Threats From Above

Air Pollution Impacts on Ecosystems and Biological Diversity in the Eastern United States

The Nature Conservancy and the Cary Institute of Ecosystem Studies

June 2008

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SUGGESTED CITATION

Lovett, G.M., and T.H. Tear. 2008. Threats from Above: Air Pollution Impacts on Ecosystems and Biological Diversity in the Eastern United States. The Nature Conservancy and the Cary Institute of Ecosystem Studies.

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Top: Coal-fired power plants are among the leading sources of airborne mercury, sulfur and nitrogen pollution. © Eric Middelkoop/BigStockPhoto.com
Botom: A newly hatched common loon chick is watched by its parent as it takes its first swim. © Daniel Poleschook Jr. and Ginger Gumm

Threats From Above

Air Pollution Impacts on Ecosystems and Biological Diversity in the Eastern United States

THE NATURE CONSERVANCY AND
THE CARY INSTITUTE OF ECOSYSTEM STUDIES

JUNE 2008

executive summary

Air pollution harms every major ecosystem in the northeastern United States, producing economic losses, reducing scenic beauty, decreasing the value of conservation investments and damaging forests, lakes, rivers, wetlands and coastal waters. These negative impacts demand swift action to reduce air pollution and further evaluate its effects.

A team of 32 experts, convened by the Nature Conservancy and the Cary Institute of Ecosystems Studies, recently evaluated air pollution's effects in the Northeast and Mid-Atlantic regions of the United States and identified the conservation implications.[1] This report summarizes their findings about the significant air pollution impacts to several major ecosystem types, evaluates the use of air pollution loading limits to conserve biological resources and presents a Call to Action for advancing critical loads and expanding national air pollution monitoring.

The air in cities contains ozone, nitrogen oxides and other pollutants. In addition to affecting the health of city residents, these pollutants can harm natural ecosystems downwind of the city.

The substantial weight of evidence established through decades of research by hundreds of scientists shows that:

- Air pollution harms natural ecosystems and threatens biological diversity in the eastern U.S.;
- Conventional land conservation and existing air quality regulations are necessary but insufficient to conserve natural ecosystems and their valuable services;
- Limits on air pollution loading, such as critical loads, should be established for sensitive ecosystems to reduce ongoing environmental damage; and
- The monitoring of air pollution and its effects must expand to better safeguard the nation's natural resources and assess the effectiveness of air pollution policies.

Air pollution harms natural ecosystems and threatens biological diversity in the eastern U.S.

Air pollution has rained down and drifted into the eastern U.S. for more than a century, altering forests, lakes, rivers, coastal waters and other ecosystems to the detriment of the plants and animals that live there. In aquatic ecosystems, air pollution acidifies surface waters, reducing their ability to sustain native fish. In estuaries and coastal waters, it contributes to nutrient over-enrichment, producing algal blooms, foul smells and low oxygen levels. It also causes mercury to accumulate in aquatic food webs, threatening the health of both people and wild animals.

In forests, air pollution acidifies soils, depleting important nutrients and reducing the productivity of some forest trees. It adds excess nitrogen, altering nutrient levels and decreasing disease resistance. It also induces ozone impacts, decreasing the ability of many plant species to harness the energy of the sun for growth and other vital functions.

Though subtle, these ecological effects can be quite serious. For example, mercury contamination may not kill fish outright, but it may threaten human health and reduce the reproductive success of the loons that eat the tainted fish. Compounding the effects of air pollution are other human-caused environmental factors including climate change, sprawl and the introduction of non-native species. As threats to the health of natural systems become more diverse and complex, our approaches to conservation and public policy must adapt.

Conventional land conservation and existing air quality regulations are necessary but insufficient to conserve natural ecosystems and their valuable services.

In the past several decades, land protection has been the primary approach to conserving biological diversity and other natural resources. Land acquisition and easements came into favor when the main threat to biodiversity was assumed to be the conversion of forests and farmlands to housing and commercial developments. The effectiveness of these conventional tools spurred the growth of the land trust movement, giving rise to the more than 580 land trusts that now exist in the Northeast alone. The Nature Conservancy itself invests tens of millions of dollars in land protection each year for the purpose of conserving global biological diversity.

Unfortunately, air pollution is pervasive and does not recognize property boundaries. Habitats and landscapes cannot be conserved by land protection alone—action to reduce air pollution must be part of the solution. Given the extent and severity of air pollution's effects on ecosystems, it is time for the conservation community, government agencies and Congress to directly address this serious threat. An important approach to expanding the suite of conservation strategies is establishing pollution loading limits.

Limits on air pollution loading, such as critical loads, should be established for sensitive ecosystems in order to reduce ongoing environmental damage.

U.S. air quality regulations currently focus on impacts to human health. While the federal Clean Air Act sets both primary standards to protect human health and secondary standards to protect general welfare and the environment, the U.S. has not fully implemented the ecologically based secondary standards. In addition, current air quality regulations focus on what is emitted into the atmosphere but do not actually limit the amount of pollution deposited to the landscape.

It is time to refocus and expand the existing approach to air pollution control in order to address ecosystem effects. In addition to establishing secondary standards, limits should be placed on the amount – or load – of a given pollutant that can be deposited. One method of setting pollution loading limits is by specifying "critical loads" for ecosystems. A critical load is the amount of pollution that can be deposited into a specified ecosystem without causing significant adverse environmental effects. Critical loads should be established for sensitive U.S. ecosystems to limit air pollution, assess federal and state regulations and manage public lands.

Many forests and lakes in the Adirondack Mountains of New York are affected by acid deposition and mercury pollution. © William Porter, Huntington Wildlife Forest

The monitoring of air pollution and its effects must expand to better safeguard the nation's natural resources and assess the effectiveness of air pollution policies.

Many important monitoring programs exist in the U.S., but there is currently no comprehensive integrated network to measure atmospheric deposition, soil and surface water concentrations of pollutants and biological effects. Biological measurements are particularly scant. Without this information, it is impossible to determine the effectiveness of the federal Clean Air Act's air pollution mandates. Existing monitoring programs must be supported and expanded to improve estimates of total air pollution deposition, measure changes in soil and surface water chemistry and track trends in plants, animals, habitats and the services they provide to humans. This expanded monitoring is critical to evaluating the efficacy of public policies aimed at decreasing air pollution impacts.

I. threats from above

Scientists have studied the environmental effects of air pollution for decades[2]. To synthesize the current knowledge of air pollution effects, The Nature Conservancy and the Cary Institute of Ecosystems Studies convened a workshop of 32 experts to assess the impacts of four major air pollutants (sulfur, nitrogen, ground-level ozone and mercury) to six target ecosystems in the Northeast and Mid-Atlantic regions of the United States. This report draws from the workshop's findings on the known biological effects of the four pollutants and evaluates the conservation implications. In general, the impacts of these four pollutants are significant and widespread across all ecosystem types, disrupting vital functions and threatening biological diversity (see Table 1).

Air pollution in the United States originates from local, regional and global sources. Pollutants are emitted into the air primarily through smokestacks, tailpipes and agricultural operations. After they are released, the pollutants may travel hundreds of miles in the air before they are deposited back to earth, either in wet deposition (rain and snow) or dry deposition (dry particles and gases). The largest U.S. sources of sulfur dioxide and nitrogen oxide emissions that produce acid rain are power plants, cars and trucks, and industrial facilities[4]. Nitrogen oxide and hydrocarbon emissions that react in the atmosphere generate ground-level ozone. The largest sources of mercury pollution in the U.S. are coal-fired power plants, followed by industrial sources and waste incinerators[5]. Many of these same sources also emit carbon dioxide, one of the most abundant greenhouse gases that contribute to climate change.

The Northeast and Mid-Atlantic regions receive some of the highest levels of atmospheric deposition (air pollution deposited to the landscape) in all of North America because of their location downwind from large industrial and urban pollution sources.

This report summarizes the biological effects for three types of terrestrial ecosystems:

(1) forests,

(2) bogs and other wetlands, and

(3) alpine and subalpine ecosystems;

In addition to stationary sources, mobile sources of air pollutants such as cars, trucks, and tractors contribute significantly to air pollution.

and three types of aquatic ecosystems:

(1) streams and rivers,

(2) lakes and ponds, and

(3) coastal waters.

While the high pollution loading in the Northeast and Mid-Atlantic regions makes these areas the subject of many scientific studies, areas throughout the U.S. suffer from the effects of acidity, ozone and mercury, underscoring that air pollution is truly a national issue.[5]

A. Air Pollution and its Ecological Effects

Air pollution has damaged many terrestrial and aquatic ecosystems in the Northeast and Mid-Atlantic regions of the United States. Among the most affected terrestrial ecosystems are forests and wetlands. Some of the most impaired aquatic ecosystems include streams and rivers, lakes and ponds and coastal waters. These ecosystems, which contain sensitive species, are common to the region and have received sufficient study to inform an evaluation of air pollution impacts.

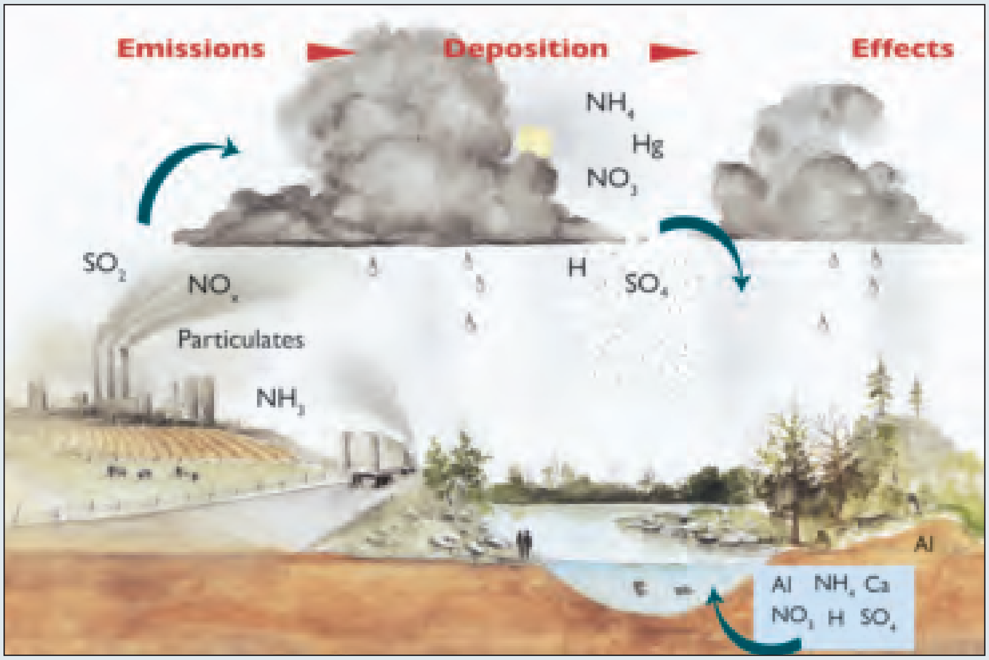
What are the biological effects of excess nitrogen, acid deposition, ozone and mercury pollution? The following sections summarize the relevant scientific literature for the major terrestrial and aquatic ecosystems following the path most pollutants take from upland forests and alpine regions to streams and rivers, flowing on to lakes and ponds and ultimately to coastal waters.

1. Nitrogen

Nitrogen is the most abundant element in the earth's atmosphere; however, its most common form, dinitrogen gas (N_2), is not directly available to most plants and animals. Because of its limited availability yet critical biological role, nitrogen controls the growth and productivity of many ecosystems. To be available to living organisms, nitrogen in the atmosphere must be converted from N_2 to a reactive form (Nr). This conversion process occurs naturally via specialized organisms, lightning and fires. However, human-driven processes such as producing nitrogen fertilizer and burning fossil fuels also produce reactive nitrogen and now play a dominant role in the nitrogen cycle.

Table 1: Ecological Effects of Air Pollution in the Northeast and Mid-Atlantic

POLLUTANT	GENERAL EFFECTS	TERRESTRIAL EFFECTS	AQUATIC EFFECTS
Nitrogen	Contributes to acidic deposition, ground-level ozone, and over-enrichment of soil and surface water.	Reduces forest productivity (under high loading). Increases potential vulnerability to pests and pathogens. Causes declines in some sensitive wetland plant populations. Alters plant species composition.	Increases algal growth and reduces water clarity in some systems. Contributes to declines in dissolved oxygen and degradation of nursery habitats in estuaries.
Acid deposition	Acidifies soils and waters, and enhances the process that makes toxic mercury available to animals.	Increases acidification of soils. Enhances the mobilization of toxic aluminum from soils to tree roots. Increases sulfate and nitrate leaching from soils to surface waters. Promotes the loss of important buffering nutrients from soils. Enhances mercury methylation in wetlands.	Mobilizes toxic aluminum to surface waters which can kill fish and other aquatic organisms. Reduces ecosystem productivity. Reduces fish species richness. Decreases invertebrate richness and abundance.
Ozone	Oxidant that damages plants and animals.	May cause foliar damage. Reduces photosynthesis and growth rate in some plants. Impairs lung function in some animals.	No documented effects.
Mercury	Known neurotoxin that accumulates in individual animals and is magnified in the food web.	Causes neurological, behavioral, and physiological effects, especially in longer-lived species and those feeding at the top of food webs. Elevated levels found in some mountain-dwelling songbirds, bats, fur-bearing mammals, reptiles, amphibians, and insects.	Causes neurological, behavioral and physiological effects in some fish species and fish-eating birds. High concentrations found in some commercial fish, game fish, and forage fish. Causes reproductive declines in fish-eating birds such as common loons and bald eagles.



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Air pollution is a complex problem. Emissions of sulfur dioxide (SO_2) and nitrogen oxide (NO_x) gases from smokestacks and vehicles react in the atmosphere to form sulfate (SO_4) and nitrate (NO_3) particles as well as sulfuric and nitric acids in clouds and rain. Mercury (Hg) is also emitted to the atmosphere from coal burning and incinerators. Agricultural activities contribute to the nitrogen pollution problem by releasing ammonia (NH_3). All of these gases, particles and dissolved chemicals can be deposited to natural ecosystems downwind of the sources. Nitrogen can accumulate in ecosystems and cause nutrient imbalances, while acid precipitation can strip important nutrients such as calcium (Ca) from the soil and mobilize toxic metals such as aluminum (Al). Acid and aluminum harm trees in the forest and fish and other aquatic animals in streams and lakes.

During the past 50 years, human actions have more than doubled the rate reactive nitrogen is added to the environment—and the rate continues to rise[6]. This accumulation of reactive nitrogen is altering the nitrogen cycle at local and global scales with serious consequences. A single atom of reactive nitrogen can cause damage throughout the environment as it moves from air to soil, fresh waters, plants and coastal waters. The term "nitrogen cascade" describes this chain of nitrogen's environmental effects[7].

In terrestrial ecosystems, excess nitrogen can lead to decreased soil fertility, reduced productivity and even tree death. The suite of nitrogen pollution impacts are described as "nitrogen saturation,"[8] which is the process of adding more nitrogen than plants and microbes can absorb, resulting in increased nitrogen leaching, changes in plant growth and, in some cases, elevated tree mortality.

Alpine and subalpine regions in the eastern U.S. receive high levels of nitrogen deposition due to the prevalence of pollutant-laden clouds and fog. However, most studies on the effects of nitrogen deposition on alpine and subalpine ecosystems have occurred in the Rocky Mountains and in Europe. At Niwot Ridge in the Rocky Mountains of Colorado, a nitrogen addition study in an alpine meadow showed that added nitrogen initially increases overall plant diversity, but the authors suggest that higher levels of nitrogen deposition or long-term accumulation may cause the reverse to occur—a decrease in plant species diversity as nitrogen "loving" (nitrophilous) species start to dominate[9]. The plant responses in this study were evident at nitrogen deposition rates as low as 4 kilograms of nitrogen per hectare per year (4 kg N/ha-yr).

These experiments in the Rockies and the overall similarity among plants of alpine ecosystems in the Rockies and the eastern U.S. suggest that nitrogen deposition may be damaging high-elevation ecosystems in the eastern U.S. Deposition loads of 10 to 40 kg N/ha-yr[10] in high-elevation areas in the East are much higher than in the West and have probably been at that level for several decades. It is possible that productivity and species shifts have already occurred in eastern alpine ecosystems.

Below the alpine zone, **spruce-fir forests and hardwood forests** dominate the terrestrial landscape of the eastern U.S. In areas where pollution is minimal, nitrogen levels are often low enough to limit forest growth. Under these conditions, added nitrogen can stimulate tree growth. However, some forests now receive too much nitrogen as a result of air pollution. Under conditions of high nitrogen deposition, the leaching of nitrate from soils to surface waters has been observed in the Northeast, suggesting that supply is exceeding demand and these forests may be in the initial stages of nitrogen saturation[11]. Nitrate leaching appears to be rare in forests receiving less than 5 kg N/ha-yr and increasingly common as deposition levels exceed 8 kg N/ha-yr[12]. Nitrate leaching can acidify soils, stripping away important buffering nutrients such as calcium and magnesium, and mobilizing harmful aluminum that can impair the function of tree roots and move into rivers and streams.


Streams in mountainous areas, such as this stream in Virginia's Shenandoah National Park, can be acidified by air pollution. © Drew Finley/BigStockPhoto.com

The question of whether current nitrogen pollution levels in the U.S. enhance or reduce tree growth is controversial[13]. However, most reports indicate that tree growth has remained stable or declined over the past two decades, suggesting it is unlikely that nitrogen pollution has had a beneficial fertilizing effect over large areas in the long term[14]. The effect of nitrogen pollution on the composition of plant species in forests is an area of active research. Shifts in tree species composition under current nitrogen deposition levels would be difficult to assess because of the long lifespan of trees and confounding effects of local land use history. Changes in abundance and composition of understory shrubs and non-woody plants have occurred in response to nitrogen deposition in Europe[15], and might be expected in the eastern U.S.


Mountaintop spruce-fir forests receive large amounts of air pollutant deposition, often in the form of wind-blown fog and mist. © Chris Galbraith/BigStockPhoto.com

Nitrogen pollution can also impose more subtle impacts on forests by altering basic processes. For example, plant-eating insects tend to prefer vegetation with higher nitrogen content, and there is some evidence that increased nitrogen may be predisposing trees to insect pest attacks[16]. Increased susceptibility to pests could be a serious liability for eastern forests, given the number of exotic insect pests that are being introduced continually through enhanced global trade[17].

During the past 15 years, several experimental studies have examined the effects of intentionally adding nitrogen to forests in this region. The nitrogen application rates in these studies vary from about two to 15 times existing nitrogen deposition levels. Most forest stands where nitrogen was added have shown increases in plant nitrogen content, production and leaching of nitrate and leaching of important nutrients such as magnesium and calcium. In three cases, the nitrogen addition resulted in declines in productivity and increases in tree mortality[18]. While tree mortality does not currently appear to be a widespread response to nitrogen deposition in the eastern U.S., it is unclear whether forests will respond the same way to future long-term accumulation of nitrogen from atmospheric deposition as they do to these experimental nitrogen additions.

Wetlands interspersed across the forested landscape are not immune to the effects of nitrogen pollution. Some wetlands, in particular bogs and fens, are among the most nitrogen-sensitive ecosystems in the region. Under pristine conditions, bogs and fens have very low levels of available nitrogen. Nitrogen pollution can be problematic for plants that have adapted to survive in these low nutrient environments. As nitrogen levels increase, unique bog plants are replaced by competitors that can take advantage of the available nutrients. Shifting plant species composition is one of the most significant impacts of nitrogen on bogs and fens[19]. This subject has received extensive research attention in Europe, where increases in nitrogen deposition have been associated with declines in typical bog species such as the sundew and certain species of sphagnum moss. A nitrogen enrichment study of bogs in New England showed substantial declines in growth and reproduction of a specialized carnivorous plant — the pitcher plant – and suggests that nitrogen deposition above 5 kg N/ha-yr decreases the survival of pitcher plant populations[20]. The authors project that if there is no change in current nitrogen deposition rates, there is a high probability that local pitcher plant populations will become extinct within 100 to 250 years (see Box 1)[21].

Box 1. Nitrogen impacts on the pitcher plant

The pitcher plant, a common sight in northeastern bogs, is a carnivorous plant that has adapted to low nutrient conditions by evolving the ability to capture insects and digest them in its "pitcher," a modified leaf. The addition of excess nitrogen to pitchers changes pitcher plants by causing them to have fewer and smaller pitchers and more photosynthetic leaves. Even slight increases in nitrogen deposition above current levels in bogs studied in the Northeast will increase the risk of extinction of pitcher plants.

As nitrogen pollution "cascades" through upland landscapes, some drains into nearby surface waters (i.e. streams, rivers, lakes and ponds) where it can change the nutrient balance, contribute to acidification and, in severe cases, cause eutrophication. Eutrophication is the addition of an essential but limited nutrient (such as nitrogen or phosphorus) that stimulates the growth of aquatic plants.[22] The decomposition of this excess plant matter depletes oxygen from the water, to the detriment of many animals. Nitrogen is not usually considered a limiting nutrient in temperate freshwater ecosystems; however, there is some recent evidence that very low-nitrogen surface waters may be limited or co-limited by nitrogen and the potential for eutrophication effects is currently being re-assessed[23].

The effects of nitrogen in **estuaries, bays and salt marshes** are better understood than the impacts to freshwaters. In coastal water, nitrogen pollution is associated with excessive plant growth, reduced dissolved oxygen and harmful algal blooms[24]. Nitrogen inputs to these ecosystems include agricultural and urban runoff, industrial and municipal wastewater and atmospheric deposition to the estuary and to its watershed. The mix of these sources is unique to each watershed but typically atmospheric deposition accounts for 25 percent to 40 percent of the total[25].

Most estuaries and bays in the Northeast and Mid-Atlantic regions exhibit some degree of eutrophication due to excess nitrogen loading[26]. A recent national assessment found that 65 percent of the assessed ecosystems had moderate to high eutrophic conditions[27]. In the Northeast, none of the 12 estuaries assessed ranked high in eutrophic conditions; however 60 percent were listed as "moderate or moderate to high"[28]. In the Mid-Atlantic region, 70 percent of the 22 estuaries evaluated were rated "moderate to high" or "high" in eutrophic conditions. Estuaries with high eutrophic conditions generally had received the greatest nitrogen loads.

Salt marshes are well known for their ability to incorporate most forms of nitrogen pollution, often responding with higher plant growth[29]. Nutrient additions to salt marshes can change species composition, generally allowing tall-form smooth cordgrass to expand in coverage at the expense of other marsh plants. These plant changes have measurable effects on animals such as annelid worms, which are important consumers in the salt marsh sediments[30]. Furthermore, comparative studies of salt marshes in Rhode Island show a negative relationship between nitrogen loading (where most of the variation is driven by sewage loads) and plant species richness. Over a range of watershed nitrogen loadings from 1 to 30 kg N/ha marsh area -yr, species richness declined by half [31].

The Chesapeake Bay, like other East Coast estuaries, suffers from pollution by excess nitrogen. © David Dorner/BigStockPhoto.com

Submerged aquatic vegetation such as eelgrass provides important habitat for shellfish and finfish[32]. These habitats are also known to be very sensitive to the effects of eutrophication. At Waquoit Bay in Massachusetts, researchers found a strong negative relationship between nitrogen loading and measured eelgrass area based on measurements of eelgrass coverage from 1951 to 1992[33].

There have been several attempts to determine impact levels for nitrogen in coastal waters. Shifts in plant composition have occurred at loadings of about 25 kg N/ha-yr (evaluated per hectare of estuary and marsh area) and possibly less[34]. Not only are these levels probably many times higher than a century ago, they are likely to increase with continued human population growth, especially in the coastal corridors of the eastern U.S.

2. Acid deposition

Emissions of sulfur dioxide, nitrogen oxides and other acid-forming compounds cause acid rain or, more broadly, acid deposition. Acid deposition can acidify soils and surface waters and leach important nutrients from soils. The amount of sulfur deposited from the atmosphere far exceeds the needs of forests plants in the Northeast and Mid-Atlantic regions of the U.S. As a result, most of the sulfur is either leached from the ecosystem as sulfate or retained in the soils. In glaciated regions of the Northeast, soils have little capacity to retain sulfate, so most of the sulfate deposition leaches through the soils, stripping away important soil nutrients such as calcium and magnesium. Nitrogen pollution contributes to the leaching of nitrate from soils with similar ramifications. The resulting acidification of soils mobilizes harmful aluminum, which can be toxic to tree roots, fish and other aquatic organisms[35].

The fog and mist that are so prevalent in **alpine and subalpine ecosystems** carry high loads of acid pollution[36]. There have been few studies on acid deposition's impact on alpine ecosystems in the eastern or western U.S. However, the effects of acid deposition in the subalpine zone of the eastern U.S. have been studied in great detail. There, acid deposition leaches calcium from the needles of red spruce trees, rendering the tree less frost hardy and causing winter damage and, in many cases, tree death (see Box 2)[37]. This impact is thought to be responsible for the widespread spruce decline observed in northeastern mountains during the 1980s, a problem that continues to this day[38].

Box 2. Damage in the Mountains


© Paul Schaberg

Mountain forests of the eastern U.S. are subject to high levels of acid deposition, partly because they are frequently bathed in acidic clouds[42]. The acid deposition depletes nutrients such as calcium and magnesium from the soil while stripping those nutrients from the trees' needles. This "one-two punch" can knock out sensitive species, particularly red spruce. Research in Vermont and elsewhere has shown that the loss of calcium from red spruce needles reduces their cold-hardiness and leads to freezing damage during cold winters[43]. The red spruce in this photo shows the reddish needles that are characteristic of freezing damage. This acid-induced cold sensitivity was probably the main cause of the observed decline of red spruce in the Northeast's mountains during the 1980s, which is an ongoing problem today[44].

In lower-elevation **hardwood forests**, the loss of soil nutrients can stress plants that require a high calcium or magnesium supply such as sugar maple, white ash, basswood and flowering dogwood. Declines in sugar maple, an economically important tree species, have been observed in calcium-poor areas in central and western Pennsylvania and are attributed to a combination of acid deposition and insect outbreaks[39]. Poor regeneration of sugar maple has also been linked to the loss of available soil calcium associated with acid rain[40]. Fertilization of plots with calcium and magnesium appears to reverse the decline[41].

Animals that inhabit forest ecosystems also may be affected by soil acidification. Earthworms, slugs, centipedes and other arthropods with high-calcium needs are among the soil animals known to be sensitive to acidity, although most of the studies are from high-deposition areas in Europe[45]. Few studies have been conducted on higher-order animals. One study reports that the productivity of wood thrush populations is negatively correlated with acid deposition levels across the northeastern U.S.[46] This is a correlative result, but the proposed mechanism for the response is plausible—that acid rain reduces the quantity or quality of the soil invertebrates that are the main source of calcium for wood thrushes. The reduction in acid-sensitive invertebrates is also reported to have caused declines in European birds[47]. In an acidified forest in Pennsylvania, adding lime to increase calcium levels improved the bird habitat[48].

Wetlands are generally less impaired by acid deposition than other types of ecosystems. However, recent research has documented an important synergistic effect between sulfur deposition and the increased production of methylmercury, a form of mercury that readily biomagnifies through food webs in the environment. Added sulfur can stimulate the activity of specialized bacteria in wetland sediments, which convert inorganic mercury to methylmercury. Given the decades-long deposition of sulfur to the wetland-rich landscape of the

Northeast and Mid-Atlantic regions, the impact is widespread and severe. (See page 12 for more on mercury pollution.)

The impacts of acid deposition on upland forests and wetlands have adverse consequences for downstream **surface waters**. Much of the sulfate, nitrate and aluminum that is leached from the soil eventually flows into lakes and streams. As a result, acid deposition lowers the pH (increases the acidity) of surface waters, decreases acid neutralizing capacity and increases the concentrations of toxic forms of aluminum[49]. Acid-neutralizing capacity (ANC), the ability of water to neutralize strong acids, is a primary indicator of sensitivity to acidification. These effects of acid deposition have been well known since the 1970s, and there is little doubt about the serious impact acidification has on a wide range of aquatic organisms.

Aquatic organisms vary widely in their sensitivity to acidification. The most sensitive organisms tend to be adversely affected when pH drops below about 6, while some tolerant organisms can survive in waters as acid as pH 4. (The pH scale is logarithmic, so that pH 4 is 100 times more acidic than pH 6.) The sensitivity of various organisms to acidification has been well documented and the general patterns are summarized in Box 3. As stream acidity increases, sensitive species either die out or seek refuge in less-acidified sections of the stream. Animals that can move downstream such as fish and invertebrates will often "drift" in search of better habitat conditions.

Stream and lake acidification can be chronic (persistent throughout most of the year) or episodic (occurring primarily after rainstorms or snowmelt events). When surface waters become chronically acidic, both fish populations and fish species diversity can decline. For example, research at Shenandoah National Park in Virginia demonstrated that one fish species is lost for approximately every 21 micro-equivalents per liter decrease in minimum ANC levels from 160 to -10 micro-equivalents per liter[50]. In the Adirondack Mountains of New York, one fish species is lost for every 0.8 unit decline in lake pH from pH 6.5 to 4.0[51]. In lakes of the Adirondacks and the White Mountains in New Hampshire, an average of 2.4 zooplankton species (small animals that are consumed by fish) are lost with each pH unit decrease[52]. The effects of acidic deposition are most severe in high-elevation, headwater streams and lakes. Larger, low-gradient, lower-elevation streams and rivers in the Northeast and Mid-Atlantic show fewer impacts. In these larger watersheds, the neutralizing capacity of the watershed soils often buffer the effects of atmospheric deposition.

Episodic—or short term—acidification occurs during high-flow events such as large rainstorms or snowmelt periods. These acid pulses can release high concentrations of dissolved aluminum, which can be toxic to fish in a short period of time. In gill-breathing animals such as fish, aluminum can interrupt respiration and other vital functions[53], causing the animal to die if it cannot find refuge.

In addition to the direct impacts of acid rain on species and ecosystems, indirect effects in lake and stream ecosystems are also important. For instance, increased acidity can reduce the concentration of dissolved organic carbon (DOC) in lakes, decreasing the brown coloration of the water and allowing light to penetrate further into the lake. The increased sunlight warms the lake, alters the ability of prey species to avoid their predators, and may increase the growth of algae and other plants on the lake bottom. DOC is important for another reason: it can make aluminum less toxic, so a decrease in DOC increases the toxicity of aluminum to fish and other organisms. Waterfowl are also impacted by acid deposition through two mechanisms. First, acidity mobilizes toxic metals (such as mercury) in the food chain and these metals may accumulate in the birds. Second, acidity, aluminum or other acid-mobilized metals may kill organisms that are part of the birds' diet. In Ontario, fish-eating birds have been found to be less abundant and breed less successfully on acidified lakes[54].

3. Ozone

Ozone gas (O_3) is formed in the atmosphere when nitrogen oxides react in the presence of sunlight with other gases known as volatile organic compounds. Research on the effects of ozone has shown clear impacts on plant growth and other vital functions. Once ozone enters a plant through small pores known as stomata, it reduces the plant's ability to harness sunlight for growth. While ozone at the levels found in the eastern U.S. usually does not kill plants outright, it does slow their growth and may make them more susceptible to other fatal stresses such as insect attack or disease. Ozone exposure also can reduce the flowering of some plants, compromising the establishment of new plants[56]. In addition, ozone can slow the rate of decomposition of leaves shed from plants[57]. Because plant species vary in their sensitivity, ozone can shift the competitive balance among plant species in a forest to the detriment of sensitive species such as white ash, black cherry and American sycamore[58]. Further, ozone exposure can cause changes in the genetic structure of plant populations by reducing or eliminating sensitive individuals[59]. Studies show that ambient levels of ozone can decrease forest productivity in the Northeast from 2 percent to 16 percent[60], with potential economic consequences.

Several different indices of ozone exposure are used to assess ecological effects. Sum06, an index commonly used in plant research, represents the cumulative exposure to ozone concentrations over 0.06 parts per million (ppm). Research has shown that Sum06 levels of 8-12 ppm-hr or greater are likely to produce leaf and needle injury to some plants in natural ecosystems[61].

The effects of ozone on the plants, shrubs and mosses of alpine and wetland ecosystems have not been extensively studied. However, several of the tree species that are commonly found in or around wetlands in this region, such as green ash and speckled alder, are considered sensitive to ozone, suggesting that measurable ozone impacts are plausible.

While there is considerable research on ozone damage to plants, less information is available on the effects of ozone on wildlife. Given the well-known effects of ozone on the human respiratory system, there may be significant impacts of ozone exposure on any animals with similar respiration mechanisms[62].

4. Mercury

Mercury (Hg) is a pervasive pollutant in the eastern U.S. Although it can enter ecosystems as a result of water discharges and poor waste management at industrial sites, this report focuses on mercury emitted through smokestacks. Once emitted to the atmosphere, mercury returns to earth in wet and dry deposition and accumulates in the environment. In moist soils and wetland sediments, mercury can be converted to methylmercury, the form of mercury that readily biomagnifies and bioaccumulates. Plants appear to be insensitive to methylmercury, but methylmercury is a potent neurotoxin in animals that can cause physiological, behavioral, and, at high concentrations, reproductive harm[63]. Mercury is magnified as it moves through food webs, therefore animals high on the food chain are at the highest risk of methylmercury toxicity. Long-lived animals are also at high risk because mercury can accumulate in muscles and organs over time.

For many years, prevailing wisdom held that mercury is only a problem in aquatic environments. However, recent findings show that animals in some **terrestrial ecosystems** contain surprisingly high levels of methlymercury. For example, elevated methylmercury has been measured in birds of subalpine ecosystems, such as the blackpoll warbler and the endemic Bicknell's thrush[64]. Methylmercury concentrations in these birds seem to be greatest in areas of high mercury deposition[65]. The methylmercury in these environments may be biomagnified through forest food webs that include microscopic organisms, invertebrates and, ultimately, songbirds near the top of the food chain. While many questions remain regarding the cycling and impacts of mercury in eastern forests, existing evidence suggests the impacts may be more widespread than early research suggested[66].

Wetlands play an important role in the cycling of mercury pollution. Wetlands have high rates of methylmercury production because of the low oxygen conditions in the soils and wetland sediments[67]. The methylation process is also fed by the addition of sulfur pollution. As sulfur is deposited to wetlands, the activity of sulfur-reducing bacteria increases[68].

Ozone can damage the leaves of native trees and other plants, as illustrated by the brown spots on the needles of this white pine. © Andrew Boone from ForestryImages.org

Box 3. Sensitivity of aquatic species to acidification [55]

pH CHANGE	GENERAL BIOLOGICAL EFFECTS
6.5 to 6.0  Fathead minnow. © NY State Dept. Of Environmental Conservation	Little community change; possible effects on highly sensitive fish species (e.g. fathead minnow, striped bass).
6.0 to 5.5  May fly. © Howard Cheek/BigStockPhoto.com	Loss of sensitive species of minnows and dace (fathead minnow, blacknose dace). Perhaps decreased reproduction of walleye and lake trout; increased accumulation of filamentous green algae. Changes in species composition and decrease in species richness in phytoplankton, zooplankton and benthic invertebrate communities. Loss of some zooplankton species and many species of clams, snails, mayflies, amphipods and some crayfish.
5.5 to 5.0  Rainbow trout. © Genadj Kurlin/ BigStockPhoto.com	Loss of lake trout, walleye, rainbow trout, smallmouth bass, creek chub. Further increase in filamentous green algae. Loss of many zooplankton species as well as all snails, most clams and many species of mayflies, stoneflies and other benthic invertebrates.
5.0 to 4.5  Leopard frog	Loss of most fish species. Further decline in the biomass and species richness of zooplankton and benthic invertebrate communities. Loss of all clams and many insects and crustaceans. Reproductive failure of some acid-sensitive amphibians, including spotted salamanders, Jefferson salamanders and the northern leopard frog.

From Baker et al. 1990 [55]

These bacteria convert inorganic mercury to methylmercury, which can transfer to rivers and lakes where it biomagnifies through the food web. This interaction between sulfur and mercury increases the adverse impact of mercury in wetlands receiving inputs of sulfate[69]. Animals near the top of the food chain in fens, bogs and other wetlands, such as birds that consume invertebrates, are at a high risk for mercury accumulation in these ecosystems.

Mercury moves through wetlands and upland environments to **streams and lakes**. According to extensive research, the impacts of mercury levels on freshwater fish as well as fish-eating birds and mammals include declines in reproductive success, lower disease resistance and impairment of key survival behaviors (such as grooming and feeding).

Fish species with high mercury levels include large, long-lived species such as walleye, northern pike and largemouth and smallmouth bass. Other species with elevated mercury include yellow and white perch and lake trout. A recent synthesis of mercury research from the Northeast shows that mercury concentrations in fish tend to decrease with increasing pH, sulfate and acid neutralizing capacity in lakes[70]. The direct effects of methylmercury on fish include the inhibition of normal growth and male sex organ development[71], reduced predator avoidance[72] and decreased reproduction[73].

Northern river otters are subject to mercury accumulation because of the high proportion of fish in their diet. © Alain Turgeon/BigStockPhoto.com

There are few studies of mercury's effects on amphibians, with the important exception of salamanders. Salamanders often exhibit elevated mercury levels, and the absence of salamander species in some habitats has been linked to chemical changes such as greater acidification and increased methylmercury availability[74]. There is compelling evidence that the high input of mercury and sulfur in the Appalachian Mountains could have negative impacts on populations of the many salamander species that reside in upper watershed streams and ponds[75].

The impact of mercury contamination on birds is a serious conservation concern. Bird species in which the effects of mercury are well known from laboratory and field studies include the mallard[76], common loon and bald eagle. Mercury poisoning in these birds can lead to reduced reproductive success, behavioral changes such as reduced time spent hunting, and neurological problems such as brain lesions, spinal cord degeneration and tremors[77]. Recent research on common loons demonstrates that reproduction is lower in birds with blood mercury levels equal to or greater than 3.0 ppm[78]. Mercury has been shown to harm the reproductive success of wild populations including the bald eagle in Maine[79], the great egret in Florida[80], the clapper rail in San Francisco Bay, California[81]and the snowy egret in Nevada[82].

Mercury exposure and effect levels in mammals, particularly for fish-eating species, are relatively well known. Considerable research on mink and river otter shows they experience sublethal effects including impaired motor skills and weight loss. Laboratory studies on mink indicate that impacts in the wild are highly likely[83].

Mercury impacts can be magnified in some freshwater ecosystems due to the impacts of abundant wetlands, acidic surface waters, reservoir fluctuation and extremely high deposition near local emission sources[84]. An analysis of nearly 15,000 data points in the northeastern U.S. and southeastern Canada documented five biological mercury hotspots and nine suspected hotspots where average mercury concentrations exceed the EPA action level of 0.3 parts per million (ppm) in yellow perch or 3.0 ppm in common loons[85]. In some of these hotspots, mercury deposition is actually quite low but methylation and bioaccumulation rates are very high, demonstrating that even low annual loadings of mercury can cause significant ecological impacts.

Box 5. Mercury impacts to the common loon

A female common loon carries a chick on her back. © Daniel Poleschook Jr. and Ginger Gumm

Common loons are among the most-studied animals for mercury exposure. Loons are especially susceptible to mercury contamination because they eat fish and are thus subject to the results of biomagnification of mercury in the aquatic food web. Loons are also relatively long-lived birds and can accumulate mercury in their bodies over their lifetime. High mercury levels in loons can cause behavioral effects that can lead to reduced reproductive rates and, thus, to declining populations.

It is well known that freshwater wetlands are hotspots for mercury methylation, but the role of **coastal habitats** such as salt marshes is less well understood and of increasing concern[86]. Recent research indicates that blood mercury concentrations in the saltmarsh sharp-tailed sparrow tend to be higher than other songbirds[87] and high mercury levels may be correlated with lower reproductive success. It is likely that saltmarsh sharp-tailed sparrows have significantly higher blood mercury levels than another sparrow species sharing a similar range because they consume prey higher on the food chain[88].

B. Air Pollution and Environmental Change

Understanding the complex interactions among air pollutants and other environmental disturbances such as climate change presents a monumental challenge for scientists and conservationists alike. Not only do multiple pollutants interact, but the changing climate affects every biological and chemical process in ecosystems. For example, increases in temperature have reduced the duration of ice cover on lakes[89], and changes in temperature also affect the frost-hardiness of spruce trees subject to acid deposition[90]. Gradients of temperature and moisture strongly affect the distribution of organisms[91], so the whole assemblage of ecosystems can change as the climate shifts. While it is extremely difficult to predict the precise effects of pollutants on ecosystems in a changing climate, it is clear that pollution reduction will have positive effects under any climatic conditions.

Invasions of non-native species also interact with air pollution. Deposition of nitrogen may make some habitats more suitable for weedy invasive plants[92] and may make trees more susceptible to exotic pests[93]. Invasive aquatic species can radically change the community composition of surface waters, thus altering the effects of acid deposition on the biota.

Land use changes influence the effects of air pollution by changing the distribution of emission sources and by changing the physical characteristics of the landscape that receives the pollution[94]. For example, forest edges capture more pollution than interior forests[95] and urban lands and row crop agriculture export two to three times more nitrogen runoff per acre than forested landscapes[96]. Therefore, as watersheds fragment and urbanize, nitrogen pollution to downstream waters is likely to increase.

In general, while controlled studies have enhanced scientific understanding of the effects of air pollution, the added impacts of other environmental changes—climate change, land use change and non-native species invasions—makes it difficult to predict ecosystems' responses to changing pollutant loading. However, these complications should not be an excuse for inaction. **Lowering atmospheric deposition will reduce the likelihood of damage to natural ecosystems, no matter what other stresses are present.**

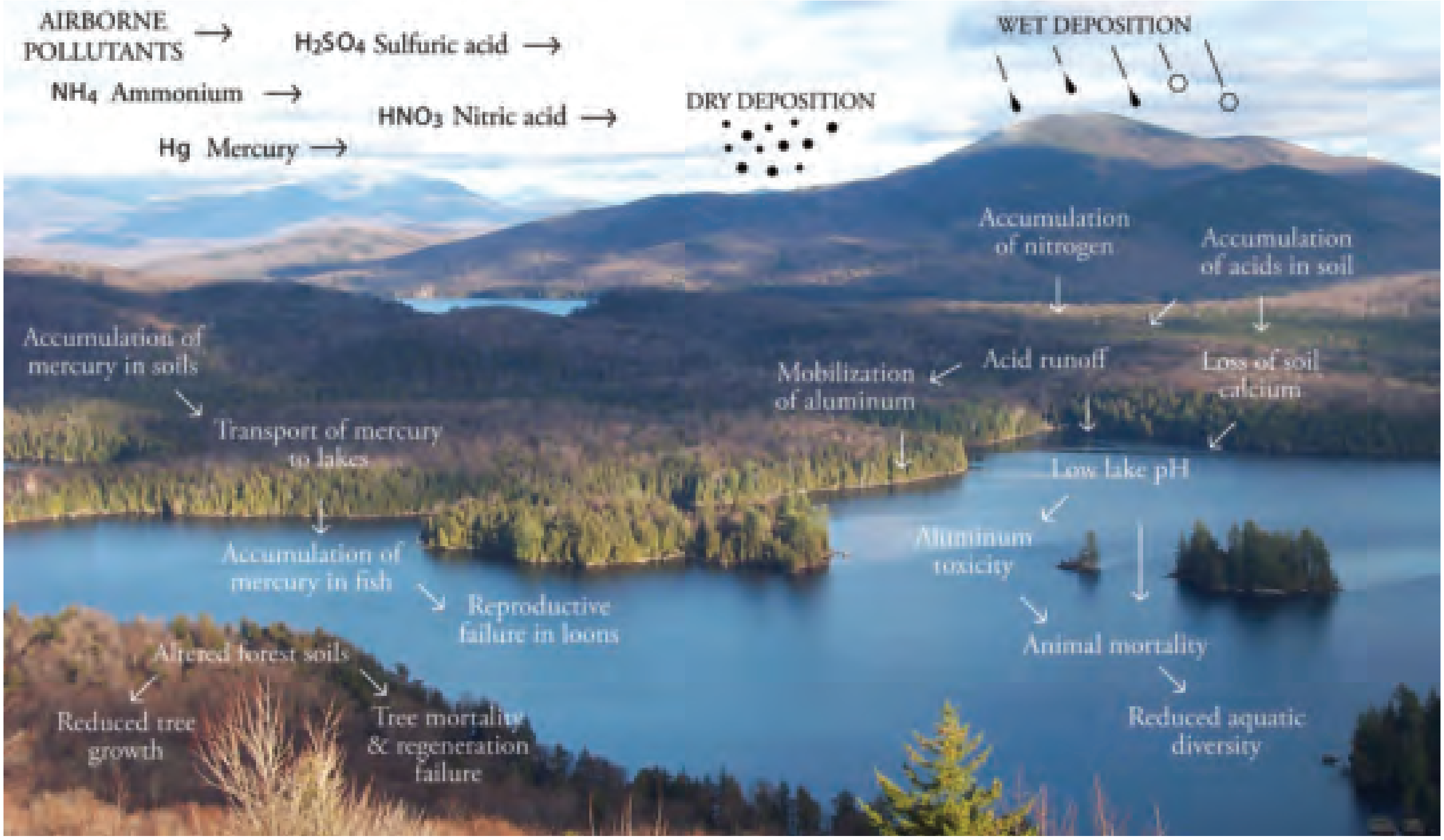
II. air pollution, biological diversity and critical loads

While important questions remain, the scientific evidence is clear: Air pollution adversely impacts most types of ecosystems in the Northeast and Mid-Atlantic regions and must be further reduced. The conservation of biological diversity and other natural resources during the past several decades has relied on conventional land protection methods such as land acquisition and the purchase or donation of conservation easements. This approach came into favor when the principal threat to biodiversity was assumed to be land conversion for residential and commercial development. The effectiveness of conservation easements and land acquisition spurred the land trust movement, giving rise to the more than 580 land trusts that now exist in the Northeast alone. The Nature Conservancy itself invests millions of dollars in land protection each year for the purpose of conserving global biological diversity.

While these investments have been important to protecting biodiversity, it is clear that the impacts of atmospheric pollution threaten to undermine these efforts. An expanded approach to conservation that accounts for atmospheric pollutants will help safeguard the centuries of personal and financial investments made to preserve these ecosystems for people and wildlife. This could be accomplished by establishing more ecologically based air pollution standards (known as secondary standards) and by developing limits on air pollution loading.

Despite the well-documented environmental harm caused by atmospheric nitrogen, sulfur, ozone and mercury pollution, the U.S. has never implemented a separate secondary standard specifically aimed at reducing the environmental effects of these pollutants. Current U.S. air quality regulations focus on what is emitted into the atmosphere, but do not actually limit the amount of pollution deposited to the landscape.

Air pollution loading limits are based on the amount of a given pollutant that is deposited to ecosystems. Several approaches are used to determine whether pollution deposition levels are acceptable. Two of the most commonly used methods are: (1) red line/green line designations and (2) critical loads.
The **red line/green line approach** was first used to help



The multiple ecological pathways and impacts of acid deposition and mercury in forested watersheds in the Eastern U.S.
(Courtesy of the Adirondack Nature Conservancy and Adirondack Land Trust - photograph by Bill Brown; conceptual diagram by Jerry Jenkins).

managers of U.S. Forest Service wilderness areas determine the potential impacts of new air pollution sources proposed upwind of wilderness areas[97]. The green line is the deposition or concentration level below which there is high certainty of no adverse impacts, and the red line is the deposition or concentration level above which there is high certainty of adverse impacts on at least some component of the ecosystem. The selection of green and red line values is largely based on existing evidence and professional judgment. Between the red line and the green line is the "yellow zone" where more information is needed to determine if air pollution will have a significant impact.

The **critical load** is a pollutant's maximum level of deposition that does not incur long-term harm to ecological health. The concept and its application first emerged in Europe to address pollution problems under the Convention on Long-range Transboundary Air Pollution (LRTAP). Critical load calculations typically determine the amount of pollution that can be deposited in a specific geographic area without harming natural resources. In theory, if pollution loads are kept below these critical values, environmental harm can be avoided or perhaps reversed. Comparing critical load values to current deposition levels can determine where and by how much current pollution levels should be reduced.

Researchers must identify and define a number of factors in order to quantitatively estimate the critical loads for atmospheric pollutants. These factors include the type of pollution causing the disturbance, the characteristics of the receiving ecosystem, the sensitive elements within that ecosystem and a definition of harm. In addition, a numerical relationship must be developed between the deposition and the impacts to the ecosystem. This relationship is generally based on either an empirical dose-response relationship or model simulation. Given the wide variation in sensitivity across the landscape, an analysis of critical loads may result in several critical load values for a given atmospheric pollutant.

The development of critical loads is a complex process that often requires years of supporting data. However, several studies provide a substantial start. Many relevant critical load studies of U.S. forests in the Northeast generally use a catchment-based approach[98]. Several critical loads of acid deposition have been estimated for lakes in the Northeast[99] and for streams in the Mid-Atlantic States and central Appalachians[100]. In the western U.S., the primary concern is establishing critical loads for nitrogen deposition affecting terrestrial and aquatic resources through eutrophication or nitrogen enrichment[101]. This considerable body of research clearly indicates that ample resources exist to begin developing and implementing critical loads in key areas of the U.S.

Several efforts are underway to promote the use of critical loads to both manage air pollution and protect key public resources in the U.S.[102] Such efforts include:

- The National Park Service, EPA and Colorado Department of Health are using critical loads at Rocky Mountain National Park. They have established a target load of 1.5 Kg N/ha-yr based on nitrogen impacts to aquatic algal communities. This work provides an excellent example to build on.
- The Conference of New England Governors and Eastern Canadian Premiers (NEG/ECP) undertook a program to estimate sustainable acidic deposition rates for upland forests of the New England States and the Eastern Canadian Provinces. They conducted regional assessments of the sensitivity of northeastern North American forests and estimated deposition rates required to maintain forest health and productivity on large spatial scales. They have also provided estimates of critical loads for surface waters in northeastern North America.
- In May 2006, the EPA, NPS, USFS, USGS and others convened a critical loads workshop that called for the development of critical loads pilot projects for sulfur and nitrogen. The EPA recently funded two projects, one in the eastern U.S. and one in the West.
- The National Atmospheric Deposition Program established an *ad hoc* committee on critical loads, demonstrating significant state and federal agency interest in moving this concept forward.

These efforts emerged in part in response to recommendations by the National Research Council (NRC) and the federal Clean Air Act Advisory Committee (CAAAC), which urged the EPA to expand its ecosystem protection and ecological assessment capacity, including exploring issues such as the use of critical loads in the development of secondary National Ambient Air Quality Standards. In its findings and recommendations to EPA[103], the NRC Committee on Air Quality Management stated:

Nitrogen deposition has serious impacts on Rocky Mountain National Park in Colorado. Critical loads have been established for this park to help evaluate the threat. © Melannie Hartman

"The CAA currently directs the administrator to protect ecosystems from criteria pollutants through the promulgation and enforcement of ambient concentration-based standards (that is, the secondary NAAQS). However, concentration-based standards are inappropriate for some resources at risk from air pollutants, including soils, groundwaters, surface waters and coastal ecosystems. For such resources, a deposition-based standard would be more appropriate. One approach for establishing such a deposition-based standard is through the use of so-called 'critical loads.' …[T]his approach has been adopted to protect ecosystems from acid rain by the European Union with some success[104]."

The CAAAC also recommends examining critical loads as a useful tool for protected ecosystems in its 2005 report to the EPA[105].

While current efforts to promote the use of critical loads in the U.S. are laudable, they have not yet reached the stage where critical load values are widely available and agreed-upon for a range of pollutants and ecosystem types; and they will be insufficient without sustained commitment, resources and organizational support. To advance critical loads efforts in the U.S., regulatory reform and investments in research and monitoring are necessary. Initial efforts should focus on establishing and attaining critical loads for sulfur, nitrogen and acid deposition in sensitive areas that are the focus of intensive research, such as the Adirondack and Catskill Mountains of New York, Acadia National Park in Maine, the northern and southern Appalachians and the Rocky Mountains. Parallel to developing critical loads for these pollutants and ecosystems, investments in research and development could expand the knowledge base in other regions and advance critical loads research for other atmospheric pollutants, particularly mercury and ozone.

Serious information gaps exist for many ecosystems. Extensive data exist for some ecosystem types in the Northeastern and Mid-Atlantic states, but air pollution impacts are probably underestimated for other ecosystem types in that region and for other regions of the United States. The important monitoring networks that currently exist should be expanded to form a comprehensive, integrated network to measure atmospheric deposition, soil and surface water chemistry and biological effects.

The current networks that provide important information about atmospheric deposition and water chemistry include four networks that measure different aspects of air quality and deposition—the National Atmospheric Deposition Network (NADP), the Mercury Deposition Network (MDN), the Clean Air Status and Trends Network (CASTNET) and Integrated Monitoring of Protected Visual Environments (IMPROVE)—and two networks that measure trends in stream and lake chemistry in the East—the Temporally Integrated Monitoring of Ecosystems (TIME) and Long-Term Monitoring Network (LTM). It is essential that each of these networks receive the funding they need to thrive. But supporting existing monitoring is not enough. Establishing a more comprehensive, integrated monitoring network would provide the information needed to evaluate and refine critical loads for sulfur and nitrogen, develop critical loads for mercury and track ecological responses to changes in air pollution loading over time.

III. a call to action

Air pollution harms every major ecosystem type in the Northeastern and Mid-Atlantic states, producing economic losses, reducing scenic beauty, decreasing the value of conservation investments, and damaging forests, lakes, rivers, wetlands and coastal waters. Despite these widespread impacts, there are no standards in place to actually limit the amount of pollution deposited to the landscape.

Conventional land protection tools and current air pollution regulations are necessary but insufficient to protect the nation's life support systems from high levels of atmospheric pollutants such as sulfur, nitrogen, mercury and ozone. The science shows that we must act to address this dangerous gap. Investments that serve to reduce air pollution can reap benefits for ecosystem productivity, human health and economic livelihoods.

In 2006, The Nature Conservancy and the Cary Institute of Ecosystem Studies convened a workshop of scientists and conservationists to examine air pollution impacts on plants, animals and habitats in the Northeast and Mid-Atlantic states. The participants produced a workshop report detailing the nature and scope of the problem (Lovett and Tear 2007, see www.ecostudies.org/reprints/Effects_of_atmospheric_deposition_on_biodiversity.pdf).

Based on the cumulative weight of the scientific evidence, The Nature Conservancy and the Cary Institute of Ecosystem Studies issue this call to action to confront the pervasive problem of air pollution damage to our nation's natural resources.

We call on Congress, federal and state agencies, conservation groups and scientists to work together to (A) establish critical loads to conserve sensitive ecosystems and (B) expand monitoring of air pollution and its effects to create a comprehensive national program.

Brook trout, though relatively acid-tolerant, cannot survive in highly acidified streams and lakes. Photo: Barry Baldigo, U.S. Geological Survey

A. Establish Critical Loads to Conserve Sensitive Ecosystems

We recommend the development and implementation of critical loads to protect sensitive ecosystems. We know that current deposition exceeds harmful levels in many landscapes. In other regions, we lack the data needed to recommend specific deposition limits. Air pollution doesn't recognize regional boundaries and therefore requires a national solution. Members of Congress, federal and state regulators, land managers, research scientists and conservation organizations must work together to advance policy and management solutions. We offer the following specific recommendations:

1. **Congress** should direct the Environmental Protection Agency (EPA) to develop and implement critical loads for sulfur, nitrogen and mercury pollution, beginning with sensitive ecosystems that receive high deposition levels. Congress also should allocate funding for the research and monitoring needed to support this national initiative. Setting critical loads should be viewed as an evolving process, in which loading limits are established based on the best available data and later refined as more data become available from targeted studies.

2. **The EPA** should use critical loads to assess the progress made under the Clean Air Act and other regulations such as the Clean Air Interstate Rule. We cannot rely on air chemistry measurements alone to determine whether air pollution is continuing to damage our natural resources.

3. While critical load development is underway, the **EPA** should use the best available science to establish enforceable, ecologically based air quality standards for sulfur, nitrogen and ozone through the National Ambient Air Quality Standards. However, because the air quality standards only address the concentration of pollution in the air, critical loads must supplement these standards for sulfur, nitrogen and mercury.

4. **Federal land management agencies** such as the U.S. Forest Service and the National Park Service should expand their efforts to develop site-specific critical loads to protect key public resources in high-pollution areas such as the White and Green Mountain National Forests and Acadia and Shenandoah National Parks, following the precedent set in the Rocky Mountain National Park.

Bald eagles are at high risk of mercury accumulation because they often consume fish.

5. Partnerships between **research scientists and government agencies** should be formalized and expanded to further assess the impact of atmospheric deposition to our nation's biological resources and to develop dose-response relationships for specific pollutants that can be used to support and refine critical loads.

6. **Conservation organizations** should include atmospheric deposition in their conservation agendas and should advance the development of critical loads by supporting necessary legislative changes, adapting land management activities to account for impacts of atmospheric deposition and offering their lands and waters for critical loads research and development.

B. Expand Monitoring of Air Pollution and its Effects to Create a Comprehensive National Program

Despite years of research documenting the impacts of air pollution on our natural life support systems, currently there is no integrated national monitoring program in place to measure the comprehensive effects of changing emissions. Monitoring of atmospheric deposition and surface water chemistry has been essential to U.S. policy formulation and assessment, but the funding for these programs is constantly under threat. Further, there is no comprehensive monitoring of the impacts of air pollution on forests, soils, or most plants and animals. Therefore, we recommend that:

1. **Increased funding should be allocated to expand existing multi-pollutant monitoring programs** so that current efforts to monitor air pollution and surface water chemistry can expand, and new programs can be implemented to monitor forests, soils, wildlife and other natural resources that are threatened by air pollution. A comprehensive and integrated monitoring network would help address important information gaps and inform the development and refinement of critical loads.

2. **The comprehensive air pollution monitoring program should be established as soon as possible** and should build on existing efforts. As part of this effort, current air pollution monitoring programs should be fully funded. These programs include: the National Atmospheric Deposition Program, the Mercury Deposition Network, the Clean Air Status and Trends Network, Integrated Monitoring of Protected Visual Environments and the Temporally Integrated Monitoring of Ecosystems and Long-Term Monitoring Network.

3. **The comprehensive air pollution monitoring program should be long-term and national in scope**, it should use established monitoring procedures, and it should initially focus on the impacts of atmospheric deposition on natural resources. The program should also be designed with capacity to expand in the future to measure responses to other environmental changes such as climate change, invasive species and urbanization.

ACKNOWLEDGMENTS

We thank the contributors to this report, who are listed on the cover, for their valuable help with writing and reviewing the report. We are grateful to the participants in the workshop that was the genesis of this report. We also thank Charles Canham who helped us conceive the project and organize the workshop, and Gene Likens for his encouragement, assistance and participation in the workshop. This effort is possible due to a grant from the Rodney Johnson and Katherine Ordway Stewardship Fund within The Nature Conservancy.

CREDITS

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Near-shore fish sampling in the upper Hudson River. More extensive and integrated biological monitoring is needed to understand the impacts of air pollution.
Photo: Barry Baldigo, U.S. Geological Survey

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Many streams in the Shenandoah Mountains of Virginia are acidified due to air pollution. © S. Gogolev/ BigStockPhoto.com

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