ACID RAIN REVISITED

Advances in scientific understanding since the passage of the 1970 and 1990 Clean Air Act Amendments

HBRF

A Science Links™ Publication of the Hubbard Brook Research Foundation

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The HBES is a long-term ecological research study 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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Suggested format for citing this report:
Driscoll, C.T., G.B. Lawrence, A.J. Bulger, T.J. Butler, C.S. Cronan, C. Eagar, K.F. Lambert, G.E. Likens, J.L. Stoddard, K.C. Weathers. 2001. Acid Rain Revisited: advances in scientific understanding since the passage of the 1970 and 1990 Clean Air Act Amendments. Hubbard Brook Research Foundation. Science Links™ Publication. Vol. 1, no.1.

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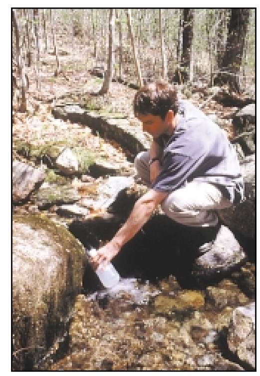

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Summary

Acid rain is still a problem and has had a greater environmental impact than previously projected.

Many people believe that the problem of acid rain was solved with the passage of the 1990 Clean Air Act Amendments (CAAA). However, research from the Hubbard Brook Experimental Forest (HBEF) in New Hampshire and other study sites in the northeastern United States (hereafter the Northeast) demonstrates that acid rain (hereafter acid deposition) is still a significant problem. Although sulfur emissions that contribute to acid deposition have declined, nitrogen emissions have not changed substantially region-wide and have actually increased in some areas of the eastern United States.

Acid deposition delivers acids and acidifying compounds to the Earth's surface, which then move through soil, vegetation, and surface waters and, in turn, set off a cascade of adverse ecological effects. Recent research shows that the ability of some ecosystems to neutralize acid deposition has diminished over time, delaying the recovery of forests, lakes, and streams. Moreover, while the Clean Air Acts of 1970 and 1990 have improved air quality somewhat, the emissions reductions mandated in 1990 are not likely to bring about full ecosystem recovery in sensitive areas of the Northeast.

Acid deposition has altered soils in areas of the Northeast.

Until recently, limited understanding existed of the effects of acid deposition on soil. However, current research shows that acid deposition has altered, and continues to alter, soil in a number of ways:

- Acid deposition has accelerated the leaching of base cations — elements such as calcium and magnesium that help counteract acid deposition — from the soil in acid-sensitive areas of the Northeast. For example, the amount of available calcium in the soil at the HBEF appears to have declined more than 50 percent over the past several decades.
- A strong positive relationship exists between inputs of sulfur and nitrogen and the concentrations of these elements in forest soils. As a consequence, sulfur and nitrogen have accumulated in forest soils across the region.
- Acid deposition has increased the concentration of dissolved inorganic aluminum in soil waters. Dissolved inorganic aluminum (hereafter simply aluminum) is an ecologically harmful form of aluminum. At high concentrations, aluminum can hinder the uptake of water and essential nutrients by tree roots.

The alteration of soils by acid deposition has serious consequences for acid-sensitive ecosystems. Soils that are compromised by acid deposition are less able to neutralize additional amounts of acid deposition, provide poorer growing conditions for plants, and delay ecosystem recovery.

Acid deposition has stressed trees in areas of the Northeast.

The 1990 National Acid Precipitation Assessment Program (NAPAP) report to Congress concluded there was insubstantial evidence that acid deposition had caused the decline of trees other than red spruce growing at high-elevations. More recent research shows that acid deposition has contributed to the decline of red spruce trees throughout the eastern U.S. and sugar maple trees in central and western Pennsylvania. Symptoms of tree decline include poor crown condition, reduced tree growth, and unusually high levels of tree mortality. Red spruce and sugar maple are the species that have been the most intensively studied and research to date has shown that:

- Acid deposition leaches essential calcium from needles (i.e., foliage) of red spruce, rendering them more susceptible to freezing injury. Increased freezing injury has lead to the mortality of more than half of large canopy red spruce trees in some forests in the Northeast.
- Extensive mortality among sugar maples in Pennsylvania appears to result from deficiencies of base cations, coupled with other stresses such as insect defoliation or drought. The data show that sugar maples are most prone to die on sites where base cation concentrations in soil or foliage are lowest.

Acid deposition has impaired lakes and streams in the Northeast.

Acid deposition has impaired, and continues to impair, the water quality of lakes and streams in three important ways: lowering pH levels (i.e., increasing the acidity); decreasing acid-neutralizing capacity (ANC); and increasing aluminum concentrations. High concentrations of aluminum and increased acidity have reduced the species diversity and abundance of aquatic life in many lakes and streams in the Northeast. Fish have received the most attention to date, but entire food webs are often negatively affected. Recent water quality data show that:

- 41 percent of lakes in the Adirondack Mountain region of New York and 15 percent of lakes in New England exhibit signs of chronic and/or episodic acidification.
- Only modest improvements in ANC, an important measure of water quality, have occurred in New England. No significant improvement in ANC has been measured in the Adirondack or Catskill Mountains of New York.
- Elevated concentrations of aluminum have been measured in acid-impacted surface waters throughout the Northeast.

The Clean Air Act has had positive effects, but emissions and deposition remain high compared to background conditions.

Regulatory controls initiated in the 1970s and 1990s decreased sulfur dioxide emissions, yet these emissions remain high compared to background conditions. Controls on nitrogen oxides and ammonia have not been fully addressed; consequently, emissions of these compounds are high and have remained largely unchanged in recent years. In the period 1995-1997, wet deposition of sulfate in the Northeast was approximately 20 percent lower than levels in the preceding three years with implementation of the 1990 CAAA. However, wet deposition of nitrogen has not changed significantly since the 1980s. Importantly, the emission and atmospheric deposition of base cations that help counteract acid deposition have declined significantly since the early 1960s with the enactment of pollution controls on particulate matter.

The rate and extent of ecosystem recovery from acid deposition are directly related to the timing and degree of emissions reductions.

Given the loss of acid-neutralizing base cations and the accumulation of sulfur and nitrogen in the soil, many ecosystems are now more sensitive to the input of additional acids and recovery from acid deposition will likely be delayed. Research shows that emissions reductions mandated by the 1990 CAAA are not sufficient to achieve full ecosystem recovery in watersheds in the Northeast that are similar to the HBEF within the next 25-50 years. Analyses of policy proposals calling for an additional 40-80 percent reduction *in electric utility emissions* of sulfur beyond the levels set by the 1990 CAAA show that such proposals would result in measurable improvements in chemical conditions. Specifically, with an additional 80 percent reduction in sulfur emissions from electric utilities, streams such as those at the HBEF would change from acidic to non-acidic in approximately 20-25 years. *In sum, long-term research suggests that deeper emissions cuts will lead to greater and faster recovery from acid deposition in the Northeast.*

Is acid rain still a problem?

Research from the northeastern United States demonstrates that acid rain is still a problem.

SUMMARY: Many people believe that the problem of acid rain was solved with the passage of the 1990 Clean Air Act Amendments (CAAA). Research from the Hubbard Brook Experimental Forest (HBEF) in New Hampshire and from other study sites in the northeastern United States (hereafter the Northeast) demonstrates that acid rain (hereafter acid deposition, a more accurate term) is still a problem.

DETAILS: Although sulfur emissions that contribute to acid deposition have declined, nitrogen emissions have not decreased substantially region-wide and have actually increased in some areas of the eastern United States.[1] Moreover, the ability of ecosystems to neutralize acid deposition has decreased in some regions. Consequently, lakes, streams, and soils in many parts of the Northeast are still acidic and exhibit signs of degradation linked to acid deposition.

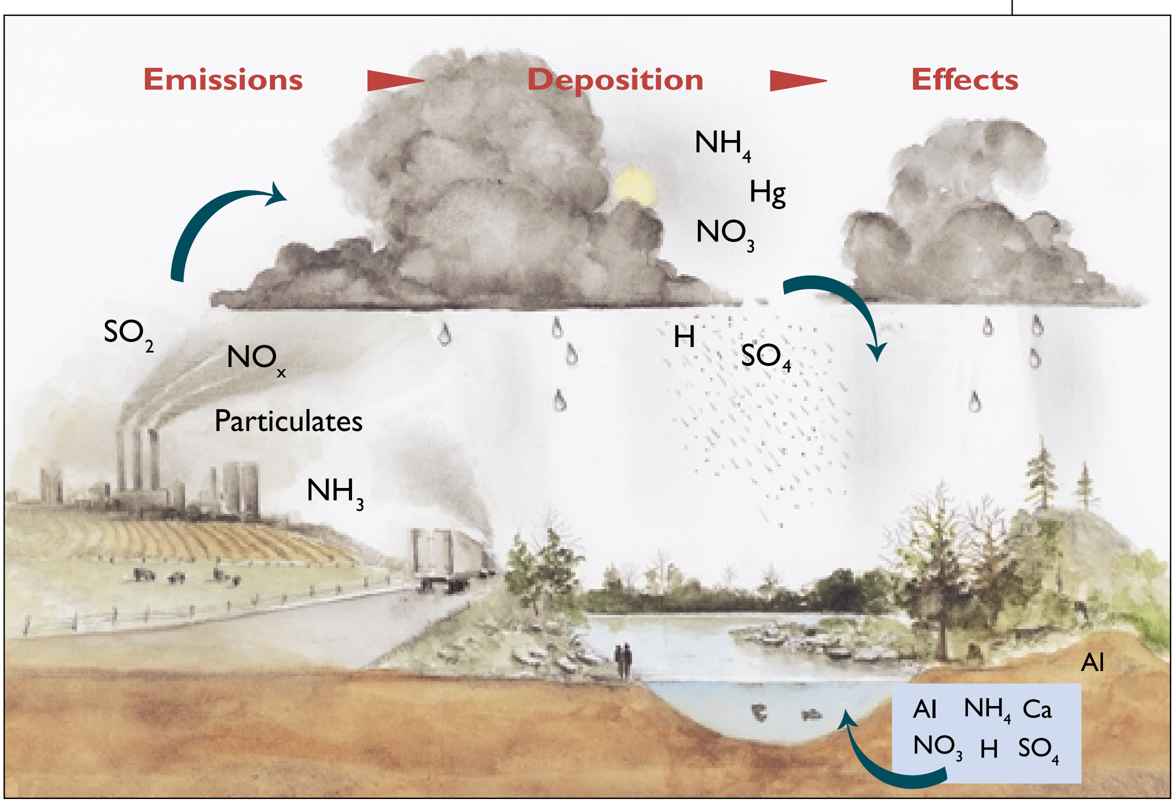
Over the past ten years, scientists have gained greater insight into the ways in which acid deposition alters ecosystems. When it was first identified in the early 1970s, acid deposition was viewed as a simple problem that was limited in scope. Scientists now know that acids and acidifying compounds move through soil, vegetation, and surface waters, setting off a cascade of adverse ecological effects (see Figure 1). Further, the same emissions that cause acid rain contribute to other important environmental issues, such as smog, climate change, mercury contamination in fish and over-fertilization of coastal waters.

Over the past decade, advances have also been made in understanding the mechanisms and processes of ecosystem recovery. This report presents recent research into acid and acidifying emissions, trends in acid deposition, the ecological effects of acid deposition, and the process and likelihood of ecosystem recovery from acid deposition. The report focuses on the Northeast and relies heavily on long-term data from the Hubbard Brook Experimental Forest (HBEF).

Since 1990, scientists have gained greater insight into the ways in which acid deposition alters ecosystems.

[1] *The term* **emissions** *refers to the pollution released from smokestacks, tailpipes, and other sources, whereas* **deposition** *pertains to the pollution that is deposited on the surface of the land or water.*

FIGURE 1: *Acid deposition is a complex problem that originates with the burning of fossil fuels and leads to the deposition of acids, setting off a series of ecological effects.*



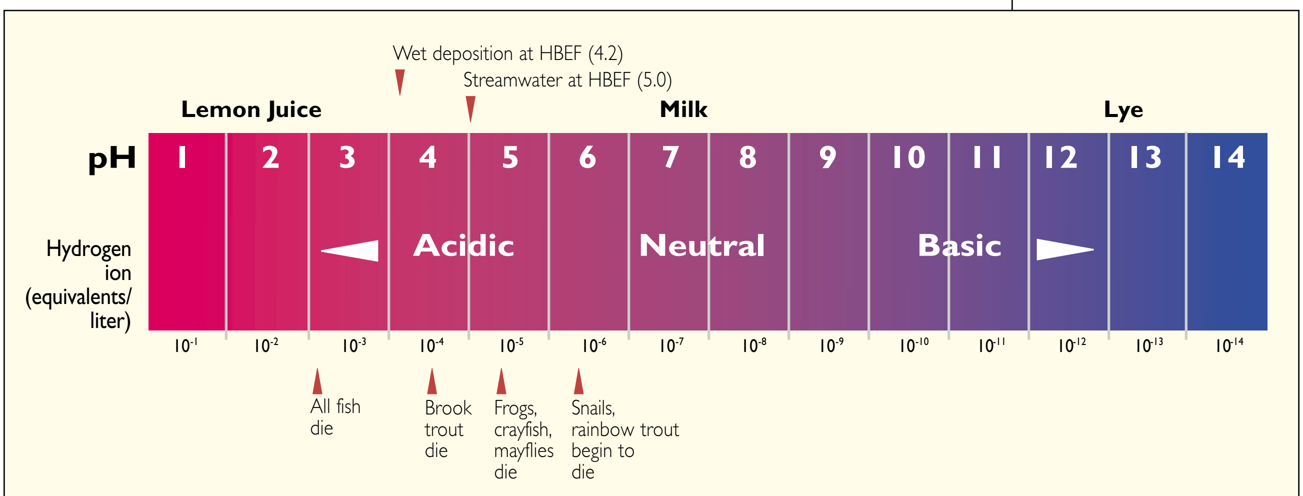
What is acid deposition?

Acid deposition is the input of acids from the atmosphere to the Earth's surface.

SUMMARY: Acid deposition is comprised of sulfuric acid, nitric acid and ammonium derived from sulfur dioxide (SO_2), nitrogen oxides (NO_x), and ammonia (NH_3). These compounds are emitted by the burning of fossil fuels and by agricultural activities. Once these compounds enter an ecosystem, they can acidify soil and surface waters and bring about a series of ecological changes. The term acid *deposition* encompasses all the forms in which these compounds are transported from the atmosphere to the Earth, including gases, particles, rain, snow, clouds, and fog.

DETAILS: Sulfuric and nitric acid lower the pH of rain, snow, soil, lakes, and streams. pH is a gauge of acidity, as measured by the concentration of hydrogen ion (see Figure 2). In 1997, wet deposition in the Northeast (i.e., deposition from forms of precipitation such as rain, snow, sleet, and hail) had an average pH of 4.4, which is about ten times more acidic than background conditions. In general, low pH levels in lakes and streams create conditions that are inhospitable to fish and other aquatic organisms. Similarly, low pH conditions alter forest soils, degrading growing conditions for some tree species.

FIGURE 2: *pH scale*



How is acid deposition monitored?

Acid deposition occurs in three forms: **wet deposition,** which falls as rain, snow, sleet, and hail; **dry deposition,** which includes particles, gases, and vapor; and **cloud** or **fog deposition** which occurs at high altitudes and in coastal areas. Wet deposition has been monitored at more than 200 sites, some such as the HBEF since 1963, by both independent researchers and the inter-agency National Atmospheric Deposition Program/National Trends Network. Dry deposition is monitored at 70 sites nationwide by the U.S. Environmental Protection Agency Clean Air Status and Trends Network and at 13 other sites by the National Oceanic and Atmospheric Administration AIRMoN-dry Network. Cloud and fog deposition has been monitored for limited periods at selected high-elevation sites, largely by independent researchers. Dry and cloud deposition patterns are extremely variable over space and time, making it difficult to characterize regional patterns. Therefore, even though cloud and dry deposition comprise a significant proportion of total deposition, this report primarily presents general patterns and trends of wet deposition.

What causes acid deposition?

Acid deposition is caused primarily by the emission of sulfur and nitrogen oxides from the burning of fossil fuels by electric utilities and motor vehicles.

SUMMARY: Electric utilities account for the greatest proportion of sulfur dioxide emissions in the United States. The transportation sector, however, is the largest source of nitrogen oxide emissions. Ammonia emissions derive largely from livestock waste and fertilized soil.

DETAILS: In 1997, the major sources of sulfur dioxide emissions were electric utilities (60 percent), industrial combustion (17 percent), and industrial processes (8 percent). Transportation sources — including cars, trucks, and non-road vehicles (i.e., construction equipment) — accounted for more than 50 percent of all nitrogen oxide emissions. Other major sources of nitrogen oxides include electric utilities (26 percent) and industrial combustion (14 percent). According to regional studies conducted by the United States Environmental Protection Agency (EPA) since 1990, agricultural activities, in particular manure handling, constitute the largest source of ammonia emissions. Motor vehicles and industrial processes also contribute to ammonia emissions.

Electric utilities account for the greatest proportion of sulfur dioxide emissions in the United States.

Where does acid deposition originate?

The mid-western United States emits the greatest amount of sulfur and nitrogen oxides of any region in the nation.

SUMMARY: Emissions of sulfur dioxide are highest in the mid-western United States (hereafter the Midwest), with seven states in the Ohio River Valley accounting for 41 percent of total national emissions in 1997.[2]

DETAILS: Analysis of continental air currents shows that the seven states in the Ohio River Valley comprise the dominant source area for sulfur dioxide emissions that travel downwind to the Northeast (see Figure 3). Five of these states are also among the highest emitters of nitrogen oxides and contributed 20 percent of total national emissions in 1997.[3] Moreover, the Midwest is a significant source of atmospheric ammonia. In addition to pollution sources in the Midwest, local emissions of sulfur dioxide and nitrogen oxides from electric utilities and motor vehicles have significant impacts on local air quality in the Northeast.

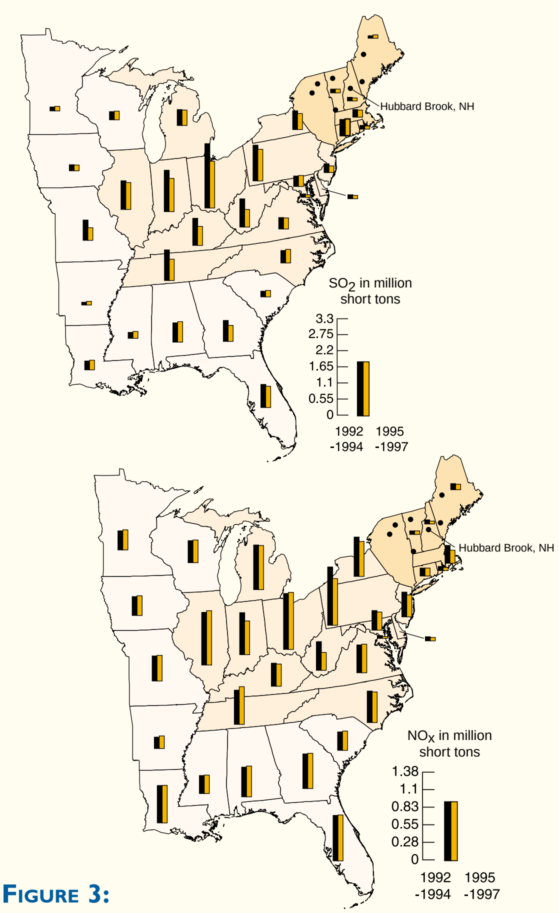


FIGURE 3: *Spatial patterns of sulfur dioxide and nitrogen oxide emissions in the eastern United States. The shaded area shows the source area from which pollution travels downwind to the Northeast.*

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[2] *Illinois, Indiana, Kentucky, Ohio, Pennsylvania, Tennessee, and West Virginia.*
[3] *The same states as above, minus West Virginia and Kentucky.*

How have emissions changed over time?

Some emissions that cause acid deposition have decreased, but overall acid and acidifying emissions remain high compared to background conditions.

SUMMARY: Although regulatory controls in the 1970s and 1990s decreased sulfur dioxide emissions, levels remain high compared to background conditions. Controls on nitrogen oxides and ammonia were not fully addressed during the same period; consequently, emissions of these compounds remain high and have gone largely unchanged in recent years (see Figure 4). Importantly, emissions and deposition of base cations (i.e., elements such as calcium and magnesium that help counteract acid deposition) have declined substantially since the early 1960s with the enactment of pollution controls to reduce particulate matter.

Controls on nitrogen oxide were not fully addressed in 1990. Consequently, emissions remain high and largely unchanged in recent years.

DETAILS: Total sulfur dioxide emissions in the United States peaked in the early 1970s at approximately 32 million short tons annually. The 1970 and 1990 CAAA led to a 38 percent decrease in sulfur dioxide emissions nationwide, in turn causing them to drop from 32 million short tons annually in 1973 to approximately 20 million short tons in 1998. The 1990 CAAA set a cap of 15.4 million short tons of total annual sulfur dioxide emissions to be achieved by 2010 (see Figure 4). The cap on electric utilities is set at 8.9 million short tons and the cap on industrial sources is 6.2 million short tons to be reached by 2010.

TOTAL U.S. EMISSIONS

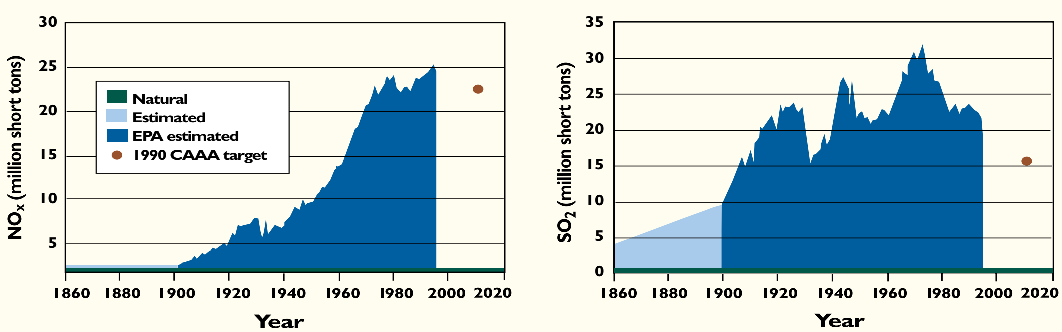


FIGURE 4:
Long-term trends in total sulfur and nitrogen oxide emissions in the United States compared with estimated natural emissions and emission targets estimated based on the 1990 CAAA (after U.S. EPA 2000).

In contrast to sulfur dioxide, nitrogen oxide emissions increased more slowly through most of the last century, peaking at nearly 25 million short tons in 1990. The 1990 CAAA resulted in a nominal 4 percent decrease in total nitrogen oxide emissions between 1994-1998. The 1990 CAAA calls for an additional reduction that will result in the emission of two million fewer tons of nitrogen oxide than the level that would have occurred without the CAAA. However, no cap on total annual emissions of nitrogen oxides was set. It is therefore expected that nitrogen emissions will increase gradually in the future as both the U.S. population and fossil fuel consumption increase.

Ammonia emissions play an important role in the acidification of soil and surface waters. Deposition of ammonium accounts for approximately 30 percent of the total nitrogen deposition measured at the HBEF and has not changed appreciably over the past 30 years. Trends in national ammonia emissions are consistent with this pattern and show little change over the past 10 years.

How has acid deposition changed over time?

Acid deposition trends in the Northeast mirror emission trends. Sulfur has declined, whereas nitrogen has remained largely unchanged.

SUMMARY: As expected, acid deposition trends in the Northeast mirror emission trends in the source area which extends to the Midwest. Over the past 30 years, sulfate deposition has declined but nitrogen deposition has remained largely unchanged.

DETAILS: Long-term data from the HBEF show declining concentrations of sulfate in wet deposition since the mid-1960s (see Figure 5). Based on these long-term data, scientists have determined that a strong positive correlation exists between sulfur dioxide emissions in the source area and sulfate concentrations in wet deposition at the HBEF. Therefore, it is now expected that the sulfate concentration of wet deposition will increase or decrease in a direct linear response to the increase or decrease of sulfur dioxide emissions in the source area.

The relationship between sulfur dioxide emissions and wet sulfate deposition extends beyond the HBEF throughout the eastern United States. The portion of the eastern United States with high wet deposition of sulfate decreased markedly between 1983-1997 (see Figure 6). According to recent estimates, wet sulfate deposition in the eastern United States declined 20 percent between 1992-1994 and 1995-1997. These reductions in wet sulfate deposition are consistent with the emissions reductions called for in the 1990 CAAA. However, a recent analysis of the effectiveness of the 1990 CAAA shows that decreases in sulfate concentrations in wet deposition at the HBEF that have occurred since 1990 do not depart significantly from the 37-year trend (see Likens et al. 2000).

In contrast to sulfate trends in wet deposition, concentrations of nitrate or ammonium at the HBEF have not changed significantly since 1963 (see Figure 5). Wet deposition of nitrogen at the HBEF is consistent with the pattern across the entire eastern United States which shows limited change over the last several years (see Figure 7).

LONG-TERM TRENDS IN WET DEPOSITION

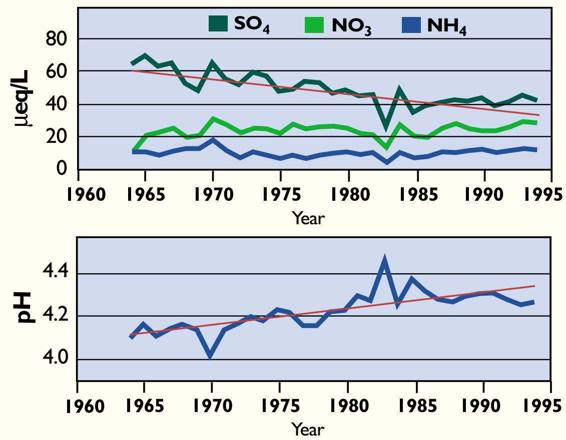
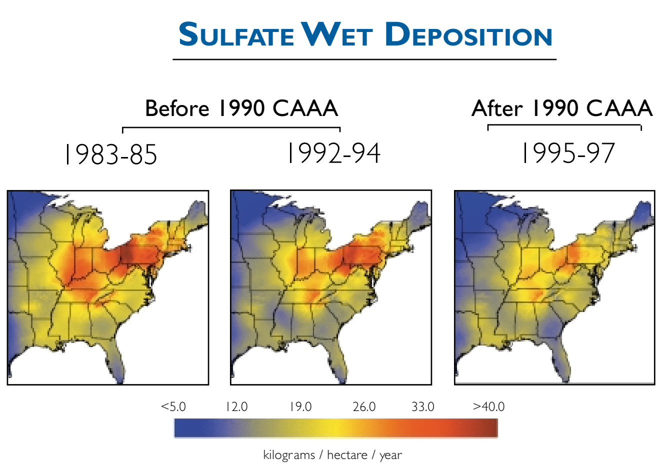
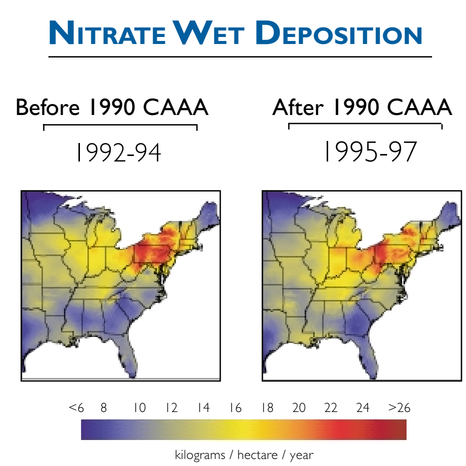


FIGURE 5: *Long-term trends in sulfate, nitrate, and ammonium concentrations and pH in wet deposition at the HBEF, 1963-1994. The solid lines indicate statistically significant trends.*

FIGURES 6 & 7: *Recent patterns of wet deposition before and after the implementation of the 1990 CAAA (after Grimm & Lynch 1997). Note: 1 hectare equals 2.47 acres.*





How does acid deposition affect Northeast ecosystems?

Acid deposition has had a greater environmental impact than previously projected.

Across the Northeast, acid deposition alters soils, stresses forest vegetation, acidifies lakes and streams, and harms fish and other aquatic life. These effects can interfere with important ecosystem benefits such as forest productivity and water quality. Years of acid deposition have also made many ecosystems more sensitive to continuing pollution. Moreover, the same pollutants that cause acid deposition contribute to a wide array of other important environmental issues at local, regional, and global scales (see Table 1).

TABLE 1: *Links between sulfur dioxide and nitrogen oxide emissions, and other environmental issues.*

Issue	Linkage to Emissions	Reference
Coastal eutrophication	Atmospheric deposition adds nitrogen to coastal waters.	Jaworski et al. 1997
Mercury	Surface water acidification enhances mercury accumulation in fish.	Driscoll et al. 1994
Visibility	Sulfate aerosols diminish visibility and views.	Malm et al. 1994
Climate Change	Sulfate aerosols may offset global warming in the short-term, but nitrous oxide is a potent greenhouse gas.	Moore et al. 1997
Tropospheric ozone	Emissions of nitrogen oxides contribute to the formation of ozone.	NAPAP 1998

Acid deposition has altered soils in areas of the Northeast.

SUMMARY: Until recently, understanding of the effects of acid deposition on soils was limited. However, current research shows that acid deposition has chemically altered soils with serious consequences for acid-sensitive ecosystems. Soils compromised by acid deposition lose their ability to neutralize continuing inputs of strong acids, provide poorer growing conditions for plants, and extend the time needed for ecosystems to recover from acid deposition.

Acid deposition has chemically altered soils with serious consequences for acid-sensitive ecosystems.

DETAILS: Acid deposition has altered and continues to alter soils in parts of the Northeast in three important ways. Acid deposition depletes calcium and other base cations from the soil; facilitates the mobilization of dissolved inorganic aluminum (hereafter referred to simply as aluminum) into soil water; and increases the accumulation of sulfur and nitrogen in the soil.

► Loss of calcium and other base cations

In the past 50-60 years, acid deposition has accelerated the loss of large amounts of available calcium from the soil at the HBEF and other acid-sensitive areas in the Northeast. This conclusion is based on a limited number of soil studies, but at present calcium depletion has been documented at more than a dozen study sites throughout the Northeast, including sites in the Adirondacks, the White Mountains, the Green Mountains, and the state of Maine. Depletion occurs when base cations are displaced from the soil by acid deposition at a rate faster than they can be replenished by the slow breakdown of rocks or the deposition of base cations from the atmosphere. This depletion of base cations fundamentally alters soil processes, compromises the nutrition of some trees, and hinders the capacity for sensitive soils to recover.

► Mobilization of aluminum

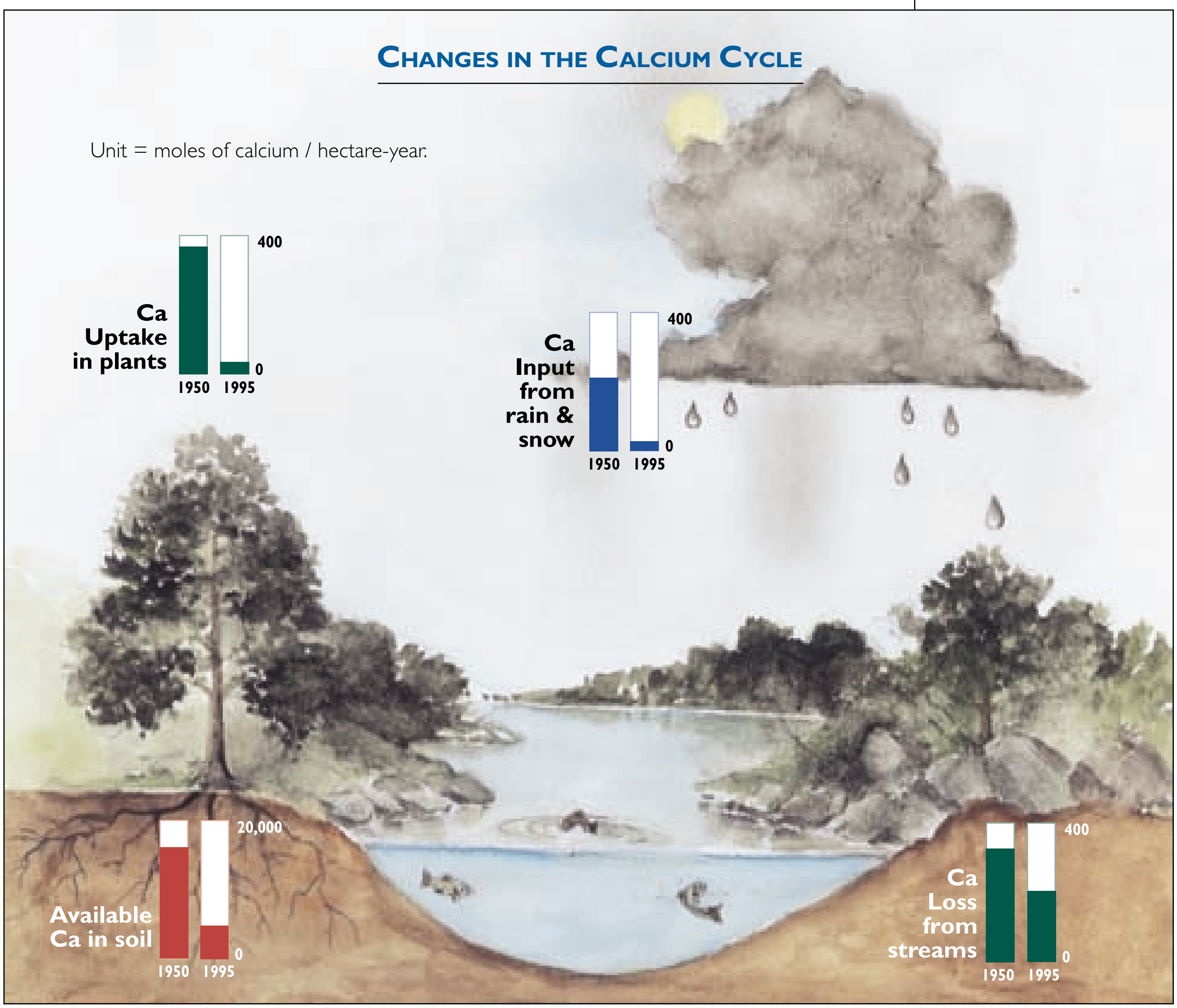
Aluminum is often released from soil to soil water, vegetation, lakes, and streams in forested regions with high acid deposition, low stores of available calcium, and high soil acidity. High concentrations of aluminum can be toxic to plants, fish, and other organisms. Concentrations of aluminum in streams at the HBEF are often above levels considered toxic to fish and much greater than concentrations observed in forested watersheds receiving low levels of acid deposition.

► Accumulation of sulfur and nitrogen

Acid deposition results in the accumulation of sulfur and nitrogen in forest soils. As sulfate is released from the soil, it acidifies nearby streams and lakes. The recovery of surface waters in response to emission controls has therefore been delayed and will not be complete until the sulfate left by a long legacy of acid deposition is released from the soil.

Similarly, nitrogen has accumulated in soil beyond the amount needed by the forest and appears now to be leaching into surface waters in many parts of the Northeast. This process also acidifies lakes and streams. Forests typically require more nitrogen for growth than is available in the soil. However, several recent studies suggest that in some areas, nitrogen levels are above what forests can use and retain.

FIGURE 8: *Acid deposition has altered the calcium cycle in watersheds in the Northeast that are similar to the HBEF.*



Acid deposition has stressed trees in areas of the Northeast.

SUMMARY: The 1990 National Acid Precipitation Assessment Program (NAPAP) report to Congress concluded there was insubstantial evidence that acid deposition had caused the decline of trees other than red spruce growing at high-elevations. More recent research shows that acid deposition has contributed to the decline of red spruce trees throughout the eastern U.S. and sugar maple trees in central and western Pennsylvania. Symptoms of tree decline include poor crown condition, reduced tree growth, and unusually high levels of tree mortality.

DETAILS: Declines of red spruce and sugar maple in the northeastern United States have occurred during the past four decades. Factors associated with declines of both species, have been studied and include important links to acid deposition.

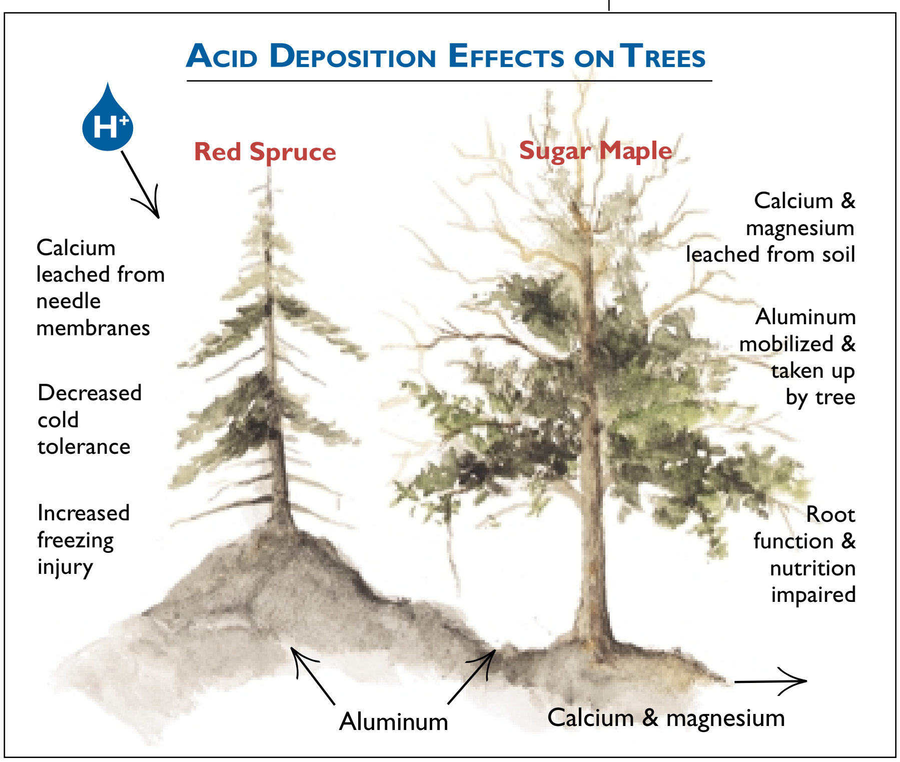
Recent research shows that acid deposition has contributed to the decline of red spruce throughout the eastern U.S. and sugar maple in central and western Pennsylvania.

Red Spruce

Since the 1960s, more than half of large canopy red spruce in the Adirondack Mountains of New York and the Green Mountains of Vermont and approximately one quarter of large canopy red spruce in the White Mountains of New Hampshire have died. Significant growth declines and winter injury to red spruce have been observed throughout its range. Acid deposition is the major cause of red spruce decline at high elevations in the Northeast. Red spruce decline occurs by both direct and indirect effects of acid deposition. *Direct effects* include the leaching of calcium from a tree's leaves and needles (i.e., foliage), whereas *indirect effects* refer to changes in the underlying soil chemistry.

Recent research suggests that the decline of red spruce is linked to the leaching of calcium from cell membranes in spruce needles by acid rain, mist or fog. The loss of calcium renders the needles more susceptible to freezing damage, thereby reducing a tree's tolerance to low temperatures and increasing the occurrence of winter injury and subsequent tree damage or death (see Figure 9). In addition, elevated aluminum concentrations in the soil may limit the ability of red spruce to take up water and nutrients through its roots. Water and nutrient deficiencies can lower a tree's tolerance to other environmental stresses and cause decline.

FIGURE 9: *Mechanisms of acid deposition stress to red spruce and sugar maple trees.*

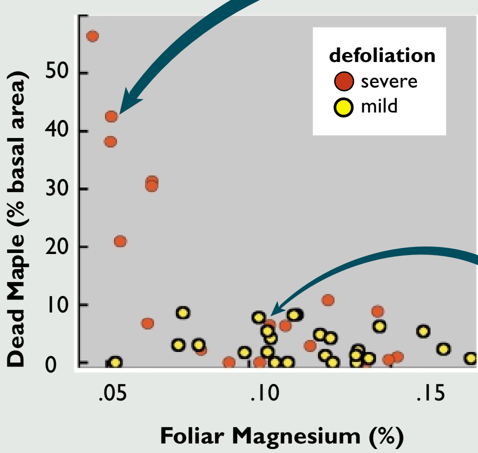


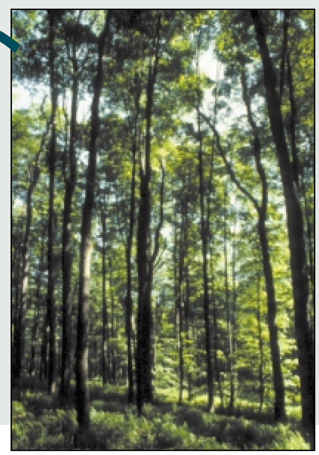
Sugar Maple

The decline of sugar maple has been studied in the eastern United States since the 1950s. Extensive mortality among sugar maples in Pennsylvania appears to have resulted from deficiencies of base cations, coupled with other stresses such as insect defoliation or drought (see Figure 10). According to research studies, the probability of the loss of sugar maple crown vigor or the incidence of tree death increased on sites where supplies of calcium and magnesium in the soil and foliage were the lowest and stress from insect defoliation and/or drought was high. In northwestern and north central Pennsylvania, soils on the upper slopes of unglaciated sites contain low calcium and magnesium supplies as a result of more than half a million years of weathering combined with the leaching of these elements by acid deposition. Low levels of these base cations can cause a nutrient imbalance and reduce a tree's ability to respond to stresses such as insect infestation and drought (see Figure 10).

Sugar Maple Decline: a multiple stress syndrome

FIGURE 10





Multiple stresses have led to sugar maple decline at a forest in Ridgway Township, Pennsylvania. As shown here, there has been severe sugar maple mortality on the upper slopes of this forest where long-term leaching has produced nutrient poor soils and high levels of acid deposition have contributed to the loss of additional base cations from the soil. Two years of moderate to severe insect defoliation produced high levels of crown dieback and tree mortality. In contrast, a nearby site at a lower elevation in the same watershed that is richer in nutrients and therefore more buffered from the effects of acid deposition, was subject to the same level of insect defoliation, but was able to withstand the stress and does not show symptoms of decline (after Horsley et al. 2000).

In addition to the forest stands in Pennsylvania, forests in other areas of the Northeast contain sugar maples with foliage having low calcium and magnesium concentrations. Sugar maple trees in these forests may be susceptible to decline if stress levels surpass a threshold. For example, twig and branch dieback, gaps in the forest canopy and premature coloration of leaves have been observed at the HBEF and may represent the early stages of tree decline.

Finally, it is logical to consider whether hardwood species such as white ash and basswood that seem to be found primarily on sites high in base cations may also be susceptible to decline similar to that of sugar maple. Mortality of white ash has been associated with ash yellows, caused by pathogens, but an association between nutrient imbalance and mortality of white ash or basswood has yet to be clearly documented.

Premature coloration and twig and branch dieback in a sugar maple at the HBEF.

Acid deposition has degraded water quality in many Northeast lakes and streams.

SUMMARY: Acid deposition degrades water quality by lowering pH levels (i.e., increasing acidity); decreasing acid-neutralizing capacity (ANC); and increasing aluminum concentrations. While sulfate concentrations in lakes and streams have decreased over the last 20 years, they remain high compared to background conditions. Moreover, improvement in the acidity of lakes and streams in the Northeast has been limited.

DETAILS: A recent survey in the Northeast concluded that 41 percent of lakes in the Adirondack region are still acidic or subject to short-term pulses in acidity associated with snowmelt or rain storms. In the Catskill region and New England as a whole, 15 percent of lakes exhibit these characteristics. Eighty-three percent of the impacted lakes are acidic due to acid deposition. The remaining 17 percent are probably acidic under natural conditions, but have been made more acidic by acid deposition. This survey presents a conservative estimate of lakes impaired by acid deposition. Data were collected from lakes that are one hectare or larger and included only samples that were collected during the summer, when conditions are relatively less acidic.

Stream data from the HBEF reveal a number of long-term trends that are consistent with trends in lakes and streams across the Northeast (see Figure 11). Specifically, the concentration of sulfate in streams at the HBEF declined 20 percent between 1963-1994. The pH of streams subsequently increased from 4.8 to 5.0. Although this represents an important improvement in water quality, streams at the HBEF remain acidic compared to background conditions, estimated to be above 6.0. Moreover, ANC – an important measure of a lake or stream's susceptibility to acid inputs – has not improved significantly at the HBEF over the past thirty years.

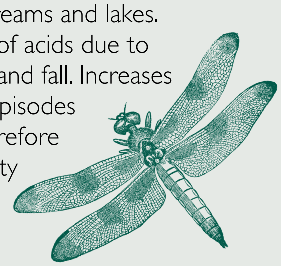
41 percent of lakes in the Adirondack region are still acidic or subject to short-term pulses in acidity associated with snowmelt or rain storms.

What is ANC?

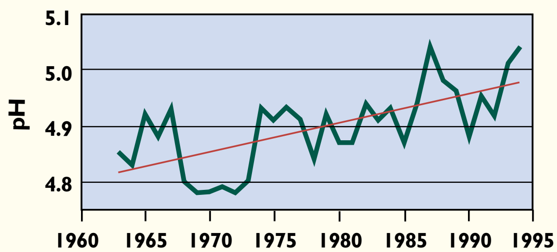
Acid-neutralizing capacity, or ANC, is the ability of water taken from a lake or stream to neutralize strong acid. ANC is an important measure of the impact of acid deposition as well as an indicator of chemical recovery from acid deposition. Surface waters with ANC values below 0 micro equivalents per liter (μeq/L) during base flow conditions are considered chronically acidic. Waters with ANC values ranging from 0-50 μeq/L are not chronically acidic but are susceptible to episodic acidification. Waters with ANC values greater than 50 μeq/L are less sensitive to acid deposition. The capacity of a watershed to prevent decreases in ANC and resist the effects of acid deposition depends on many factors, including climate, soil conditions, surficial and bedrock geology, and land-use history.

Seasonal and episodic acidification

Seasonal acidification is the seasonal increase in acidity and the corresponding decrease in pH and ANC in streams and lakes. Episodic acidification is caused by the sudden pulse of acids due to spring snowmelt and large rain events in the spring and fall. Increases in nitrate are important to the occurrence of acid episodes and tend to occur when trees are dormant and therefore using less nitrogen. Short-term increases in the acidity of surface waters can reach levels that are lethal to fish and other aquatic organisms.



Long-term Trends in Stream Chemistry



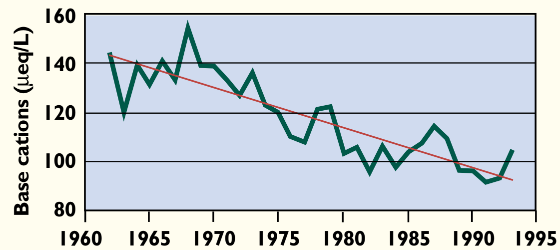
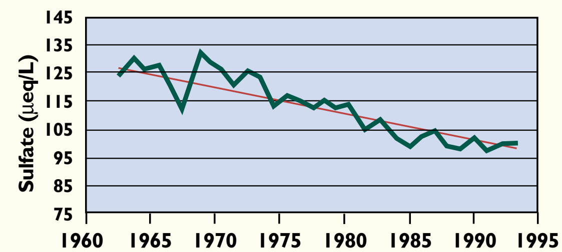


Figure 11:

Long-term trends in stream sulfate and base cation concentrations and pH at the HBEF from 1963-1994. The solid lines indicate statistically significant trends.



Regional trends in surface water chemistry indicate that the slow recovery of the streams at the HBEF is characteristic of sensitive lakes and streams throughout the Northeast. Twenty-five lakes and streams in the Adirondack and Catskill Mountains and seventeen in New England have been intensively monitored since 1982. A recent analysis shows that these lakes and streams exhibit limited recovery in pH and acid neutralizing capacity (see Figure 12).

Three factors account for the slow recovery in chemical water quality at the HBEF and across the Northeast, despite the decreased deposition of sulfur associated with the CAAA. First, acid-neutralizing base cations have been depleted from the soil due to acid deposition and, to a lesser extent, a reduction in atmospheric inputs of base cations. Second, inputs of nitric acid have acidified surface waters and elevated their concentration of nitrate in many regions of the Northeast, particularly the Adirondack and Catskill regions of New York. Finally, sulfur has accumulated in the soil and is now being released to surface waters as sulfate, even though sulfate deposition has decreased.

Figure 12:

Trends in surface water chemistry from 1982-1998. The arrows indicate the magnitude and direction of statistically significant trends. N = the number of lakes and streams monitored.

Chemistry of lakes & streams	Adirondacks & Catskills (N=25)	New England (N=17)
Sulfate	↓	↓
Nitrate	no significant change	no significant change
Base Cations	↓	↓
Acid Neutralizing Capacity	no significant change	↑

Acid deposition has reduced the diversity and abundance of aquatic organisms in many Northeast lakes and streams.

SUMMARY: Decreases in pH and elevated concentrations of aluminum have reduced the species diversity and abundance of aquatic life in many streams and lakes in acid-sensitive areas of the Northeast. Fish have received the most attention to date, but entire food webs are often adversely affected.

DETAILS: Decreases in pH and increases in aluminum concentrations have diminished the species diversity and abundance of plankton, invertebrates, and fish in acid-impacted surface waters in the Northeast. In the Adirondacks, a significant positive relationship exists between the pH and ANC of lakes and the number of fish species present in those lakes (see Figure 13). Surveys of 1,469 Adirondack lakes conducted in 1984 and 1987 show that 24 percent of lakes (i.e., 346) in this region do not support fish. These lakes had consistently lower pH and ANC, and higher concentrations of aluminum than lakes that contained one or more species of fish. Even acid-tolerant fish species such as brook trout have been eliminated from some waters in the Northeast.

Acid episodes are particularly harmful to aquatic life because abrupt changes in water chemistry allow fish few areas of refuge (see Figure 14). High concentrations of aluminum are directly toxic to fish and are a primary cause of fish mortality during acid episodes. High acidity and aluminum levels disrupt the salt and water balance in fish, causing red blood cells to rupture and blood viscosity to increase. Studies show that the viscous blood strains the fish's heart, resulting in a lethal heart attack.

The absence of fish and the presence of aluminum in lakes provides important information about the condition of soils within a watershed. The release of aluminum from the soil into rivers and streams usually indicates that the available calcium in the soil is low and has been depleted. Furthermore, trees growing in such soils may experience greater nutritional stress.

FIGURE 13:
The mean number of fish species for pH classes from 4.0 to 8.0 in lakes in the Adirondack region of New York. N represents the number of lakes in each pH class.

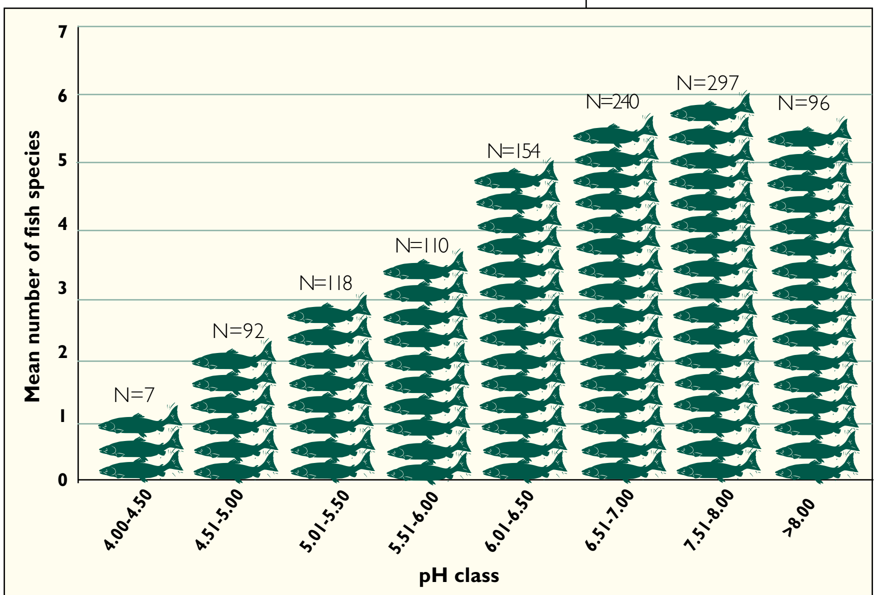
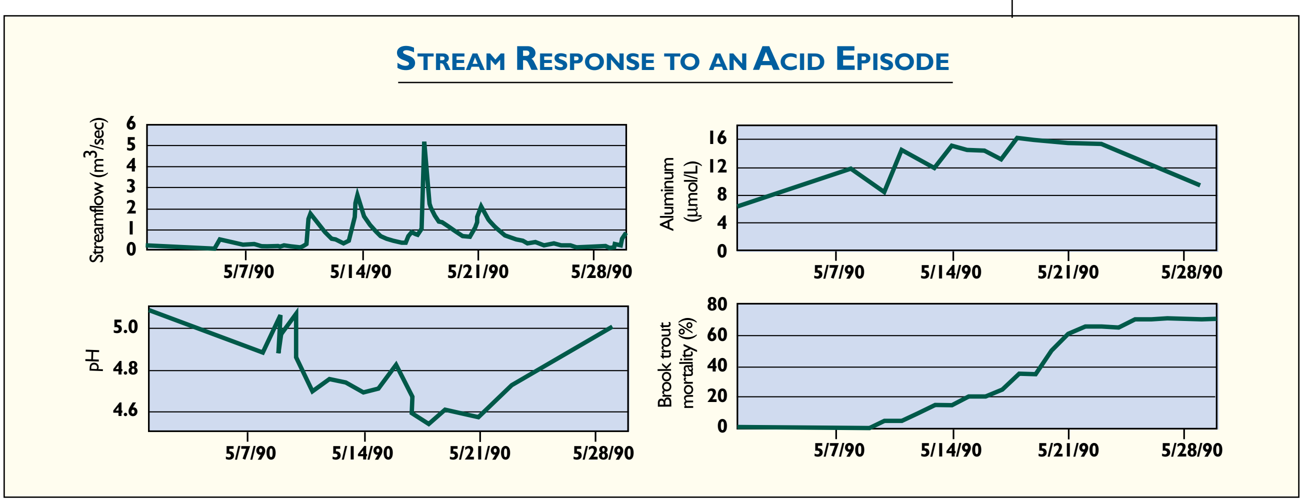


FIGURE 14:
Short-term changes in water quality and brook trout mortality in an experiment associated with an acid episode in 1990. Buck Creek, New York.



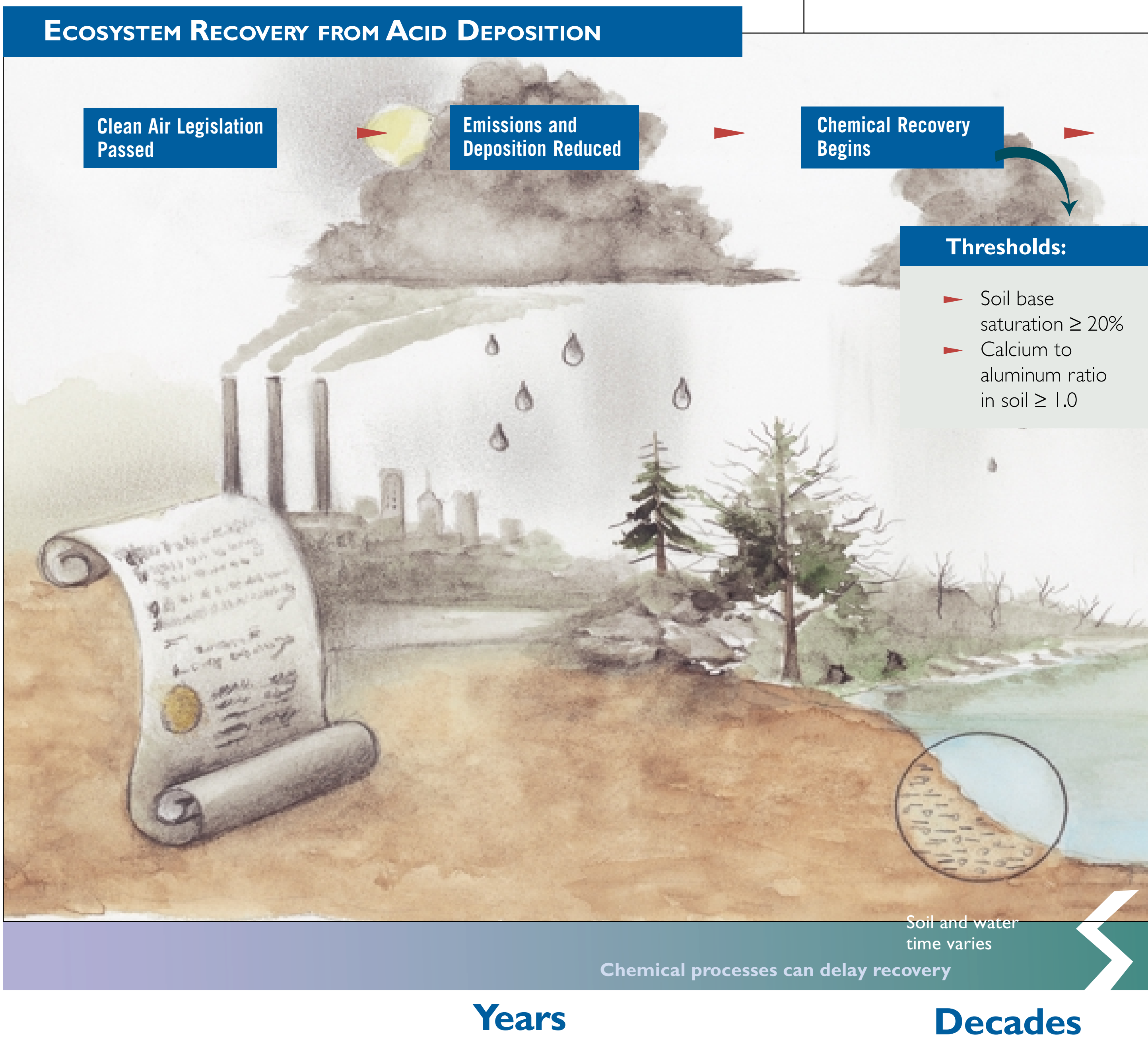
What is ecosystem recovery?

Ecosystem recovery is a phased process that involves the reversal of degraded chemical and biological conditions.

SUMMARY: Recovery from acid deposition involves decreases in emissions resulting from regulatory controls, which in turn lead to reductions in acid deposition and allow chemical recovery (see Figure 15). **Chemical recovery** is characterized by decreased concentrations of sulfate, nitrate, and aluminum in soils and surface waters. If sufficient, these reductions will eventually lead to increased pH and ANC, as well as higher concentrations of base cations. As chemical conditions improve, the potential for the second phase of ecosystem recovery**, biological recovery,** is greatly enhanced.

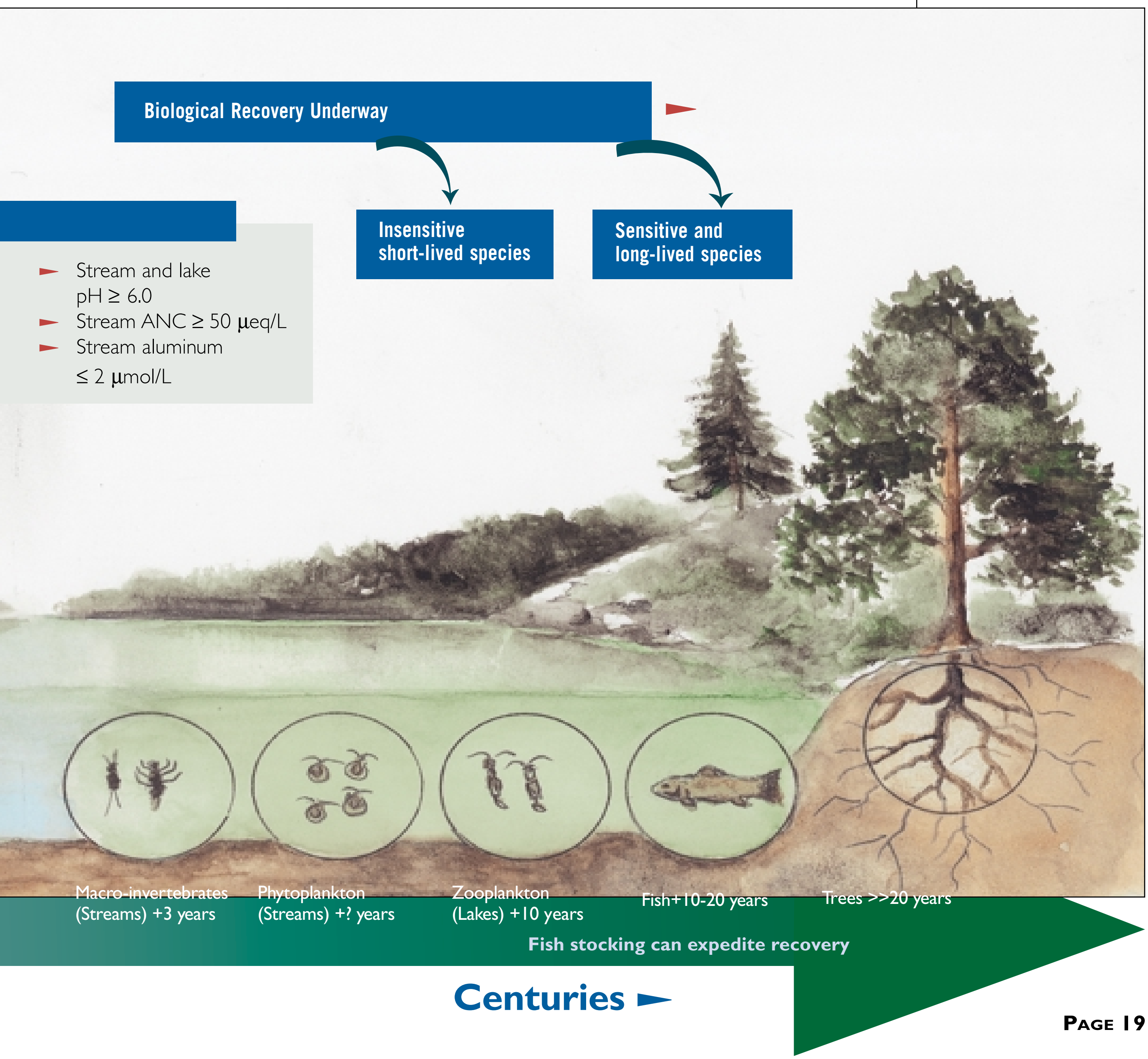
DETAILS: An analysis of the scientific literature suggests that the following five thresholds can serve as indicators of chemical recovery. If chemical conditions in

FIGURE 15: *The process of ecosystem recovery from acid deposition includes decreases in emissions that lead to improved soil and surface water chemistry which in turn enhances the recovery of aquatic organisms and trees with time.*



an ecosystem are above these thresholds, (or in the case of aluminum, are below the threshold) it is unlikely that the ecosystem has been substantially impaired by acid deposition. Conversely, if chemical conditions are below these thresholds, (or in the case of aluminum, above the threshold) it is likely that the ecosystem has been, or will be, impaired by acid deposition (see Figure 15).

As chemical conditions in soils and surface waters improve, **biological recovery** is enhanced. Biological recovery is likely to occur in stages, since not all organisms can recover at the same rate and may vary in their sensitivity to acid deposition. The current understanding of species' responses to improvements in chemical conditions is incomplete, but research suggests that stream macro-invertebrates may recover relatively rapidly (i.e., within 3 years), while lake zooplankton may need a decade or more to fully re-establish. Fish populations in streams and lakes should recover in 5-10 years following the recovery of the macro-invertebrates and zooplankton which serve as food sources. It is possible that, with improved chemical conditions and the return of other members of the aquatic food web, the stocking of streams and lakes could help to accelerate the recovery of fish.



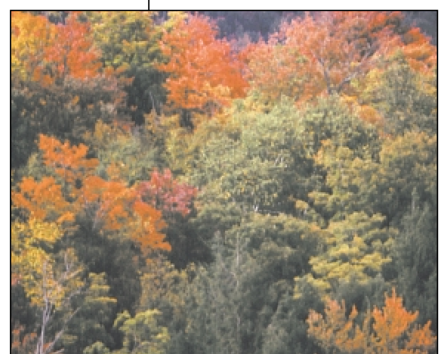
Terrestrial recovery is even more difficult to project than aquatic recovery. Given the life span of trees and the delay in the response of soil to decreases in acid deposition, it is reasonable to suggest that decades will be required for affected trees on sensitive sites to recover once chemical conditions in the soil are restored.

The time required for chemical recovery varies widely among ecosystems in the Northeast, and is primarily a function of:

- the historic rate of sulfur and nitrogen deposition;
- the rate and magnitude of decreases in acid deposition;
- the extent to which base cations such as calcium have been depleted from the soil;
- the extent to which sulfur and nitrogen have accumulated in the soil and the rate at which they are released as deposition declines;
- the weathering rate of the soil and underlying rock and the associated supply of base cations to the ecosystem; and
- the rate of atmospheric deposition of base cations.

Overall, the timing and extent of chemical and biological recovery depend on how soon and to what extent emissions that cause acid deposition are reduced.

Will ecosystems in the Northeast recover?



The Clean Air Act has had positive effects, but is not sufficient to fully recover acid-sensitive ecosystems in the Northeast.

SUMMARY: To date, national electric utilities have met or surpassed the emissions targets set by the 1990 CAAA. Nevertheless, data suggest that these targets will not be sufficient to achieve the full recovery of sensitive ecosystems. In order to evaluate the extent to which historic and future emissions reductions will facilitate ecosystem recovery from acid deposition, a computer model was used to estimate the relationship between emissions, deposition, and chemical recovery at the intensively studied HBEF.

DETAILS: The five chemical indicators defined in the previous sections were used in the computer model PnET-BGC to predict how future reductions in sulfur dioxide emissions may affect chemical conditions at the HBEF. The model compared current emissions reductions required by the 1990 CAAA with an additional 40 percent and 80 percent cut in *electric utility emissions* of sulfur dioxide (i.e., the equivalent of 22 and 44 percent of total sulfur dioxide emissions) by 2010. These scenarios are based on the electric utility sulfur dioxide emission reductions embodied in five bills introduced in Congress.

The computer model considered only changes in sulfur dioxide emissions. It was assumed that nitrogen oxide and ammonia would remain basically unchanged. While nitrogen is ecologically important, in the absence of a pollution cap, decreases in nitrogen oxide emissions are not expected to be large enough over the next ten years to contribute significantly to recovery. Nevertheless, nitrogen oxides play an important role in the frequency and intensity of periodic acid episodes and are an important part of emissions control strategies.

Acidification models

Scientists have developed computer models that depict the physical, chemical and biological processes within forest watersheds. Acid deposition models can be used as research and management tools to investigate factors responsible for the historical acidification of soil and water as well as the ecosystem response to anticipated future changes in acid deposition. In order to effectively predict the pH, ANC and aluminum concentrations in streams, all major chemicals must be accurately simulated (e.g., sulfate, nitrate, calcium, magnesium). The acidification model PnET-BGC was used for this assessment because it has been rigorously tested at the HBEF and other sites in the Northeast, and it allows the user of the model to consider the ecosystem response to multiple chemicals simultaneously.

The rate and extent of ecosystem recovery in the Northeast are directly related to the timing and degree of emissions reductions.

SUMMARY: According to the results of the computer model, the 1990 CAAA will have a positive effect on sulfate deposition but will not facilitate appreciable progress toward chemical recovery in Northeast watersheds similar to the HBEF.

DETAILS: With an additional 40 percent reduction in *electric utility emissions* of sulfur dioxide beyond the requirements of the 1990 CAAA, measurable chemical improvements occur. However, none of the five indicators reach the threshold needed to support complete biological recovery at the HBEF by 2050. An 80 percent reduction in *electric utility emissions* beyond the 1990 CAAA hastens and promotes more significant improvements in chemical conditions (see Table 2). For example, under this scenario streams in watersheds similar to the HBEF would change from acidic to non-acidic in roughly 20-25 years. By 2050, stream aluminum and the base cation content of the soil in these watersheds would begin to approach recovery thresholds or pre-industrial levels.

	Baseline Conditions			Emissions Scenarios		
Chemical Indicator	1850	Threshold	1970	2050 with 1990 CAAA	2050 with 40% deeper SO_2 utility cuts	2050 with 80% deeper SO_2 utility cuts
Sulfate wet deposition ($g/m^2 \bullet yr$)	0.23	–	1.69	0.89	0.69	0.50
Stream sulfate	9.6	–	62.0	34.3	28.9	23.5
Stream ANC (µeq/L)	42.7	>50	-5.4	-1.0	0.6	2.5
Stream pH	6.3	>6.0	4.8	5.3	5.5	5.7
Stream aluminum (µmol/L)	1.5	<2.0	12.1	6.4	5.6	4.3
Soil base saturation (%)	21.8	>20	13.4	12.3	13.3	14.4

TABLE 2: *Results from a computer model showing chemical conditions at the HBEF under three emissions scenarios.*

The model results further demonstrate that the process of recovery will be slow, particularly for sensitive systems such as the HBEF. To put these findings in perspective, approximately 6 percent of the lakes and streams in the Northeast (or 30 percent of those that are considered sensitive) are more vulnerable to acid deposition than the HBEF. This percentage is likely to be higher in areas that receive greater inputs of acid deposition and are less well buffered, such as the Adirondack Mountains of New York.

In Summary

Acid deposition is a pervasive problem that has had greater impacts on soils, surface waters, and trees than previously projected. Although the 1970 and 1990 Clean Air Acts have had positive effects, emissions remain high compared to background conditions. Given the accumulation of acids and loss of buffering capacity in the soil, many areas in the Northeast are now more sensitive to acid deposition and have developed an inertia that will delay recovery. Nevertheless, the computer model results presented here show that deeper emissions cuts will lead to greater and faster recovery from acid deposition in the northeastern United States.

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Acknowledgments

Acid Rain Revisited is a publication of the HBRF Science Links™ program. Science Links™ has been funded by:

Jessie B. Cox Charitable Trust
Davis Conservation Foundation
Geraldine R. Dodge Foundation
McCabe Environmental Fund
Merck Family Fund
John Merck Fund
Harold Whitworth Pierce Charitable Trust
The Sudbury Foundation
The Switzer Environmental Leadership Fund of the New Hampshire Charitable Foundation

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

Other credits:

Special thanks to Elizabeth Farnsworth for her review, analysis and contribution to the text and figures.

Some data used in this publication was obtained by scientists of the Hubbard Brook Ecosystem Study. The Hubbard Brook Experimental Forest is operated and maintained by the Northeastern Research Station, U.S. Department of Agriculture, Newtown Square, Pennsylvania.

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Edited by: Sharon Pickett & Associates (Bethesda, Maryland)
Designed by: Mirabile Design (Montpelier, Vermont)
Printed by: Queen City Printers (Burlington, Vermont)

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