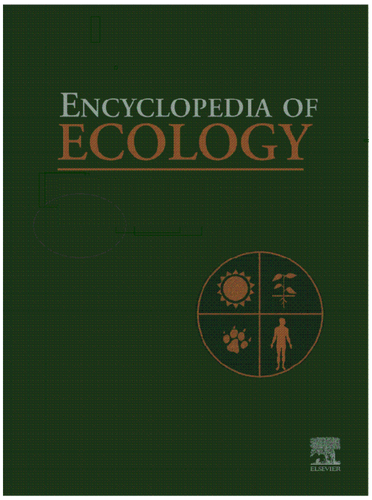

C T Driscoll. Ecological Effects of Acidic Deposition. In Sven Erik Jørgensen and Brian D. Fath (Editor-in-Chief), General Ecology. Vol. [2] of Encyclopedia of Ecology, 5 vols. pp. [1012-1019] Oxford: Elsevier.

Ecological Effects of Acidic Deposition

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Introduction

Detailed studies by a large community of scientists for more than three decades have provided considerable insight into the ways in which atmospheric deposition alters ecosystems. When it was first identified, acidic deposition was viewed as a simple problem that was limited in scope. Scientists know now that acids and acidifying compounds largely enter ecosystems from atmospheric deposition and are transported through soil, vegetation, and surface waters, resulting in a range of adverse ecosystem effects.

In this article, information is synthesized on patterns of acidic deposition, and the effects of atmospheric deposition of sulfur and nitrogen on sensitive forest and freshwater resources.

Acidic Deposition

Acidic deposition is largely comprised of sulfuric and nitric acid derived from sulfur dioxide and nitrogen oxides, respectively, and ammonium resulting from emissions of ammonia. Sulfur dioxide and nitrogen oxides, originating from human activities, are largely emitted into the atmosphere by the burning of fossil fuels, while ammonia is largely the result of agricultural activities. Once these compounds enter an ecosystem, they can acidify soil and surface waters, bringing about a series of ecological changes. The term acidic deposition encompasses all of the forms of these compounds that are transported from the atmosphere to the Earth, including gases, particles, rain, snow, clouds, and fog. Acidic deposition occurs as: (1) wet deposition as rain, snow, sleet or hail; (2) dry deposition as particles or vapor; or (3) cloud or fog deposition, which is more common at high elevations and in coastal areas. Wet deposition is fairly well characterized by monitoring at more than 200 National Atmospheric Deposition Programs (NADP; nadp.sws.uiuc.edu) in the US. In contrast, dry deposition is highly dependent on metrological condition and vegetation characteristics, which can vary markedly over short distances in complex terrains. As a result, dry deposition is poorly quantified and highly uncertain. Dry deposition is characterized through the Clean Air Status and Trends Network (CASTNet; www.epa.gov/castnet), which includes about 100 sites in the US.

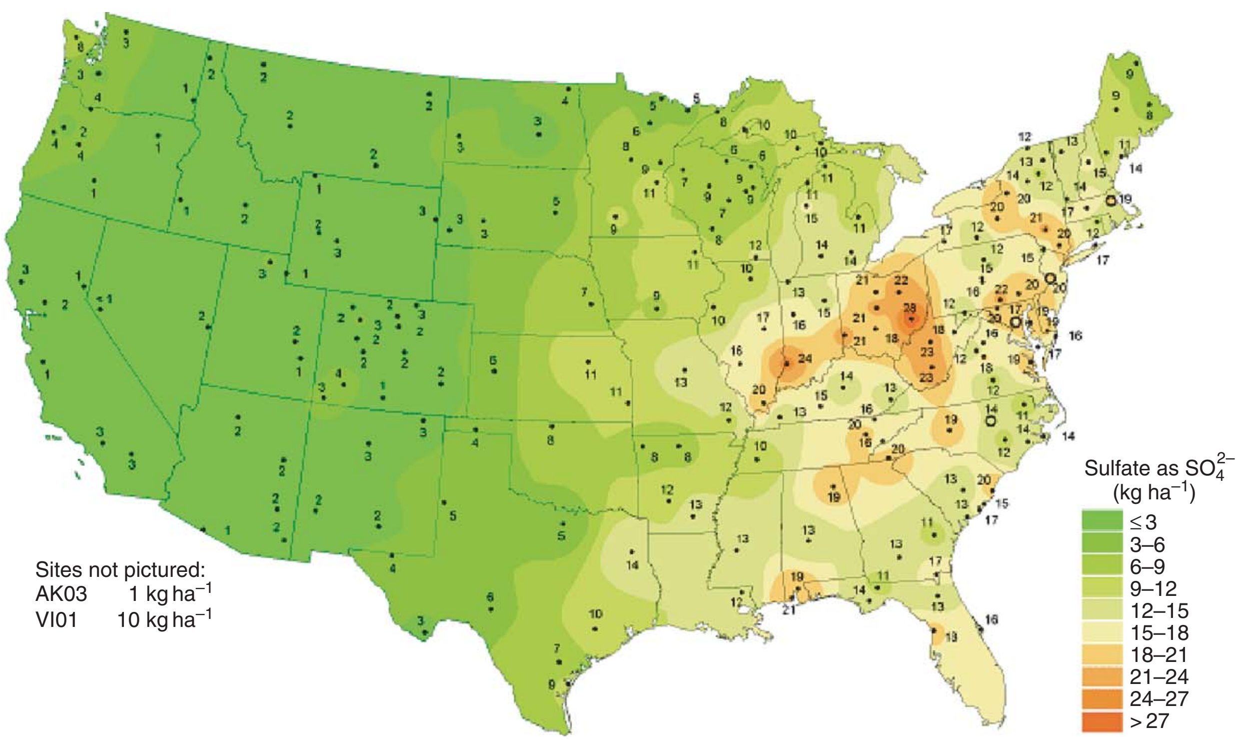
Sulfuric and nitric acids lower the pH of rain, snow, soil, lakes, and streams. Areas experiencing elevated acidic deposition include eastern North America (**Figure 1**), the western US, Europe, and Asia. In 2002–04, wet deposition (i.e., deposition from forms of precipitation such as rain, snow, sleet, and hail) in acid-sensitive regions of the eastern US had average pH values of 4.3–4.5, which is about 3–5 times more acidic than background conditions.

Acidic deposition trends in the eastern US and Europe mirror emission trends in the atmospheric source area or airshed. Long-term data from across the eastern US and Europe show declining concentrations of sulfate in wet deposition since the mid-1970s, coincident with decreases in sulfur dioxide emissions. Based on these long-term data, a strong positive correlation exists between sulfur dioxide emissions in the source area and sulfate concentrations in wet deposition. It is expected that the sulfate concentration of wet deposition will decrease (or increase) in a direct linear response to the decrease (or increase) of sulfur dioxide emissions in the atmospheric source area. These observations strongly suggest a cause and effect relationship between emissions of sulfur dioxide and deposition of sulfate in sensitive regions. A similar relationship is starting to become evident between emissions of nitrogen oxides and wet deposition of nitrate. This relationship for nitrate is not as strong as the relationship for sulfur because emissions of nitrogen oxides have been relatively constant over the last 20 years. However, it appears that recent decreases in emissions of nitrogen oxides from electric utilities are starting to result in decreases in atmospheric deposition of nitrate.

Effects of Acidic Deposition on Forest Ecosystems

In acid-sensitive regions, acidic deposition alters soils, stresses forest vegetation, acidifies lakes and streams, and harms fish and other aquatic life. These effects can

Sulfate ion wet deposition, 2005



Nitrate ion wet deposition, 2005

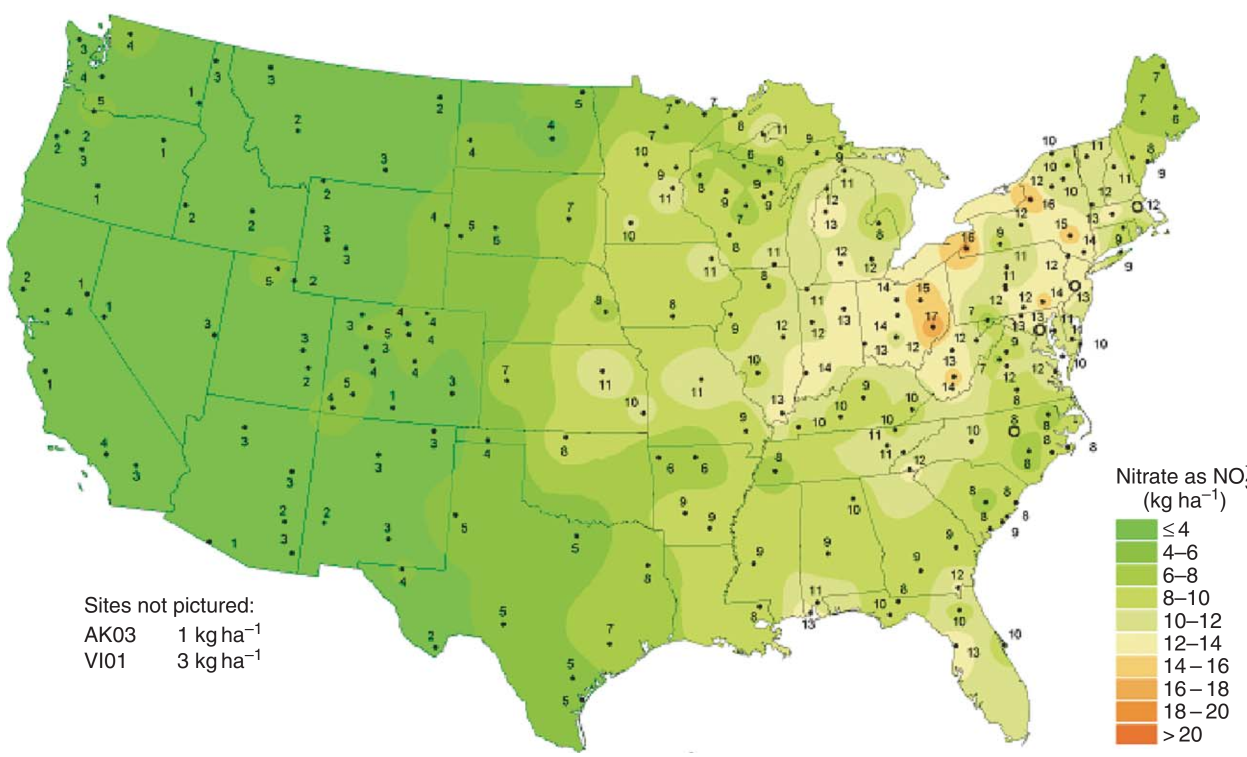


Figure 1 Map of wet sulfate and nitrate deposition for the US for 2005. Data are from the National Atmospheric Deposition Program (NADP) network.

Table 1 The links between sulfur dioxide and nitrogen oxide emissions, acidic deposition, and other important environmental issues

Problem	*Linkage to acid deposition*
Coastal eutrophication	Atmospheric deposition adds nitrogen to coastal waters.
Mercury	Surface water acidification increases mercury accumulation in fish.
Visibility	Sulfate aerosols diminish visibility and views.
Tropospheric ozone	Emissions of nitrogen oxides contribute to the formation of ozone.

interfere with important ecosystem functions and services such as forest diversity and productivity and water quality. Years of acidic deposition have also made many ecosystems more sensitive to continuing pollution. Moreover, the same pollutants that cause acidic deposition contribute to a wide array of other important environmental issues at local, regional, and global scales (see Table 1).

Effects of Acidic Deposition on Forest Soils

Research has shown that acidic deposition has chemically altered soils with serious consequences for acid-sensitive ecosystems. Soils compromised by acidic 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 acidic deposition.

Acidic deposition has altered and continues to alter soils in sensitive regions in three important ways. Acidic deposition depletes available calcium and other nutrient cations from exchange sites in soil, facilitates the mobilization of dissolved inorganic aluminum into soil water, and increases the accumulation of sulfur and nitrogen in soil.

Loss of calcium and other nutrient cations

The cycling of calcium and other nutrient cations in forest ecosystems involves the inputs and losses of these materials (Figure 2). For most forest ecosystems the supply of calcium and other nutrient cations largely occurs by weathering (i.e., the breakdown of rocks and minerals in soil). Calcium and other nutrient cations may also enter forests by atmospheric deposition, although this pathway is generally much smaller than weathering. Losses largely occur by vegetation uptake and drainage waters. An important pool of ecosystem calcium and nutrient cations is the soil available pool or the soil cation exchange complex. Plants are generally able to utilize this source of nutrients. Forest ecosystems that are naturally sensitive to acidic deposition are generally characterized by low rates of weathering and generally low quantities of available nutrient cations. Under conditions of elevated inputs of acidic deposition and subsequent transport of sulfate and nitrate in drainage waters, nutrient cations will be displaced from available pools and leached from soil.

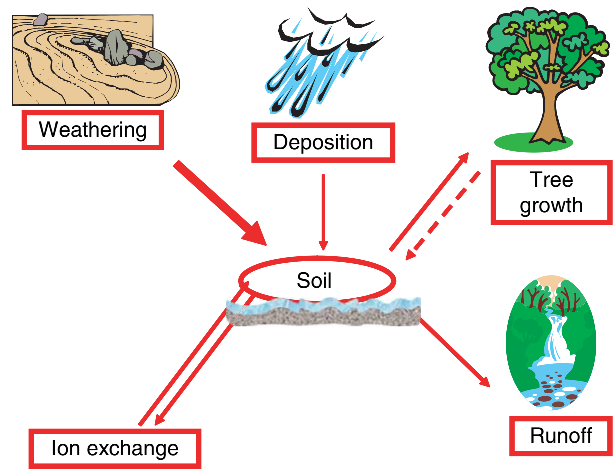


Figure 2 Conceptual diagram illustrating the inputs and losses of calcium and other nutrient cations for forest ecosystems. Ecosystems with low weathering rates have low supplies of calcium and other nutrient cations available to soil and trees. High inputs of acidic deposition increase the leaching of calcium and other nutrient cations from soil. In acid-sensitive regions with low weathering rates this can deplete soil pools of available calcium and other nutrient cations and limit quantities available for tree growth.

This condition is not problematic for areas with high weathering rates and high pools of available nutrient cations. However, in acid-sensitive areas with shallow soil and which contain minerals that are resistant to weathering, the enhanced loss of calcium and other nutrient cations can result in a depletion of soil available pools.

Over the last century, acidic deposition has accelerated the loss of large amounts of available calcium from acid-sensitive soil in acid-sensitive areas. This conclusion is based on more than 20 studies conducted throughout the world. Depletion occurs when nutrient cations are displaced from the soil by acidic deposition at a rate faster than they can be replenished by the slow breakdown of rocks or the deposition of nutrient cations from the atmosphere. This depletion of nutrient cations fundamentally alters soil processes, compromises the nutrition of some trees, and hinders the capacity for sensitive soils to recover. For example, more than half of the available calcium has been lost from soil at the Hubbard Brook Experimental Forest, New Hampshire, over the past 60 years. Note that while acidic deposition to acid-sensitive areas is decreasing and there is some associated recovery of the acid-neutralizing capacity (ANC) of surface waters (see below), it appears that forest soils continue to exhibit depletion of exchangeable nutrient cations.

Mobilization of aluminum

Aluminum is often released from soil to soil water, lakes, and streams in forested regions with high acidic deposition, low stores of available calcium, and high soil acidity. One of the most significant ecological effects of acidic deposition is the mobilization of aluminum from soil and a shift in the form of aluminum in water from nontoxic organic forms to highly toxic inorganic forms.

Concentrations of aluminum increase markedly with decreases in pH, particularly the toxic inorganic forms of aluminum. It is evident that concentrations of aluminum increase exponentially when surface water pH decreases below 6. Aluminum concentrations are thought to be ecologically significant when they increase to values above 2 $\mu mol\ l^{-1}$. This condition clearly occurs below pH 6.0.

High concentrations of dissolved inorganic aluminum can be toxic to plants, fish, and other organisms. Concentrations of dissolved inorganic aluminum in streams in eastern North America and areas of Europe are often above levels considered toxic to fish and much greater than concentrations observed in forest watersheds that receive low inputs of acidic deposition.

Effects of Acidic Deposition on Trees

Acidic deposition has contributed to the decline of red spruce and sugar maple trees in the eastern US (Figure 3). Symptoms of tree decline include poor condition of the canopy, reduced growth, and unusually high levels of mortality. Declines of red spruce and sugar maple in the northeastern US have occurred during the past four decades. Factors associated with declines of both species have been studied and include important links to acidic deposition.

Red spruce

Since the 1960s, more than half of large canopy trees in the Adirondack Mountains of New York and the Green Mountains of Vermont and approximately one-quarter of large canopy trees in the White Mountains of New Hampshire have died. Significant growth declines and winter injury to red spruce have been observed throughout its range. Acidic 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 acidic deposition. Direct effects include the leaching of calcium from leaves and needles of trees (i.e., foliage), whereas indirect effects refer to acidification of the underlying soil chemistry.

The decline of red spruce is linked to the leaching of calcium from cell membranes in spruce needles by acid

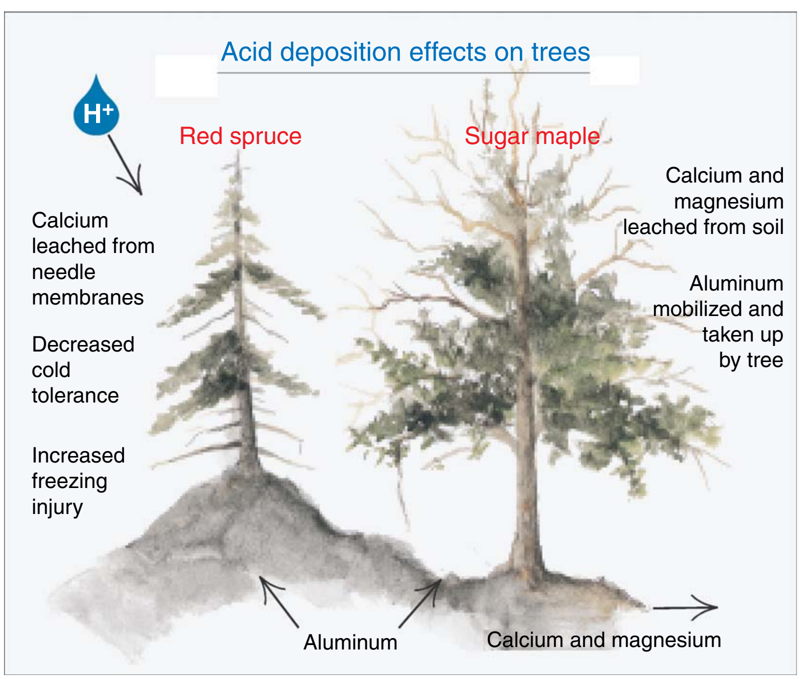


Figure 3 Conceptual diagram illustrating the mechanisms by which acidic deposition impacts red spruce and sugar maple. Acidic deposition impacts red spruce through loss of membrane calcium due to direct leaching from foliage or reduced uptake of calcium from soil. The loss of membrane calcium makes red spruce more susceptible to winter injury. Acidic deposition results show loss of soil available calcium and magnesium and less uptake by sugar maple. This condition may make sugar maple more susceptible to insect or drought stress.

mist or fog. The loss of calcium renders the needles more susceptible to freezing damage, thereby reducing the tolerance of trees to low temperatures and increasing the occurrence of winter injury and subsequent tree damage or death. 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 the tolerance of trees to other environmental stresses and cause decline.

Sugar maple

The decline of sugar maple has been studied in the eastern US since the 1950s. Extensive mortality among sugar maples appears to have resulted from deficiencies of nutrient cations, coupled with other stresses such as insect defoliation or drought. The probability of decreases in the vigor of the sugar maple canopy or incidence of tree death increased on sites where the supply of calcium and magnesium to soil and foliage are lowest and stress from insect defoliation and/or drought is high. Low levels of nutrient cations can cause a nutrient imbalance and reduce the ability of a tree to respond to stresses such as insect infestation and drought.

Effects of Acidic Deposition on Freshwater Aquatic Ecosystems

Surface Water Acidification

Acidic deposition degrades surface water quality by lowering pH (i.e., increasing acidity); decreasing ANC; and increasing dissolved inorganic aluminum concentrations. While sulfate concentrations in lakes and streams have decreased in the eastern North America and Europe over the last 20 years, they remain high compared to background conditions (e.g., approximately $20\,\mu eq\,l^{-1}$). Moreover, improvement in other chemical conditions in many lakes and streams in acid-impacted regions has been limited.

Acidification of surface waters due to elevated inputs of acidic deposition has been reported in many acid-sensitive areas receiving elevated inputs of acidic deposition, including Great Britain, Nordic countries, Northern, Central and Eastern Europe, southwestern China, southeastern Canada, the northeastern US, the Upper Midwest and the Appalachian mountain region of the US. Large portions of the high-elevation western US are also potentially sensitive to acidic deposition; however, atmospheric deposition to this region is relatively low. Concern over effects of acidic deposition in the mountains of western US may be overshadowed by potential effects of elevated nitrogen deposition, including eutrophication of naturally nitrogen-limited lakes.

To illustrate the regional impacts of acidic deposition, a comprehensive survey of lakes greater than 0.2 ha in surface area in the Adirondack region of New York was conducted to obtain detailed information on the acid-base status of waters in this region. Of the 1469 lakes surveyed, 24% had summer pH values below 5.0. Also 27% of the lakes surveyed were chronically acidic (i.e., ANC less than $0\,\mu eq\,l^{-1}$) and an additional 21% were susceptible to episodic acidification (i.e., ANC between 0 and $50\,\mu eq\,l^{-1}$). An analysis of the anion content of these lakes illustrates that these lakes have predominantly been acidified by atmospheric deposition of sulfate.

Seasonal acidification is the periodic increase in acidity and the corresponding decrease in pH and ANC in streams and lakes, which generally occurs during the higher flow fall, winter, and spring periods. Episodic acidification is caused by the sudden pulse of acids and a dilution of base cations (e.g., calcium, magnesium, sodium, potassium) due to spring snowmelt and large rain events in the spring and fall. Increases in nitrate are often important to the occurrence of acid episodes. These conditions tend to occur when trees are dormant and therefore retain less nitrogen. At some sites, short-term increases in sulfate and organic acids can also contribute to episodic acidification. Episodic acidification often coincides with pulsed increases in concentrations of dissolved inorganic aluminum. Short-term increases in acid inputs to surface waters can reach levels that are lethal to fish and other aquatic organisms. All of the acid-sensitive and acid-impacted regions discussed in this article have documented effects associated with episodic acidification.

Trends in surface water chemistry in Europe and eastern North America indicate that recovery of aquatic ecosystems impacted by acidic deposition is occurring over a large geographic scale since the early 1980s. Some regions show rather marked recovery, while others exhibit low or nonexistent increases in ANC. Based on long-term monitoring, virtually all surface waters impacted by acidic deposition in Europe and eastern North America exhibit decreases in sulfate concentrations. This pattern is consistent with decreases in emissions of sulfur dioxide and atmospheric sulfate deposition. The exception to this pattern is streams in unglaciated Virginia. Watersheds in this region and other portions of the southeastern US exhibit strong adsorption of atmospheric sulfate deposition by highly weathered soils. In Europe, the most marked decreases in surface water sulfate have occurred in the Czech Republic and Slovakia, regions that experienced historically very high rates of atmospheric sulfate deposition. Somewhat more than half of the surface waters monitored in Europe show increases in ANC. The rate of ANC increase in Europe is relatively high. This pattern is, in part, due to the relatively high rates of sulfate decreases, but also to the fact that decreases in base cations only account for about half of the decreases in sulfate plus nitrate, allowing for relatively large rates of ANC increases. In contrast, in the US only three regions show statistically significant increases in ANC: lakes in the Adirondacks, Upper Midwest, and streams in Northern Appalachian Plateau. In the US, decreases in the sum of base cations closely correspond to decreases in sulfate plus nitrate, limiting rates of ANC increase.

Three factors account for the slow chemical recovery of the water quality of acid-impacted surface waters, despite the decreased deposition of sulfate. First, levels of acid-neutralizing base cations in streams have decreased markedly due to a loss of base cations from the soil and, to a lesser extent, due to 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 acid-impacted regions. Finally, sulfur has accumulated in the soil and is now being released to surface water as sulfate, even though sulfate deposition has decreased. It appears that the only approach to accelerate the recovery of acid-impacted lakes is to make additional cuts in emissions of sulfur dioxide and nitrogen oxides.

The modest decreases in sulfate concentrations and increases in pH and ANC exhibited in some surface waters is an encouraging sign that impacted ecosystems are responding to emission controls and moving toward chemical recovery. Nevertheless, the magnitude of these changes is small compared to the magnitude of increases in sulfate and decreases in ANC that have occurred in acid-impacted areas following historical increases in acidic deposition. Moreover, as discussed above, in many acid-sensitive regions soils continue to acidify despite decreases in acidic deposition.

Response of Aquatic Biota to Acidification of Surface Waters by Acidic Deposition

Decreases in pH and elevated concentrations of dissolved inorganic aluminum have resulted in physiological changes to organisms, direct mortality of sensitive life-history stages, and reduced the species diversity and abundance of aquatic life in many streams and lakes in acid-impacted areas. Fish have received the most attention to date, but entire food webs are often adversely affected.

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. A detailed summary of the response of aquatic biota to the acidification of surface waters is provided in **Table 2**.

In the Adirondacks, a significant positive relationship exists between the pH and ANC levels in lakes and the number of fish species present in those lakes (**Figure 4**). Surveys of 1469 Adirondack lakes conducted in 1984 and 1987 show that 24% of lakes (i.e., 346) in this region do not support fish. These lakes had consistently lower pH

Table 2 Biological effects of surface water acidification in North America

pH decrease	*General biological effects*
6.5–6.0	Small decrease in species richness of phytoplankton, zooplankton, and benthic invertebrate communities resulting from the loss of a few highly acid-sensitive species, but no measurable change in total community abundance or production Some adverse effects (decreased reproductive success) may occur for highly acid-sensitive species (e.g., fathead minnow, striped bass)
6.0–5.5	Loss of sensitive species of minnow and dace, such as blacknose dace and fathead minnow; in some waters decreased reproductive success of lake trout and walleye, which are important sport fish species in some areas Visual accumulations of filamentous green algae in the littoral zone of many lakes, in some streams Distinct decrease in the species richness and change in species composition of the phytoplankton, zooplankton, and benthic invertebrate communities, although little if any change in total community biomass or production
5.5–5.0	Loss of several important sport fish species, including lake trout, walleye, rainbow trout, and smallmouth bass; as well as additional nongame species such as creek chub Further increase in the extent and abundance of filamentous green algae in lake littoral areas and streams Continued shift in the species composition and decline in species richness of the phytoplankton, periphyton, zooplankton, and benthic invertebrate communities; decrease in the total abundance and biomass of benthic invertebrates and zooplankton may occur in some waters Loss of several additional invertebrate species common in oligotrophic waters, including *Daphnia galeata mendotae*, *Diaphanosoma leuchtenbergianum*, *Asplanchna priodonta*; all snails, most species of clams, and many species of mayflies, stoneflies, and other benthic invertebrates Inhibition of nitrification
5.0–4.5	Loss of most fish species, including most important sport fish species such as brook trout and Atlantic salmon; few fish species able to survive and reproduce below pH 4.5 (e.g., central mudminnow, yellow perch, and in some waters, largemouth bass)

(*Continued*)

Table 2 (Continued)

pH decrease	*General biological effects*
	Measurable decline in the whole-system rates of decomposition of some forms of organic matter, potentially resulting in decreased rates of nutrient cycling
	Substantial decrease in the number of species of zooplankton and benthic invertebrates and further decline in the species richness of the phytoplankton and periphyton communities; measurable decrease in the total community biomass of zooplankton and benthic invertebrates in most waters
	Loss of zooplankton species such as *Tropocyclops prasinus mexicanus*, *Leptodora kindtii*, and *Conochilis unicornis*; and benthic invertebrate species, including all clams and many insects and crustaceans
	Reproductive failure of some acid-sensitive species of amphibians such as spotted salamanders, Jefferson salamanders, and the leopard frog

This table was previously published in Baker JP, Bernard DP, Christensen SW, and Sale MJ (1990) Biological effects of changes in surface water acid–base chemistry, Report SOS/T 13 for the National Acid Precipitation Assessment Program, Washington, DC.

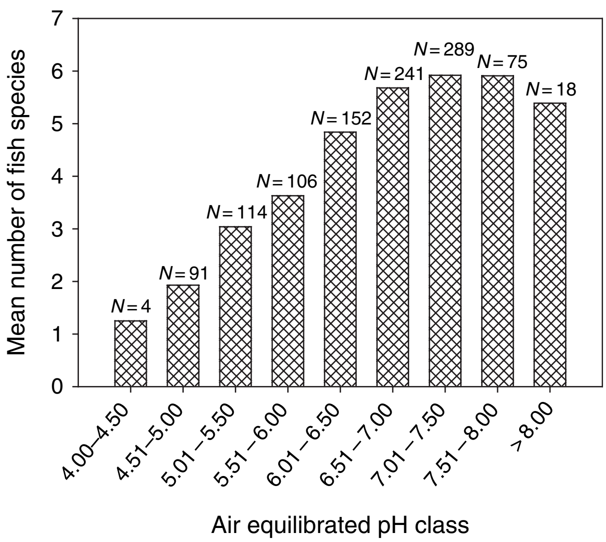


Figure 4 Distribution of the mean number of fish species for ranges of pH 4.0–8.0 in lakes of the Adirondack region of New York. N represents the number of lakes in each pH category.

and ANC, and higher concentrations of aluminum than lakes that contained one or more species of fish. Experimental studies and field observations demonstrate that even acid-tolerant fish species such as brook trout have been eliminated from some waters in New York.

Similar relationships are evident in surface waters in acid-impacted regions throughout the world. Studies demonstrate effects of acidic deposition on fish at three ecosystem levels:

- *Effects on single organisms (condition factor – the relationship between the weight and the length of a fish).* Fish condition factor is related to several chemical indicators of acid–base status, including minimum pH. This analysis suggests that fish in acidic streams use more energy to maintain internal chemistry that would otherwise be used for growth.
- *Population-level effects (increased mortality).* Bioassay experiments show greater mortality in chronically acidic streams than in high ANC streams. Eggs and fry are sensitive life-history stages for fish.
- *Community-level effects (reduced species richness).* The species richness of fish and other aquatic organisms decreases with decreasing ANC and pH.

Although chronically high acid levels stress aquatic life, acid episodes are particularly harmful because abrupt, large changes in water chemistry allow fish few areas of refuge. High concentrations of dissolved inorganic aluminum are directly toxic to fish and pulses of aluminum during acid episodes are a primary cause of fish mortality. High acidity and aluminum levels disrupt the salt and water balance of blood in a fish, causing red blood cells to rupture and blood viscosity to increase. Studies show that the viscous blood strains the heart of a fish, resulting in a lethal heart attack.

See also: Acidification; Air Quality Modeling; Atmospheric Deposition; Carbon Cycle; Nitrogen Cycle; Sulfur Cycle.

Further Reading

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Relevant Websites

http://nadp.sws.uiuc.edu – National Atmospheric Deposition Program (NADP).
http://www.epa.gov – US Environmental Protection Agency, Clean Air Status and Trends Network (CASTNET).

Ecological Efficiency

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Definitions

Historically, studies of multispecies assemblages have often focused on 'energy'. There were three general reasons for this:

1. Units of energy relate to all biological activity.
2. There was, for many years, the hope that a focus on energy would somehow bring ecology under the purview of thermodynamics.
3. Finally, once it had become customary to use energy units, there was no strong reason to change.

Concern with energy began as part of an attempt to extend the formal rigor of thermodynamics to biology. Lotka developed a diagram of an abstract ecological system at steady state. At the suggestion of Hutchinson, Lindeman used the notation of Lotka to describe the passage of energy through a lake.

In this trophic dynamic scheme, ecosystems are represented as a set of trophic levels. All the photosynthesizers (green plants, algae, and many kinds of colored bacteria) can be labeled as trophic level 0, the herbivores as level 1, carnivores feeding on herbivores as level 2, carnivores feeding on them as level 3, etc.

Ecological efficiency was rigorously defined by Lindeman as the fraction of the energy that is consumed by organisms on one trophic level that serves as nourishment for organisms on the next higher trophic level. It is a dimensionless ratio, both the numerator and denominator having units of energy/time. Estimates of the empirical value and the utility of ecological efficiency have been studied ever since Lotka and Lindeman and are still of concern.

Ecological efficiency can be measured for either plants or animals. Any definable portion of a community has an ecological efficiency if, and only if, it is possible to measure the energy per unit time taken from it by predators and the energy that it consumed from its prey or food organisms or, in the case of photosynthetic organisms, from solar radiation.

The trophic dynamic diagram of Lindeman was not perfect. There are omnivores that consume both flesh and vegetation, thereby feeding on several trophic levels. There are multiple tropic levels among the decomposers. There are also cannibals and organisms that change their trophic level as they mature. These considerations complicate assignment of particular species to particular trophic levels.

With the exception of some deep sea and hot spring bacteria, that use chemical energy in the absence of light,