. The average pH (a measure of acidity) of rain and snowfall at the Hubbard Brook Experimental Forest in New Hampshire is 4.5. This level is 10-15 times more acidic than unpolluted rainwater. 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.

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 (see Figure 11). Moreover, nitrate is the major driver in seasonal and "episodic" acidification that result 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.

What are the Health Effects of Atmospheric Nitrogen Emissions?

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

As mentioned previously, 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 (Mudway and Kelly 2000). In epidemiological studies, short-term ozone exposure has been associated with health outcomes ranging from decreased lung function to respiratory hospital admissions to premature death. Although it is difficult to separate the effects of ozone from weather (since 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 (Levy et al. 2001). Along with the effects of short-term ozone increases, 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 areas (McConnell et al. 2002) and in chronic decreases in lung function (Kunzli et al. 1997).

Nitrogen oxide emissions also contribute to the formation of fine particulate matter (PM2.5). 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, fine particulate matter (PM2.5) as a whole has been linked with numerous respiratory and cardiovascular outcomes. For example, a study of approximately 500,000 individuals across the U.S. found that long-term exposure to fine particulate matter was associated with an increased risk of premature death, principally due to respiratory or cardiovascular disease (Pope et al. 2002). Short-term exposure to PM2.5 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 (Hasselblad et al. 1992).

– Jonathan Levy, Sc.D., Harvard School of Public Health

The effects of acid rain are well documented and are described in detail in the Science Links™ report *Acid Rain Revisited*. 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 (Likens et al. 1996).

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

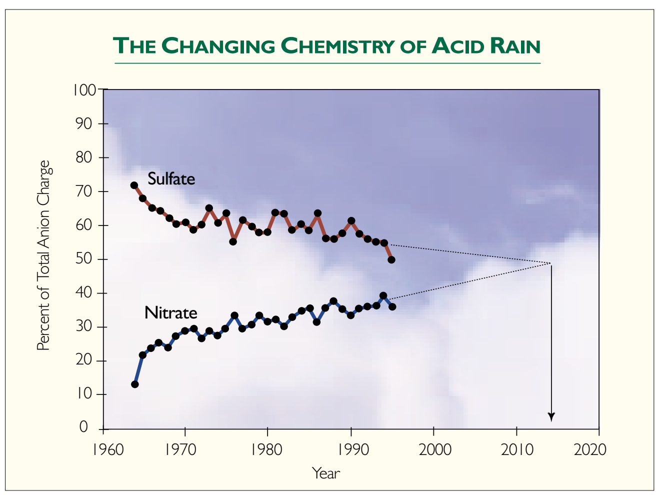


FIGURE 11: *The increasing contribution of nitrate to acid rain. From Likens and Lambert 1998.*

alone. Even brook trout, a relatively acid-tolerant species, cannot withstand inorganic aluminum concentrations above 3.7 micro-moles per liter (100 micro-grams of aluminum per liter). 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 populations 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: (1) direct impacts on foliage, and (2) 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 foliage at high elevations. This has lead 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. 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. Signs of stress connected to acid rain have been documented in sugar maple stands on sensitive soils across the region.

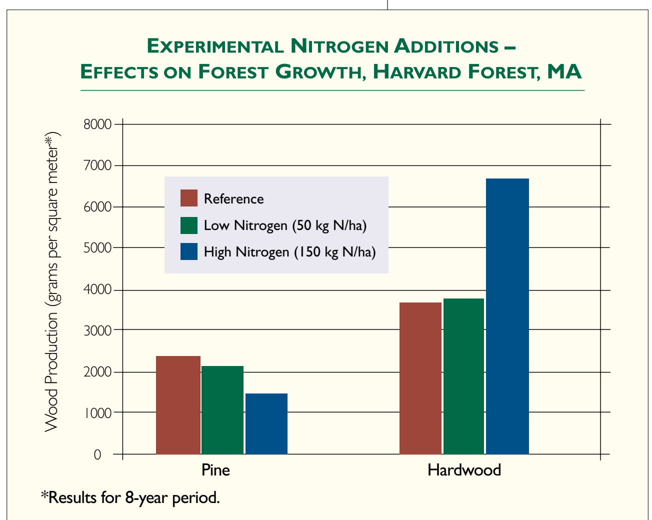
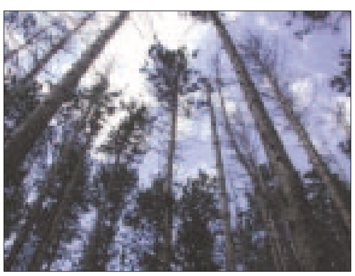


FIGURE 12:
Changes in forest growth due to added nitrogen. From Magill et al. 2000.

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 U.S. has identified a process known as "nitrogen saturation" that can result from high levels of nitrogen deposition. 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.



Pine stands that received nitrogen additions. Harvard Forest, MA.

One important concept related to nitrogen-induced change in forests is the highly variable response of forests to reactive nitrogen inputs depending on forest type, soil characteristics, land use history, climate and nitrogen deposition rates. For example, young vigorously growing forests and forests with a long history of logging or agriculture typically have a higher capacity to retain nitrogen. Therefore, they progress more slowly toward nitrogen saturation than more mature forest ecosystems.

Overall, 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 (Magill et al. 2000); see Figure 12.

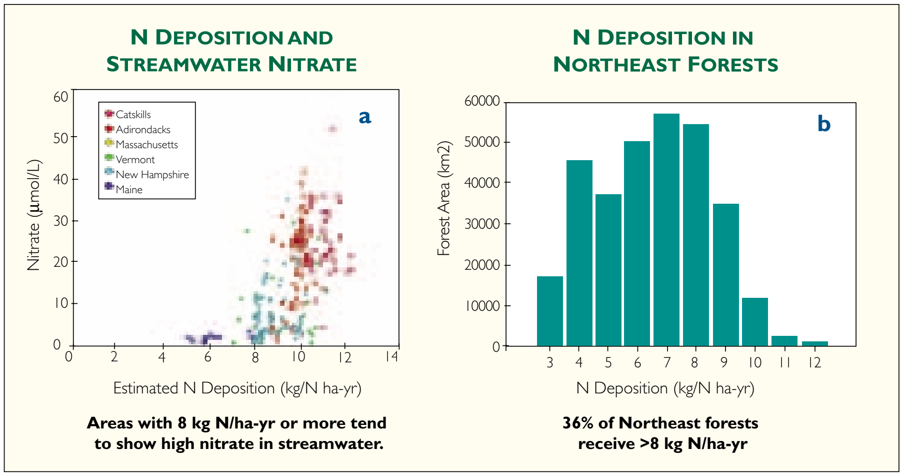


FIGURE 13a & b: *a: The relationship between nitrogen deposition and stream nitrate in the Northeast. From Aber et al. 2003.*

b: Large areas of the Northeast receive high levels of nitrogen deposition.

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 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 (Aber et al. 2003); see Figure 13a.

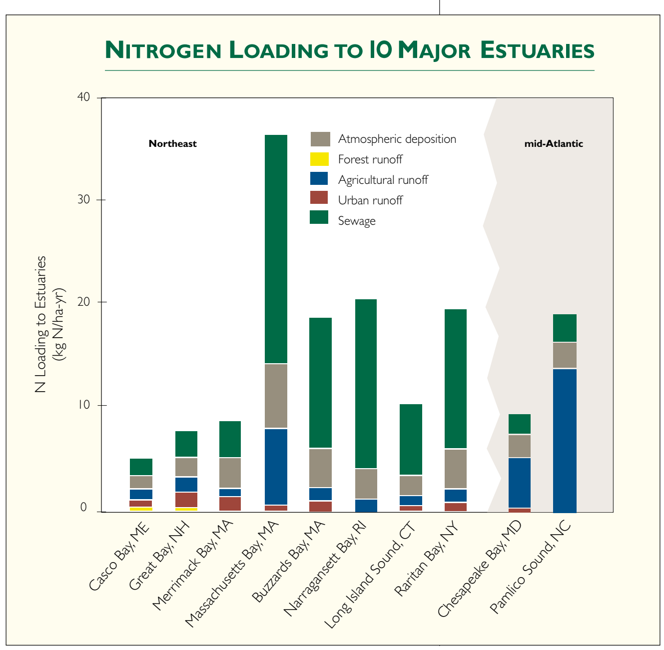
An analysis of forestland in the region shows that approximately 36 percent of Northeastern forests receive 8 kg N/ha-yr (7 lbs N/acre-yr) or more, and may be susceptible to elevated nitrate leaching, an early indicator of nitrogen saturation (see Figure 13b).

Coastal over-enrichment

In order 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 (VanBreemen et al. 2002) flows downstream to coastal estuaries. 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 14.

The sources of reactive nitrogen to estuaries in the Northeast differ considerably from those in the mid-Atlantic. For example, agricultural runoff is the major source of reactive nitrogen to Chesapeake Bay and Pamlico Sound (55 percent and 79 percent respectively); see Figure 14.

FIGURE 14: *Sources of nitrogen loading to coastal estuaries.*



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 then 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.

The contribution of reactive nitrogen to coastal waters from atmospheric 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 (see Figure 15). This reactive nitrogen originates from many sources including lawn and garden fertilizer, crop fertilizer, animal manure, urban runoff and sewer overflows.

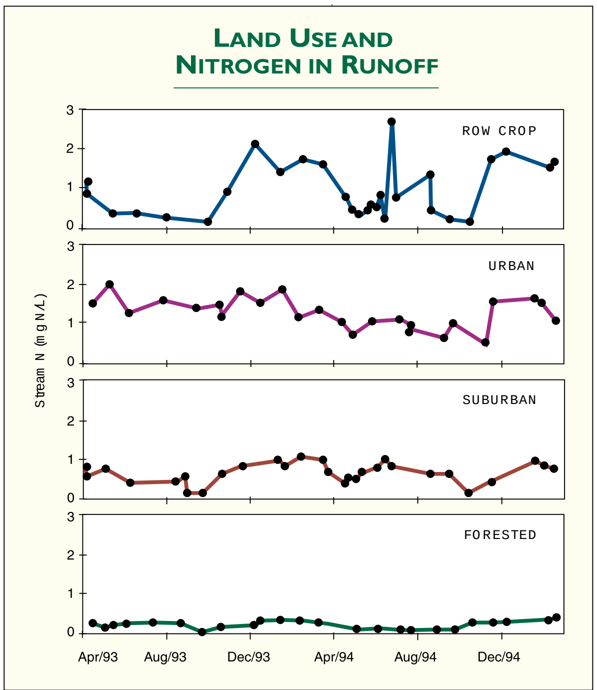


FIGURE 15: *Nitrogen concentrations in streams draining different land types.*

Coastal ecosystems are naturally very rich in plant and animal life. However, since the richness (or productivity) of saltwater ecosystems is naturally limited by the availability of reactive nitrogen, excess nitrogen can lead to a condition of over-enrichment 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 over-enrichment (Bricker et al. 1999).

The over-enrichment 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. Furthermore, 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 (see Figure 16).

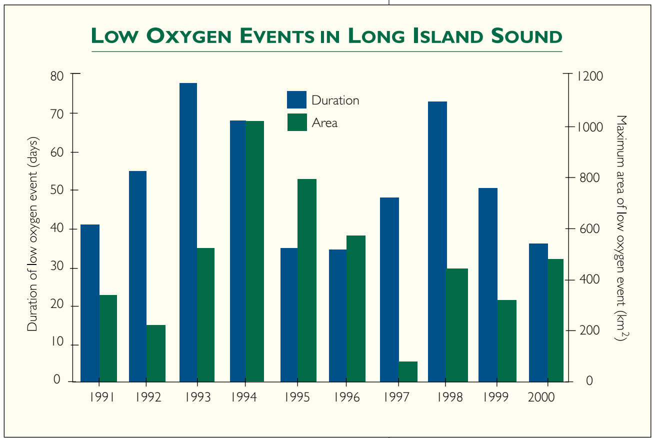
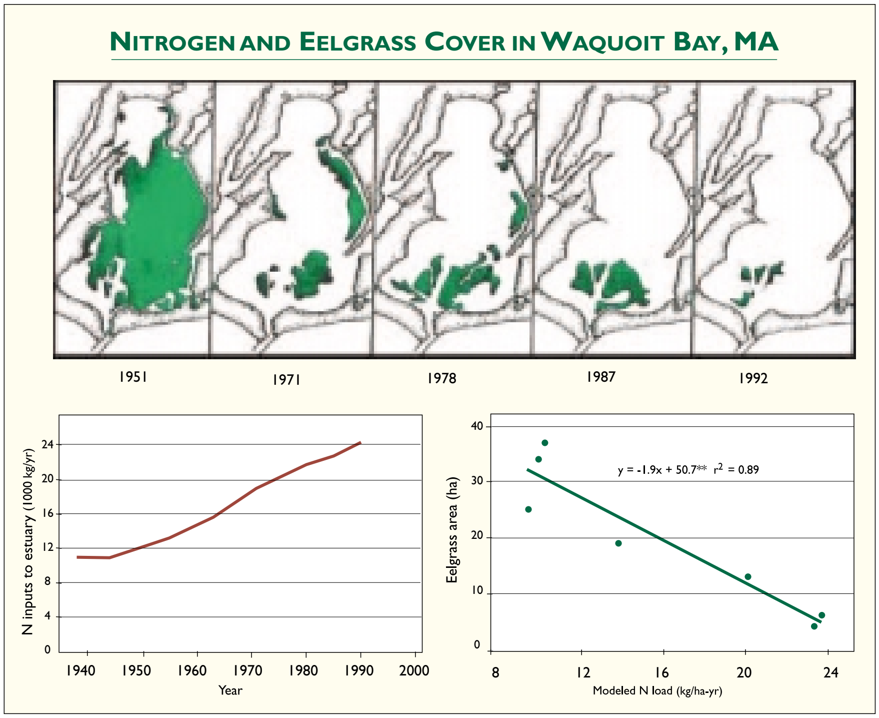


FIGURE 16: *The occurrence of low oxygen events in Long Island Sound. Data source: Connecticut Department of Environmental Protection.*

Waquoit Bay in Massachusetts is an example of an estuary where the effects of elevated nitrogen have been documented over several decades. Suburban residences on permeable soils dominate this watershed where wastewater and atmospheric deposition contribute large amounts of reactive nitrogen to the estuary. Long-term research from this site has allowed scientists to quantify the relationship between the increase in total reactive nitrogen loading to the estuary and the decreased eelgrass habitat (see Figure 17).



Pristine seagrass bed

Degraded seagrass bed

FIGURE 17: *The relationship between nitrogen loading and eelgrass coverage in Waquoit Bay, Massachusetts. From Valiela et al. 1992.*

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.

What are the most effective options for reducing airborne nitrogen pollution?

Controls on vehicle and electric utility emissions of nitrogen oxides produce the largest reductions in airborne nitrogen pollution.

The U.S. 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, the U.S. 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 over 5,750 pounds. In 1999, the U.S. 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 super low emission vehicles sold.

Nitrogen-related Air Quality Standards

Pollutant	Measurement period	Standard
Nitrogen dioxide (NO_2)	Annual mean	0.053 parts per million
Ozone	8-hour average[1] 1-hour average[2]	0.08 parts per million 0.12 parts per million
Particulate matter (10 micrometers or less in diameter)	Annual mean 24-hour average	50 micro-grams per cubic meter 150 micro-grams per cubic meter
Particulate matter (2.5 micrometers or less in diameter)	Annual mean 24-hour average	15 micro-grams per cubic meter 65 micro-grams per cubic meter

[1] Current standard
[2] Previous standard

Source: U.S. EPA. http://www.epa.gov/airs/criteria.html

For electric utilities, it is estimated that the 1990 Clean Air Act Amendments (CAAAs) 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 CAAAs 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 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.

To evaluate the effect that current and potential future policies may have on airborne nitrogen pollution in the Northeast, we used the model PnET-BGC (**P**hotosy**n**thesis and **E**vapo**T**ranspiration – **B**io**G**eo**C**hemical). 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 (see Gbondo-Tugbawa et al. 2001). The model can be used as a predictive tool to evaluate the response of forest ecosystems to changing environmental conditions, including emission scenarios. We 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.

Airborne Nitrogen Emission Reduction Scenarios

Sector	Scenario	Reduction in total nitrogen emissions
Transportation	Reduction in NO_x emissions consistent with EPA Tier 2 regulations.	24%
	90% reduction in passenger car emissions beyond EPA Tier 2 standards achieved by converting the passenger car fleet to superlow emission vehicles.	29%
Electric utilities	75% reduction in NO_x emissions beyond current levels.	10%
Agriculture	34% reduction in ammonia emissions through animal waste treatment.	2%
Integrated	90% reduction in passenger car emissions beyond EPA Tier 2 standards, 75% reduction in NO_x emissions beyond current levels and 34% reduction in ammonia emissions.	39%

* Each of these scenarios was also run with an additional 75% reduction in sulfur emissions from electric utilities beyond the emission levels required in the 1990 Clean Air Act.

Chemical Indicators of Potential Ecosystem Degradation

Indicator	Threshold
Nitrogen deposition	Greater than 8.0 kilograms of nitrogen per hectare per year (kg N/ha-yr).
Soil base saturation[1]	Less than 20%.
Stream acid neutralizing capacity (ANC)[2]	Less than 50 micro-equivalents per liter (µeq/L).
Stream acidity (pH)	Less than 6.0.
Stream aluminum (inorganic)	Greater than 2.0 micro-moles per liter (µmol/L).

Several emission 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 (see Driscoll et al. 2001 and Aber et al. 2003). We then used the PnET-BGC model to predict how these indicators are likely to change over time with each policy scenario (see Figures 18a and 18b).

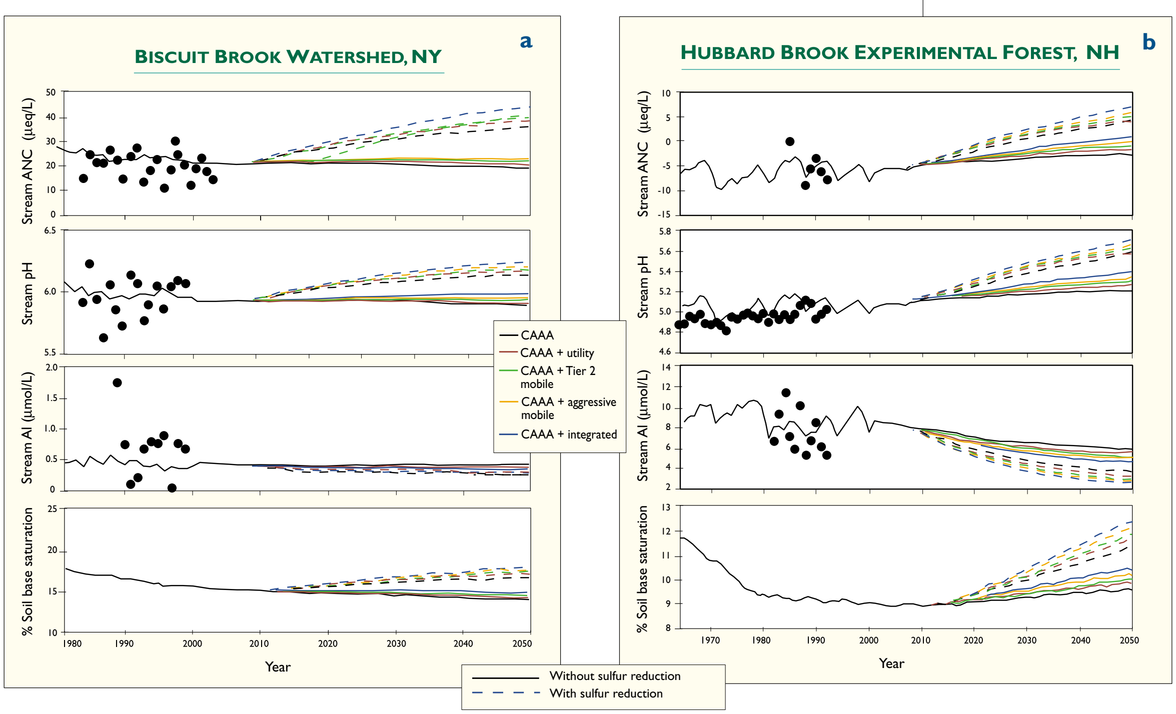
The PnET-BGC model results provide insight into the relationship between emissions reductions and ecosystem recovery. According to this analysis:

1. 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.
2. Additional reductions in total nitrogen emissions within the airshed of the Northeast (~30 percent) 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 emission reductions to reach the 8 kg N/ha-yr target. Watersheds such as the Hubbard Brook

[1] Soil base saturation reflects the amount of available nutrient cations (such as calcium and magnesium) that buffer the soil against acidity.

[2] ANC is the capacity of a liter of water to neutralize inputs of strong acid. At values less than 50 µeq/L, a stream is subject to acid episodes. Chronic acidity occurs when ANC is less than 0 µeq/L.

Figures 18a & 18b: *Model results showing the connection between nitrogen and sulfur emission reductions and ecosystem conditions. From Whitall et al. In review.*



Experimental Forest that receive lower amounts of nitrogen from atmospheric deposition would reach the 8 kg N/ha-yr target with lower emission reductions.

3. 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.
4. Under the most aggressive scenario that cuts total nitrogen emissions in the airshed by 50 percent from current levels, the targets for chemical recovery from acid rain are not reached at Hubbard Brook within 50 years. However, substantial improvements do occur, demonstrating that the emission reductions would have beneficial effects. At Biscuit Brook, the aggressive nitrogen scenario would achieve some of the targets by 2050, including stream pH (acidity). 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.
5. When cuts in sulfur dioxide emissions from electric utilities of 75 percent beyond the 1990 CAAAs are considered with nitrogen reductions, it is predicted 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.
6. The PnET-BGC model results suggest that sensitive forest ecosystems would require substantial reductions in nitrogen and sulfur emissions beyond the 1990 CAAAs in order 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 non-growing season over the long-term (Gbondo-Tugbawa and Driscoll 2002).

What are the most effective strategies for reducing nitrogen pollution to estuaries?

Nitrogen removal from wastewater at a basin-wide scale is the single most effective means of reducing nitrogen loading to estuaries in the Northeast.

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 the U.S. 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 a U.S. 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, the states of 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 estuary 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.

National Water Quality Criteria Related to Nitrogen

Pollutant	Purpose	Standard			Conditions
Nitrates	Human health	10 mg N/L			Drinking water
Ammonia	Human health	30 mg N/L			
	Aquatic life – freshwater[1]	Acute – salmonids present 36.7 mg N/L	Acute – salmonids absent 55.0 mg N/L	Chronic 3.63 mg N/L	pH dependent
	Aquatic life – saltwater[2]	Acute 9.8 mg N/L	Chronic 1.5 mg N/L		pH, salinity and temperature dependent

Source: U.S. EPA. http://epa.gov/waterscience/pc/revcom.pdf.

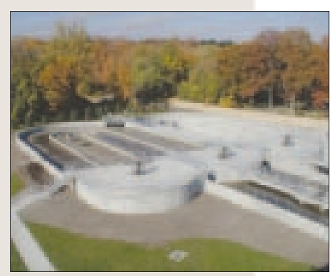
[1] Example based on pH 6.0.

[2] Example based on pH 8.0, salinity 20 grams per kilogram, temperature 15 degrees Celsius.

To compare the impact of several scenarios for reducing loading of reactive nitrogen to estuaries of the Northeast, we used the model WATERSN (Watershed Assessment Tool for Evaluating Reduction Strategies for Nitrogen). Two estuaries with differing land use characteristics were used as case studies: Long Island Sound in Connecticut and New York and Casco Bay in Maine.

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 returns to the atmosphere where it is no longer a risk to surface waters.



BNR is a three-step process that promotes the growth of organisms that break down nitrogen by exposing the wastewater to oxygen-rich and oxygen-poor conditions. In the first step, nitrogen is converted to ammonium under aerated 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.

The states of Connecticut and New York have undertaken a comprehensive effort to upgrade wastewater treatment plants with biological nitrogen removal technology in order 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 multi-billion 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.

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, deposition and nitrogen fixation in cropland) and all watershed nitrogen losses (Castro et al. 2000). Individual sources of reactive nitrogen can be altered to predict the change in estuarine nitrogen loading that would result from nitrogen pollution controls.

We defined several nitrogen reduction scenarios based on current policy options that would decrease nitrogen inputs to the estuaries. The scenarios target nitrogen reductions from each of the major sources that contribute reactive nitrogen to estuaries in the Northeast.

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% reduction in nitrogen emissions from agricultural facilities through the treatment of animal waste.
  - ~ 33% reduction in edge-of-field nitrogen runoff from agricultural facilities through increased use of best management practices.
- **Airborne nitrogen scenarios**
  - ~ 75% reduction in NO_x emissions from electric utilities from current emissions levels by 2010.
  - ~ Reductions in vehicle emissions of NO_x consistent with the U.S. EPA Tier 2 regulations.
  - ~ 90% reduction in vehicle emissions of NO_x beyond the levels achieved through Tier 2.
- **Integrated**
  - ~ Basinwide BNR, 90% reduction in NO_x emissions from vehicles beyond the Tier 2 standard, 75% reduction in NO_x emissions from electric utilities and 33% decrease in edge-of-field runoff from agricultural facilities.

The WATERSN model results (see Figure 19) are useful in guiding nitrogen management for coastal systems. The model analysis demonstrates that:

1. 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.
2. Improved wastewater treatment results in the largest reduction in reactive nitrogen loading to Long Island Sound and Casco Bay. Basinwide BNR and improvements in septic systems would achieve approximately a 55 percent reduction in reactive nitrogen loading to Long Island Sound and 40 percent to Casco Bay.

3. 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.
4. 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.

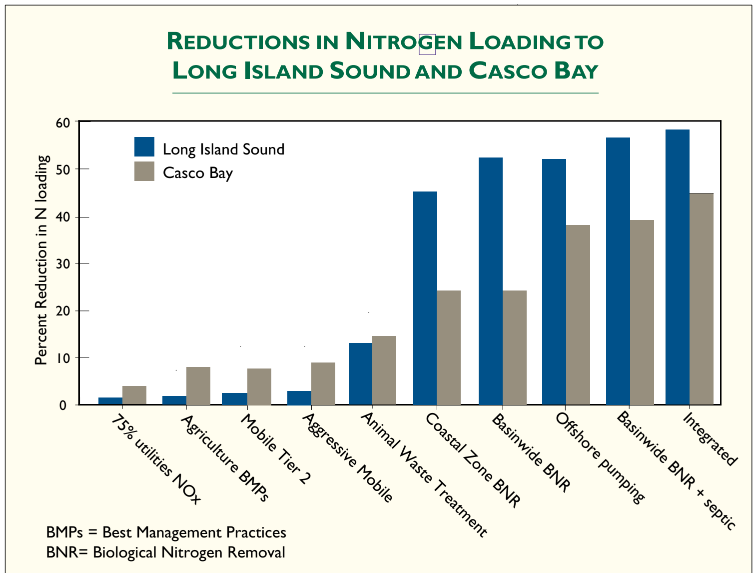


FIGURE 19: *Model results showing decreases in nitrogen loading for various management options to Long Island Sound and Casco Bay.*

In 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 over-enrichment of coastal waters. Solving the nitrogen problem will require a multi-pronged 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 in order to mitigate the impacts of high nitrogen deposition on sensitive ecosystems. Using another computer model, we determined that nitrogen loading to estuaries in the Northeast is high and dominated by nitrogen discharged from wastewater treatment plants. Moreover, 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.

Source document

The content of this report is based on the synthesis conducted by a 12-member research team convened by the Hubbard Brook Research Foundation. Except as noted, all text, tables, and figures are adapted and/or reprinted with permission from: Driscoll, C.T., D. Whitall, J.D. Aber, E.W. Boyer, C.S. Cronan, C.L. Goodale, P. Groffman, C. Hopkinson, K.F. Lambert and G.B. Lawrence. 2003. Nitrogen Pollution in the Northeastern United States: Sources, Effects and Management Options. *BioScience*. 53:4.

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The HBES is a long-term ecological research project in the White Mountains of New Hampshire. Established in 1963, the HBES first documented acid rain in North America and is one of the longest running and most comprehensive ecosystem studies in the world. The HBES is conducted at the **Hubbard Brook Experimental Forest** (HBEF), which was established in 1955 and is operated and maintained by the U.S. Forest Service Northeastern Research Station, United States Department of Agriculture.

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The findings in this report do not necessarily represent the views of the advisors.

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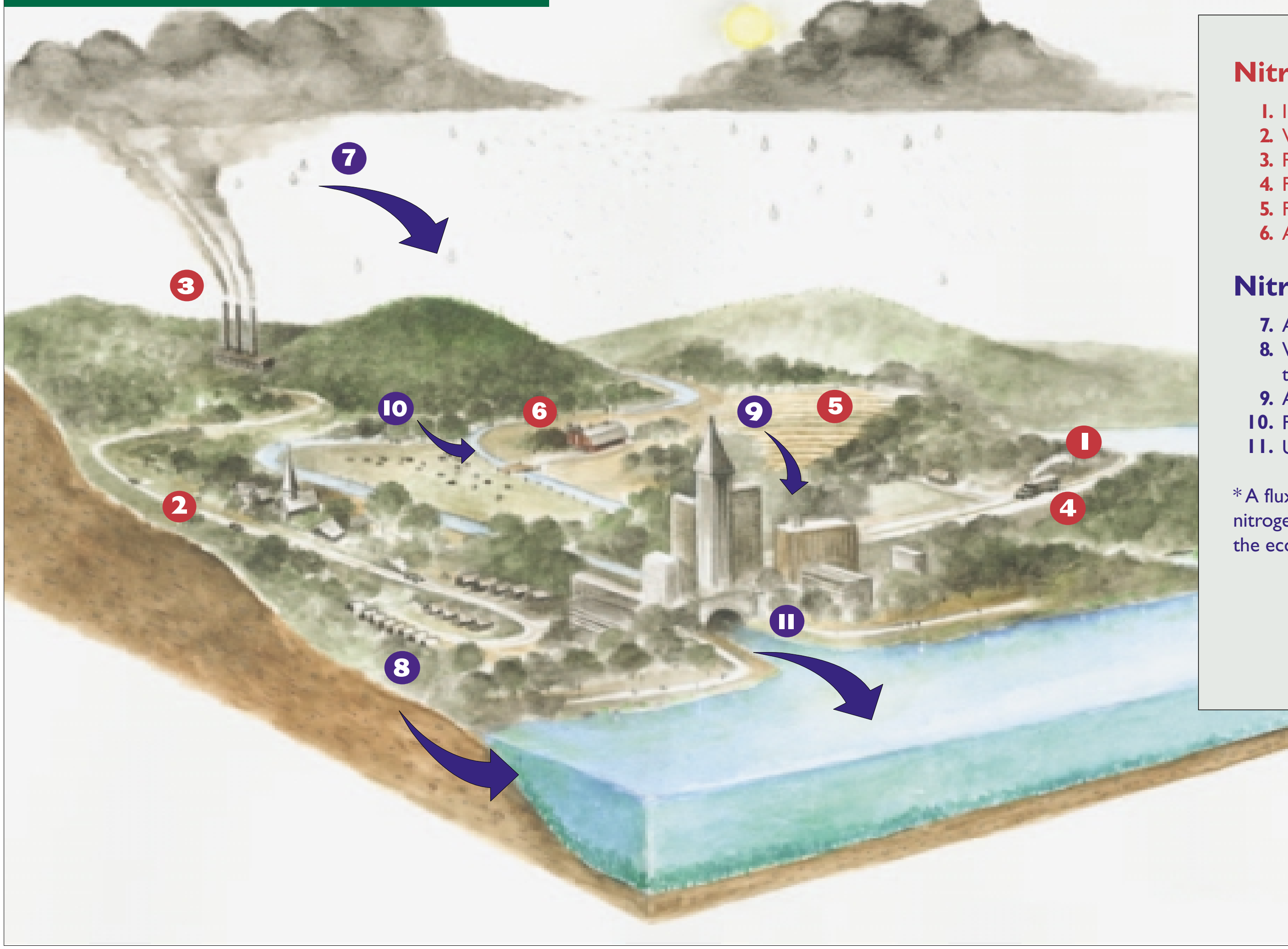
Nitrogen in a Human-Altered Landscape



Nitrogen Sources:

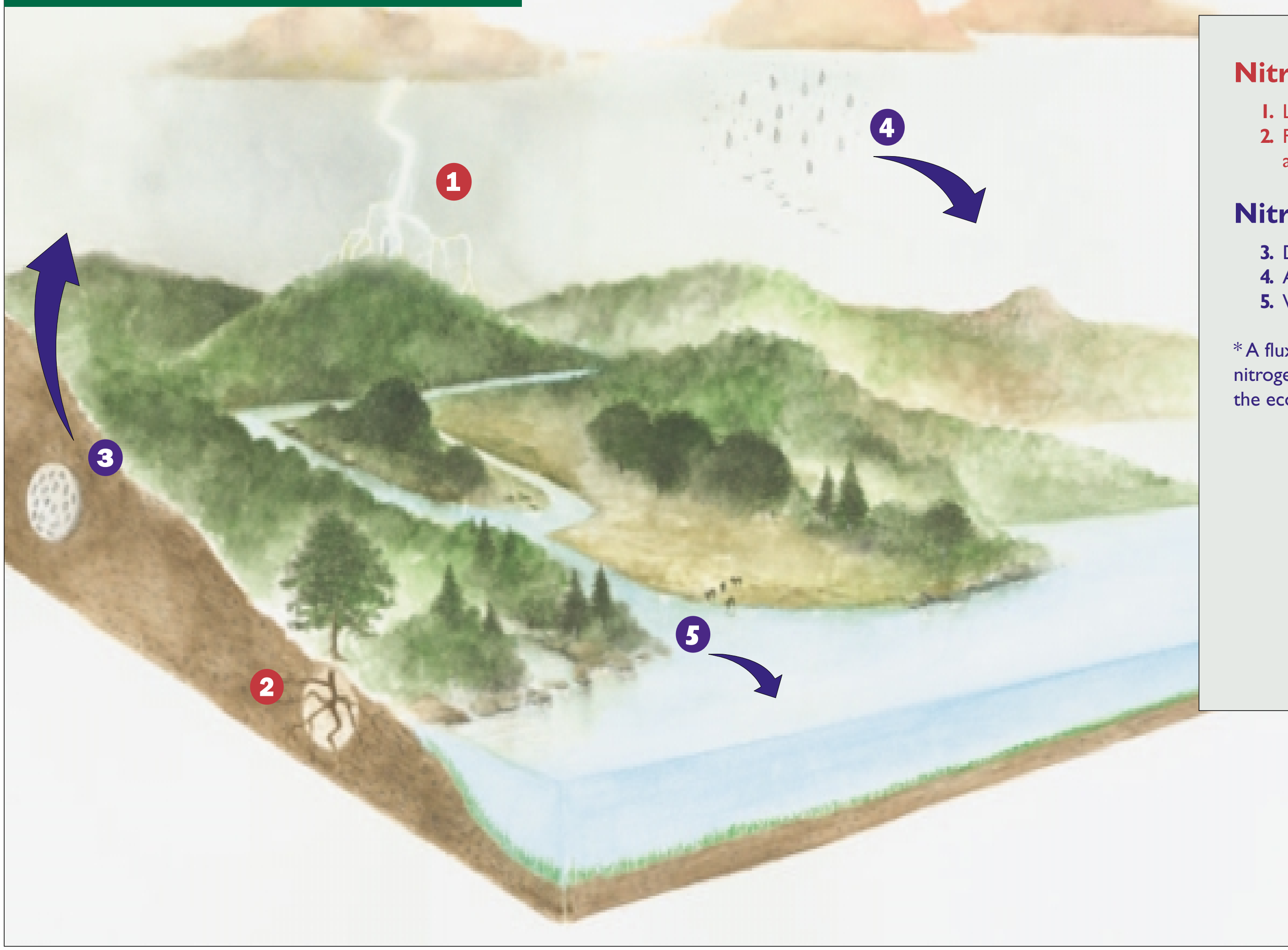
1. Imported food and feed
2. Vehicle emissions
3. Powerplant emissions
4. Fertilizer imports
5. Fixation in croplands
6. Agricultural emissions

Nitrogen Fluxes:*

7. Atmospheric deposition
8. Wastewater from septic tanks and treatment plants
9. Agricultural runoff
10. Forest runoff
11. Urban runoff

*A flux is the movement of nitrogen from one component of the ecosystem to another.

Nitrogen in a Pristine Landscape



Nitrogen Sources:

1. Lightening strikes
2. Fixation by plant-associated and soil bacteria

Nitrogen Fluxes:*

3. Denitrification by bacteria
4. Atmospheric deposition
5. Watershed runoff

* A flux is the movement of nitrogen from one component of the ecosystem to another.