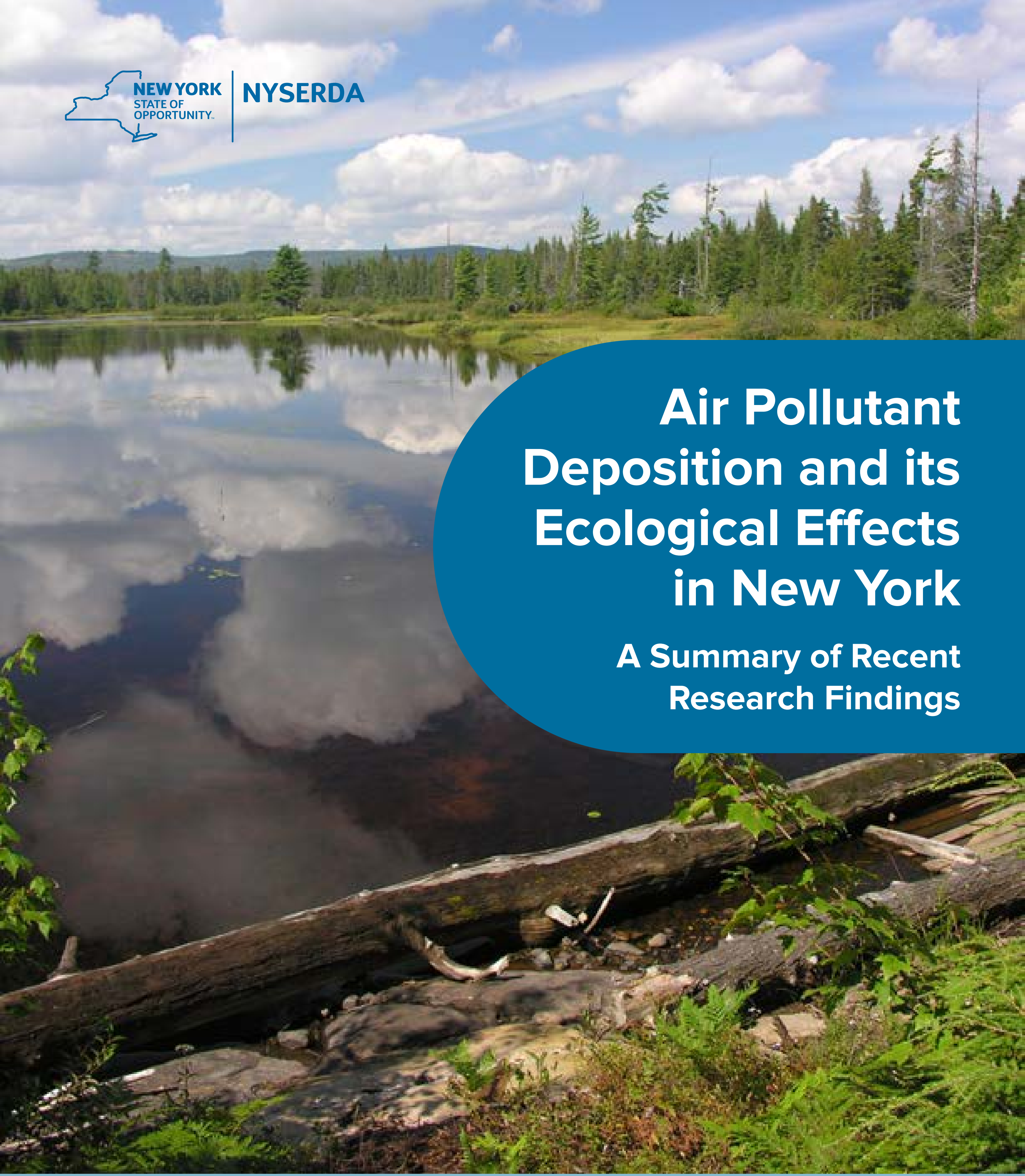

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Air Pollutant Deposition and its Ecological Effects in New York

A Summary of Recent Research Findings

August 2015

Report Number 15-21

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Serve as a catalyst – advancing energy innovation, technology, and investment; transforming New York's economy; and empowering people to choose clean and efficient energy as part of their everyday lives.

Air Pollutant Deposition and its Ecological Effects in New York

A Summary of Recent Research Findings

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NYSERDA Report 15-21 NYSERDA Contract 16299 August 2015

Notice

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Acknowledgments

This summary was prepared with funding from NYSERDA's Environmental Monitoring, Evaluation, and Protection (EMEP) program by E&S Environmental Chemistry, Inc. (E&S), Corvallis, OR. Timothy Sullivan wrote the text. Greg Lampman provided guidance and project management support. Barry Baldigo and Greg Lawrence provided photographs. We gratefully acknowledge the hard work and dedication of hundreds of scientific researchers who have uncovered the mysteries of how air pollutant deposition affects natural resources in New York.

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Cover Photo: Aquatic and terrestrial resources in portions of New York are sensitive to impacts caused by atmospheric deposition of sulfur, nitrogen, and mercury.
Photo courtesy of Barry Baldigo

1. Introduction

Atmospheric pollutant emissions of sulfur (S), nitrogen (N), and mercury (Hg), deposition from the atmosphere to the Earth's surface, and eventual biological damages to sensitive resources in New York State are linked. At various locations, damages are evident to lake plankton, stream macroinvertebrates, fish, vegetation, and other life forms. The scientific community has been studying these linkages for more than 30 years. However, between when gas and particle emissions occur and unhealthy terrestrial and aquatic organisms result, many biogeochemical changes occur. Chemicals are transported and transformed through meteorology, physics, chemistry, biology, and ecology. Soils and rocks buffer atmospheric acidity; nutrient cycles are disrupted. Inorganic Hg is converted to its highly toxic methylmercury form, which is prone to bioaccumulation; aluminum (Al) is mobilized from soil to drainage water where it can poison tree roots and fish.

Air pollution in New York State and elsewhere in the eastern United States began to increase dramatically in the 20th century. The amounts of S, N, and Hg emitted from pollution sources into the air increased steadily, reaching peak values during the last quarter of the 20th century. More recently, emissions have declined, mainly in response to federal legislation such as the Clean Air Act and its amendments. For the most part, S, N, and Hg pollutant levels continue to decline. Nevertheless, legacy effects on the environment remain. As chemical, and in some cases biological, conditions improve, the scientific community is trying to better understand how low pollution emissions need to go. Many questions need to be addressed. How good is good enough? Are the National Ambient Air Quality Standards for oxides of S and N adequate, or in need of revision? Additional emissions controls can be costly, but so too can be damages to ecosystem services caused by air pollutant deposition. Controls on S emissions will yield different benefits than comparable controls on N emissions. What are the ecological, economic, and societal trade-offs? How should New York manage sensitive and impacted resources?

Air pollution in the form of S, N, and Hg in and near New York has been, and continues to be, emitted from various sources, including power plants, motor vehicles, agriculture, incinerators, and industrial facilities. These pollutants are carried with the prevailing winds and eventually deposit to the earth's surface in the form of precipitation, air particles and gases, mountain clouds, and fog. Once deposited to vegetation or soil surfaces, pollutants move into the soil water where they can become adsorbed and stored on soil, taken up by plants and soil microbes, re-emitted into the atmosphere, or leached to surface waters. Effects in the soil, vegetation, and surface water ecosystem compartments are varied. A multitude of chemical and biological transformations occur, altering the chemical characteristics of the deposited substances and their behavior in the environment. Key processes relating to element cycling, toxicity, and bioaccumulation in the food web vary with contaminant type. Ecological impacts are diverse. Depending on the severity of impact, trees may die or fail to regenerate, plant species composition may change, fish may be eliminated from a particular body of water, estuaries may become over-enriched with nutrients, or a potent neurotoxin may bioaccumulate in fish. The toxin, in turn, might be consumed by, and have adverse impacts on, fish-eating wildlife and humans. The costs to individuals and society are diverse and often substantial.

Adverse effects of air pollutant deposition on lakes and streams and their watersheds occur throughout sensitive regions of New York. Pollutants can impact water quality and harm many species of aquatic biota. They also alter the chemistry of watershed soils, with potential impacts on plant roots and other terrestrial life forms. Scientists study the biogeochemistry of the entire landscape. The chemistry of drainage water integrates a host of terrestrial and aquatic processes that interact with water as it moves from the atmosphere as precipitation through the soil and into the ground water, and eventually to streams, lakes, rivers, and estuaries.

2. Scope

The research summarized here synthesizes air pollutant deposition levels and effects on terrestrial and aquatic resources throughout New York State. The major focus of this report is on resource sensitivity to atmospheric emissions and deposition of S, N, and Hg; impacts on surface waters, soils and vegetation; confounding influences of disturbance; and chemical and biological effects of acidification, nutrient enrichment, and mercury biomagnification in the food web.

This summary addresses air pollution effects in New York. It highlights mainly research conducted in the Adirondack and Catskill parks, Long Island Sound and associated coastal estuaries, and the Great Lakes region. It also draws extensively on research conducted elsewhere in the northeastern United States, and to some extent throughout the country and overseas. A host of ecosystem characteristics influence sensitivity to harm from atmospheric deposition of the various air pollutants. These characteristics include elements of hydrology, soils, geology, and biological communities. The principles described here are applicable to the study of air pollution and its effects globally. These principles also apply to the study of other environmental issues besides atmospheric deposition of S, N, and Hg. These cycles, processes, and transformations can also inform the study of agricultural, silvicultural, and urban pollutants; climate change; and other aspects of nonpoint and point source pollution. Some of the major findings are highlighted in the following sections.

3. Principal Findings

3.1 Acidification

In areas of New York that are both acid-sensitive and receive substantial acidic deposition, forest soils have been acidified and soil base saturation (BS) levels have decreased. Decreases in concentrations of exchangeable base cations, including calcium (Ca), in upper soil horizons have been documented, and acidic deposition has been shown to be an important causal factor. Aquatic and terrestrial acidification effects have been especially pronounced in the Adirondack and Catskill mountains, and have included decreased exchangeable Ca and Ca-to-aluminum (Ca:Al) ratios in soil solution.

Soil acidification, Al toxicity, and exposure of plant foliage to acidic deposition have collectively contributed to decline in lichens, red spruce, sugar maple, and perhaps other tree and understory plant species in New York (Figure 1). Effects in forests have likely included reduced growth and increased stress and mortality in some overstory tree species, reduced regeneration, and likely changes in plant species distributions.

Levels of atmospheric deposition of S and N in New York are illustrated in the maps in Figure 1 and Figure 2. Deposition levels of both S and N are highly variable, but are moderately high throughout much of the State. In addition, ecosystem sensitivity to acidification and nutrient enrichment vary widely. Effects are driven by both pollutant input levels and ecosystem sensitivities.

The natural movement of Al in the soil profile has been altered by acidic deposition, resulting in greater transport of inorganic Al (Ali) from the soil to streams and lakes. In sufficiently high concentrations, Ali in soil solution or surface water can be toxic to plant roots and to aquatic life, including fish.

Sulfur, in the form of sulfate (SO_4^{2-}), has been the principal human-caused agent of soil acidification in New York. Sulfate leaches Ca and other base cations (including magnesium, sodium, and potassium) from the soil, reduces the soil base saturation, and decreases the ability of the soil to neutralize acidic deposition. Sulfur retention through anion adsorption or incorporation of S into soil organic matter prevents or retards SO_4^{2-} leaching temporarily. Nevertheless, most deposited S in New York eventually leaches to surface waters, where it can contribute to water acidification.

Nitrogen deposition has decreased the carbon-to-nitrogen (C:N) ratio in soils, and has contributed to increased net nitrification in soil. Nitrogen availability in excess of biological demand by plants and microbes has become more widespread. This N saturation is reflected in elevated nitrate (NO_3^-) concentrations in some streams and lakes during the growing season. This NO_3^- can contribute to acidification. Such effects have been documented in both the Adirondack and Catskill Mountains.

Lakes and streams in some parts of New York are sensitive to both episodic and chronic acidification in response to S and N deposition. Sensitive lakes and streams often occur at moderate to high elevation in

Figure 1. Total wet plus dry sulfur (S) deposition in New York for the year 2006, expressed in units of kilograms of S deposited from the atmosphere to the earth surface per hectare per year

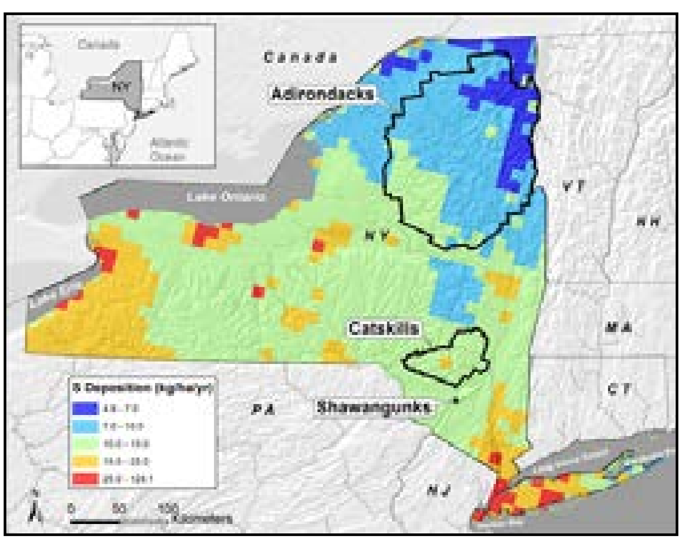
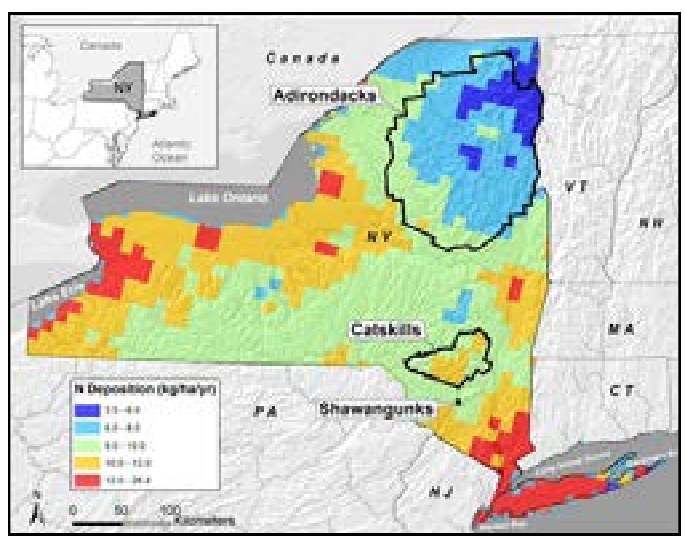


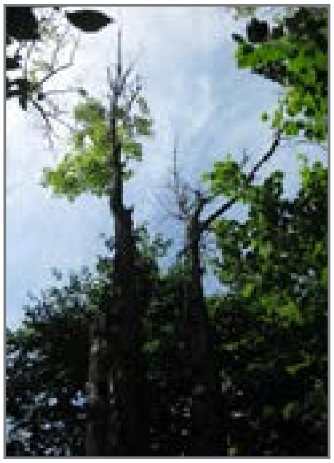
Figure 2. Total wet plus dry deposition of total (oxidized plus reduced) nitrogen (N) in New York for the year 2006

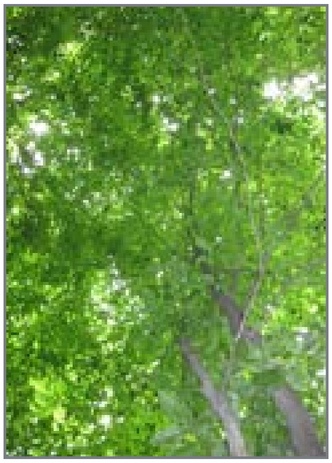


Data for Figure 1 and Figure 2 were derived using the CMAQ model (data provided by R. Dennis, U.S. EPA).

Photo courtesy of Barry Baldigo

Lake and stream water chemical conditions are more acidic and potentially toxic to aquatic biota during snowmelt and rainstorms as compared with baseflow.





Photos courtesy of Greg Lawrence

Canopy conditions are highly variable across the study sites.

areas that have base-poor bedrock, high relief, and shallow soils. Acid-sensitive lakes and streams are numerous in some regions, including major portions of the Adirondack and Catskill Mountains, where more than one-fourth of the surface waters have been adversely affected by water acidification. Within the Adirondack Mountains, both lakes and streams have been well studied. Streams tend to be somewhat more acid-sensitive than lakes. Highly sensitive aquatic ecosystems in the Catskill Mountains are mostly streams. Acidification can be episodic, operating over time scales of hours to days, or it can be chronic, affecting chemistry on an intra- and interannual basis. In some cases, long-term chronic chemistry might be suitable for maintaining the health of aquatic biota, but short-term episodes of acidity can have lethal consequences.

Aquatic biota have been impacted by acidification at virtually all levels of the food web. Effects have been most clearly documented for fish, aquatic insects, and algae. Some species and some life stages are more sensitive than others. The most sensitive species have been eliminated from many lakes and streams, and taxonomic richness has decreased. In extreme cases, all fish species have been eliminated from acidified waters. It appears likely that reduced tree growth and increased tree mortality caused by soil acidification and/or N saturation have occurred in localized areas that have experienced depletion of soil Ca and increased Ali in soil solution. Such effects interact with other ecological stressors, including climate and invasive species.

The dissolved organic carbon (DOC) concentrations in Adirondack surface waters have increased over approximately the last two decades in response to decreases in acidic deposition and perhaps also to increases in temperature. Such changes in DOC concentration can, in turn, influence the toxicity of Ali to fish and other aquatic biota; the level of organic acidity in surface waters; and the transport, methylation, and biomagnification of Hg in Adirondack watersheds. The interactions are complex. Increased concentrations of DOC can increase acidity, but reduce the toxicity of Al to biota. Increased DOC might also facilitate Hg methylation and biomagnification in fish and wildlife.

Acidic deposition and associated effects have decreased in New York over the past few decades largely in response to emissions controls mandated by the Clean Air Act (CAA) and its amendments. Despite improvements in air quality and acidic deposition, however, damages to natural ecosystems have been only partially reversed. Hundreds of streams and lakes in New York are still acidic; in other words, they have acid neutralizing capacity (ANC) less than 0 microequivalents per liter (µeq/L). Most of these waterbodies are located in the Adirondack and Catskill Mountains. Many more streams and lakes are not quite acidic but have sustained some degree of biological damage caused by water acidification. The health of

Photo courtesy of Greg Lawrence

Old growth trees like this one are found at some locations in the Adirondack Mountains.

Photo courtesy of Greg Lawrence

Forest understory is diverse at some locations in the northern hardwood forest that receive adequate light.

some tree species, mainly red spruce and sugar maple, has been adversely affected by acidic deposition. Various species of fish and other aquatic animals can no longer exist in acidified waters.

Some recovery is under way. Sulfur deposition to acid-sensitive watersheds in New York has decreased by about half during the past three decades. The pH of rainfall has increased by about one-fourth of a pH unit. Nitrogen deposition has also decreased, but to a lesser extent. Hopes for chemical and biological recovery have shifted to the prevailing current scientific consensus of a long-term (decades or longer) gradual process of chemical recovery. This recovery will involve depleting the acids that have accumulated in the soils of sensitive watersheds through more than a century of acidic deposition and restoring through the process of weathering some of the Ca and other base cations that have been lost from the soil. Weathering is a slow process and can take decades or longer to restore base cation levels on watershed soils to pre-pollution levels. Chemical recovery can be facilitated by active resource management. This management can include stocking of fish or other species that were previously extirpated from a given water body by high acidity. It can also include adding Ca and other base cations to acidified drainage waters and/or watersheds.

3.2 Nutrient Enrichment

Atmospheric inputs of N can increase growth of some plants at the expense of others. As a consequence, N deposition can alter competitive relationships among plant species and affect species composition and diversity. The extent to which such effects have occurred in New York is not known. It is well known, however, that atmospheric N deposition can increase the growth of plants in the short term. Enhanced plant growth generally occurs mainly above the ground level. This growth can cause changes in the shoot-to-root ratio, which can be detrimental to the plant because of decreased resistance to environmental stresses such as drought. At high levels of N input, tree growth can decrease and mortality can

Photo courtesy of Barry Baldigo

Many small Adirondack lakes are in the process of recovering from acidification.

increase. Data are not sufficient with which to quantify any increase or decrease in forest growth that may have occurred in New York in response to N deposition, partly because trees have been exposed to multiple stresses simultaneously.

Increased N availability from N deposition in New York has likely caused some plant species to flourish at the expense of other species. Some native species may have been replaced at some locations by nonnative opportunistic species. The extent and magnitude of these changes in New York are not known. A study is ongoing, with funding provided by NYSERDA, to document acidification impacts on herbaceous plant species in the Adirondack Mountains.

Estuaries and near-coastal marine waters tend to be sensitive to nutrient enrichment from N inputs. Some coastal waters in New York have experienced moderate to severe eutrophication. Effects of severe eutrophication can include oxygen (O_2) depletion, excessive growth of algae, fish kills, and damage to aquatic organisms at many trophic levels. Atmospheric N deposition contributes to these damages. There is a scientific consensus that N-driven eutrophication of shallow estuaries has increased over the past several decades and that the degradation of coastal ecosystems is now a widespread occurrence in New York and throughout the United States. Atmospheric N deposition constitutes one source of N input to estuaries that have experienced eutrophication. Other non-atmospheric contributions, including contributions from wastewater treatment plants and agriculture, have also been significant and in most cases have been dominant.

Fresh waters can be sensitive to nutrient enrichment effects from N deposition. In general, sensitive waters tend to be those that are highly oligotrophic. These are often found at high elevations in remote areas. Such lakes and streams are sometimes N limited, and atmospheric N deposition can cause or contribute to their eutrophication. Primary productivity in N-limited freshwaters can be increased with the addition of even small amounts of N. Eutrophication increases algal biomass, alters algal species assemblages, and may affect aquatic food webs.

Great Lakes waters in New York have experienced eutrophication in the past as a consequence of human-caused nutrient inputs. This problem has been largely attributed to phosphorous (P) addition, but N addition has also been substantial. The majority of the nutrient inputs to the Great Lakes have been of non-atmospheric origin, but atmospheric N deposition has been a contributor and is at least partly responsible for the observed eutrophication. In more recent years, the introduction and massive proliferation of non-native invasive mussels have further altered the trophic condition of these lakes and obfuscated scientific understanding of the role of atmospheric nutrient input.

Increased growth of silicate-utilizing diatoms as a result of NO_3^-- and phosphate (PO_4^{3-})-induced eutrophication, and subsequent sedimentation when the diatoms die and fall to the bottom, has changed the ratios of nutrient elements silicon (Si), N, and P in near-coastal marine waters. In turn, such changes can cause shifts from diatoms to other forms of phytoplankton. Such changes are expected to affect other levels of the food web.

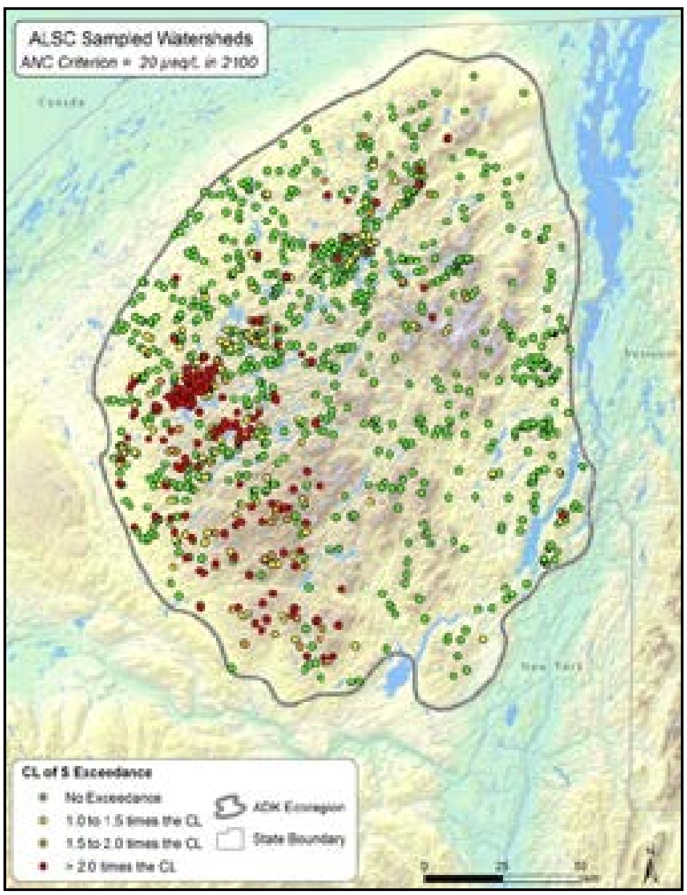
Atmospheric deposition of N adds a critical element (N) to terrestrial, transitional (i.e., wetland), and aquatic environments. In many ecosystems, N is growth limiting to algae and plants at the base of the food web. Thus, even relatively small additions of N in atmospheric deposition can alter sensitive ecosystems and affect key ecosystem processes. It is often difficult to quantify such responses because nutrient enrichment effects from N addition interact with the cycling of other elements and with the influence of climatic variability and both natural and human-caused disturbances.

In recent years, scientific understanding of nutrient enrichment effects from atmospheric N deposition has improved. Knowledge gains have occurred in multiple research areas, including ecological stoichiometry, characterization of ecosystem sensitivity, N vs. P limitation in aquatic ecosystems, quantification of denitrification, and use of stable isotopes to improve scientific understanding of N and other element cycling. Eutrophication effects of N deposition are now known to be widespread and to occur in a variety of sensitive ecosystems.

3.3 Critical and Target Loads and Ecosystem Services

Chemical indicators of ecological damage in response to atmospheric deposition have been identified along with their tipping points or levels at which biological effects become apparent in sensitive regions of New York. These levels include, for example, water ANC of 50 µeq/L to protect fish biodiversity and B-horizon soil base saturation of 12% to protect sugar maple regeneration (Figure 3).

Figure 3. Sulfur deposition critical load exceedances have been estimated for lakes throughout the Adirondack Mountains region



In this example, exceedance classes are mapped for 1,136 Adirondack lakes based on extrapolation of MAGIC model results of S critical loads (CLs) to the Adirondack Lakes Survey lakes. Exceedances were calculated for the year 2100 using a critical threshold ANC value of 20 µeq/L.

Critical and target loads of S deposition have been calculated to protect aquatic and terrestrial resources in the Adirondacks against biological impacts caused by soil and water acidification. These loads represent the deposition levels below which adverse impacts to biota are not expected to occur. These critical (long-term steady-state) and target (specific to the years 2050 and 2100) loads have been calculated using different critical indicators and tipping point values. Comparison of the critical or target load to the ambient S deposition at the receptor location yields the exceedance, or the extent to which ambient deposition exceeds the load that the ecosystem can tolerate without incurring biological harm. One example is shown on the accompanying map. In this example, the exceedance is mapped that will protect Adirondack lakes from acidification to ANC below 20 µeq/L in the year 2100. Most lakes found to be in exceedance of this tipping point are located in the southwestern portion of the Adirondack Park.

The critical or target load can inform identification of the ecosystem services that might be compromised by exceedance of the critical or target loads. These ecosystem services represent the end products of nature that are of value to humans. Many ecosystem services in New York may be affected by critical or target load exceedance. Well-known examples include the presence of a brook trout fishery, the regeneration of sugar maple trees, or the presence of submerged aquatic vegetation in an estuary. Ongoing work funded by NYSERDA is focused on documenting and quantifying effects on selected ecosystem services provided by natural resources in the Adirondack Mountains.

3.4 Mercury

Mercury is emitted from both natural and human-caused sources, including coal-fired power plants, mining, incinerators, and cement manufacturing. Mercury accumulates in the brain and kidneys of mammals and birds and biomagnifies to higher concentration at each level of trophic transfer. Methylation is a key step in the Hg cycle that affects watershed transport and bioaccumulation. Deposition of S, increased concentration of DOC, decreased drainage water ANC, wetland occurrence, and decreased dissolved oxygen (DO) all contribute to or correlate with Hg methylation and biomagnification. Effects occur statewide.

Deposition of Hg has contributed to increased concentrations of Hg in New York surface waters, especially in the Adirondack Mountains. Some of this deposited Hg becomes methylated in aquatic ecosystems

Photo courtesy of Barry Baldigo

Wetlands that drain into Adirondack lakes often provide conditions that promote methylation of mercury, which increases its bioaccumulation in the food web.

and bioaccumulated and biomagnified in the food web. Because Hg methylation is largely carried out by bacteria that require S to sustain their metabolic activities, atmospheric S deposition has further contributed to Hg methylation, biomagnification, and toxicity in New York surface waters. The Adirondack region has been identified as a hotspot for Hg methylation owing to an abundance of lakes and wetlands and the common occurrence of low surface-water ANC and pH. High organic content of water, which is mainly a consequence of wetland influence, and increased acidity provide ideal conditions for Hg bioaccumulation in fish and wildlife. Such conditions contribute to high body burdens of Hg in fish and toxic concentrations in piscivorous wildlife, including common loon, bald eagle, river otter, and others. Many species of songbirds have also been affected.

3.5 Climate

The cycling of S, N, Hg, and base cations in New York ecosystems is influenced by climatic conditions, and, by inference, change in those conditions. Rain, snowmelt, and drought all affect acidification, neutralization, and biological uptake processes. Weathering is temperature-dependent, yielding larger quantities of base cations under warmer temperature. Future changes in N availability will exacerbate shifts in species distributions that occur in response to changes in temperature, water availability, and the occurrence of invasive species. In particular, changes in snowpack development, hydrology, and freeze-thaw cycles in soil will impact ecosystem responses to air pollutant deposition. Effects are complex and interactive. The overall net impact of climate change on air pollution deposition effects is unknown and is an active area of study.

3.6 Recovery

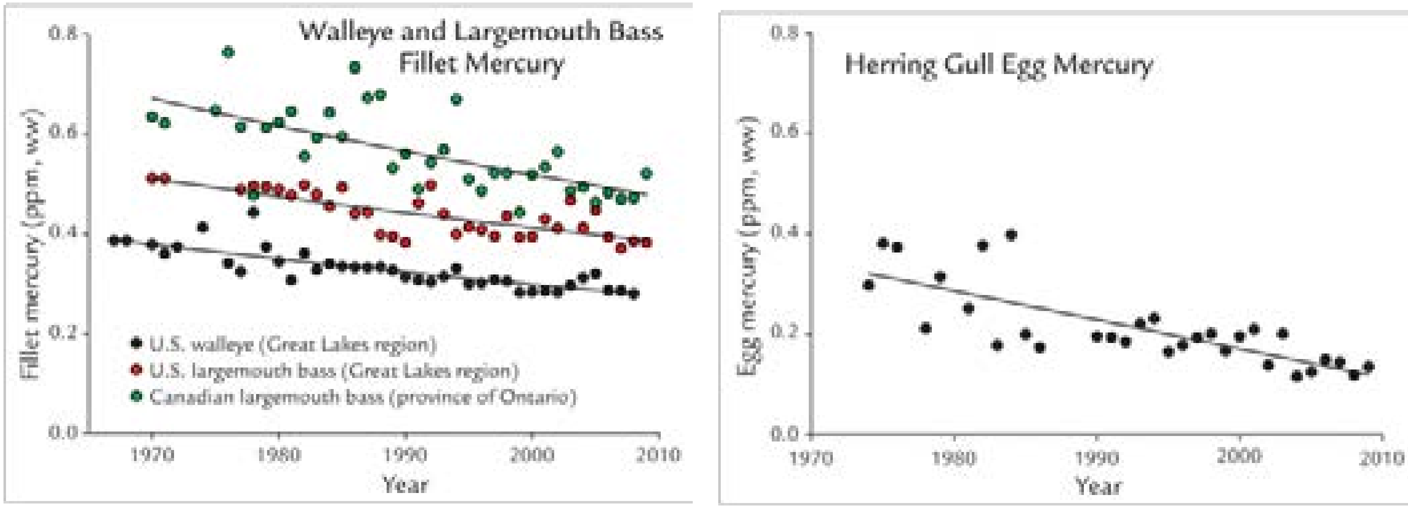
Monitoring data have supported the consensus that surface-water chemical recovery will be slow and limited. In addition, model projections have suggested that the documented ongoing chemical recovery may not be sustainable without additional emissions reductions. The ability of soils to neutralize acidic deposition changes over time. As acidity is neutralized and S and N continue to be stored in the soil, the ability of a given watershed to neutralize deposited acids is progressively reduced. This reduction affects the capacity of watersheds to recover from acidification. To the extent that emissions controls are delayed, those emissions controls will probably be less effective in mitigating the damage from soil and water acidification.

Soils can partially recover base cation reserves over time in response to reduced levels of acidic deposition. However, the recovery potential of soil-exchangeable base cations is dependent on weathering rates and operates over periods of many decades or longer. Modest emissions controls can decrease the rate of soil acidification but are unlikely to result in substantially improved soil condition for a long period of time.

Recent increases in DOC in Adirondack surface waters suggest the possibility of increased methylation potential. During hydrologic episodes, the source and amount of both DOC and Hg change. The extent of such effects to date is not known. There is some evidence, however, that Hg levels in some species of wildlife may have decreased in recent years. See Figure 4 for the Great Lakes Region. Additional research is needed.

Enhanced leaching of NO_3^- to surface waters in the northeastern United States generally occurs above a threshold of atmospheric N deposition of about 10 kg N/ha/yr. Estimated levels of N deposition in many parts of New York exceed this value. Relationships between atmospheric N deposition and NO_3^- leaching are complicated by past and current land use and climatic

Figure 4. Long-term mercury trends in fish and wildlife, 1967–2009



Mercury concentrations in fish fillets (walleye and largemouth bass, averaged by year across multiple sites in the Great Lakes and inland water bodies in the U.S. Great Lakes states and the province of Ontario) and temporal trends in mercury concentrations in herring gull eggs (averaged by year across multiple sites in the Great Lakes region). These data are characteristic of the regional trend of decreasing mercury concentrations in fish and wildlife in recent decades. Much of this decrease has been attributed to reductions in regional mercury emissions, although there may be other contributing factors as well. Sources:. (1) Evers, D.C., et al. 2011. Great Lakes Mercury Connections: The Extent and Effects of Mercury Pollution in the Great Lakes Region. Report BR1 2011-18. Biodiversity Research Institute, Gorham, ME. (2) Monson, B.A., et al. 2011. Spatiotemporal trends of mercury in walleye and largemouth bass from the Laurentian Great lakes region. Ecotoxicology 20:1555-1567. (3) Weseloh, D.V.C., et al. 2011. Current concentrations and spatial and temporal trends in mercury in Great Lakes herring gull eggs, 1974-2009. Ecotoxicology 20(7):1644-1658.

variations. Forest insect infestation and disease can also affect N cycling and leaching. Projections of changes in N retention and release from terrestrial ecosystems in response to changing levels of atmospheric N deposition are therefore highly uncertain.

4. Conclusions

Air pollution impacts appear to be generally improving in New York. Emissions controls have reduced impacts in New York and throughout much of the eastern United States. More time is needed to allow various air pollution emissions control policies to have their full beneficial effect. In addition, society faces ongoing decisions concerning the desirability of further cuts in emissions of S, N, and Hg and the possible need for additional remediation. Some surface waters that have been recovering during the past few decades may partially re-acidify in the near future unless emissions levels are further reduced. Costs and benefits must be weighed to determine the levels of air pollution and acidic, nutrient, and toxin deposition that balance competing environmental, economic, and societal goals. The future of New York's outstanding natural resources, especially those resources in the coastal areas and the Adirondack and Catskill Mountains, will be affected by the decisions that are made.

Important conclusions from several decades of atmospheric deposition effects research in New York include the following:

- Atmospheric S deposition to acid-sensitive watersheds in New York has been declining for three decades and continues to decline. Nitrogen deposition was stable for many years but started to decline after the turn of the 21st century. Existing and anticipated federal and State regulations are expected to contribute to further reductions in S and N deposition during the next decade.
- Many natural ecosystems are able to buffer some level of air pollution. Sensitivity varies across the landscape. Only some of the soil, plant, and water resources in New York are sensitive to existing air pollution levels, and many remain largely unaffected.
- Even with the recent reductions in acidic deposition, sensitive regions of New York experience air pollution levels higher than many other parts of the United States.
- Despite some recent improvements in water chemistry, levels of acidity in many lakes and streams in the Adirondack and Catskill Mountains regions are still harmful to many species of fish and other aquatic life forms.

- Ongoing chemical recovery of previously acidified Adirondack lakes has been complicated by concurrent increases in lakewater DOC. These chemical changes have caused a cascade of effects, including limiting the extent of ANC and pH increase, reducing the toxicity of Al, and perhaps increasing the methylation and biomagnification of Hg.
- Critical loads of S deposition are exceeded in many lake and stream watersheds in the Adirondack and Catskill Mountains and will remain in exceedance even with relatively aggressive further decreases in S and N deposition.
- Exposure of vegetation to continued relatively high levels of acidic and nutrient deposition and associated soil acidification will likely cause further damage to plants in the future and a decline in the abundance of the more sensitive plant species.
- Estuaries and coastal marine waters in New York have experienced varying degrees of eutrophication from N addition, and atmospheric N deposition is partly responsible.
- Some of the damages that have occurred to soils and aquatic ecosystems are only partially reversible over the next century, even with additional reductions in pollutant emissions.
- Bioaccumulation of Hg in fish and piscivorous wildlife has been pronounced in many lakes and streams throughout New York. This bioaccumulation has been attributed in part to relatively high levels of atmospheric Hg deposition, but more importantly to watershed characteristics that promote Hg methylation, transport, and bioaccumulation. Mercury accumulates in fish to levels that are potentially toxic to humans, songbirds, and piscivorous wildlife, including river otters, mink, bald eagles, and ospreys.
- Scientists and economists are just beginning to determine the ecologic, economic, and societal costs of air pollution in New York and the extent to which valuable ecosystem services will be restored by emissions controls.

5. Future Research

As detailed here, a great deal of research has been conducted on air pollution and its effects in New York. Much of that work has occurred within the last three decades. Scientific understanding of the effects of atmospherically deposited acid precursors, nutrients, and toxic materials has advanced to a relatively high level. However, many uncertainties and unknowns remain.

Existing knowledge has been formulated into various mathematical models of atmospheric processes, atmospheric deposition, nutrient cycling, biomagnification, and acid-base chemistry. Model projections shed light on pre-industrial conditions and likely future changes in resource condition as pollutant emissions and deposition levels decline in response to emissions controls. In many cases, the more sensitive biological receptors have been identified. Chemical and biological monitoring programs have yielded critical information documenting changes over time in resource condition. Nevertheless, much remains to be learned.

Some of the research areas in greatest need of further work in New York are highlighted below. The list is not intended to be exhaustive. A great many other questions have yet to be answered. In many cases, scientists don't

Photo courtesy of Barry Baldigo

Forests growing on calcium-depleted soils that receive relatively high levels of acidic deposition have experienced a variety of adverse impacts, including plant mortality and effects on canopy condition and regeneration.

even know what the important questions are or will be. The following suggestions for future work are not presented in any particular known order of importance:

- Chemical indicators of ecological damage in response to atmospheric deposition have been identified along with their tipping points or levels at which biological effects become apparent in sensitive regions of New York. These levels include, for example, water ANC of 50 µeq/L to protect fish biodiversity and B-horizon soil base saturation of 12% to protect sugar maple regeneration. Experimental and observational research is needed to identify additional sensitive biological resources, chemical indicators of adverse ecological effects, and tipping points for those indicators.

- Target loads of S deposition to protect fish biodiversity have been calculated within a management time frame for Adirondack lakes. These target-load results have been extrapolated to the full population of Adirondack lakes larger than 1 hectare. Analogous target-load values have not been calculated for acid-sensitive streams, which are common in both the Catskill and Adirondack Mountains regions. It is likely that streams are generally more sensitive to acidification than lakes. Furthermore, such target-load estimates for protecting stream resources in acid-sensitive portions of New York need to be compared with ambient S deposition loads to determine the locations and magnitude of target-load exceedances. Calculations of target load and exceedance for protection against acidification could greatly benefit from an improved ability to predict mineral weathering across the landscape.

- Some Catskill and Adirondack Mountain watersheds leach considerable NO_3^- under ambient N deposition loads, suggesting partial N saturation. The climatic, management, and chemical factors that govern this apparent N saturation are poorly known. In addition, very little empirical information is available regarding the timing of transitions between conditions of saturation and nonsaturation under varying levels of atmospheric N deposition. More research is needed to discern these relationships and drivers of ecosystem change.

- Adirondack lakes that have shown signs of recent recovery from acidification exhibit a range of anticipated responses, including increased ANC and pH and decreased concentrations of base cations and Al. However, many lakes also show increased levels of DOC, a response that limits the extent of ANC recovery. Although this DOC response was predicted 25 years ago, the magnitude of the response has been surprising to many in the scientific community who study acidic deposition. Additional work is needed to better understand this response so that it can be more effectively incorporated into mathematical acid-base chemistry models.

- Great progress has been made over the past three decades in developing a clear understanding of key processes that govern surface-water acidification and recovery in response to recent decreases in acidic deposition. In addition, some (albeit more limited) progress has been made in understanding N cycling and saturation; biological responses to improvements in water acid-base chemistry; nutrient enrichment effects; and Hg deposition, methylation, and biomagnification. Chemical and biological long-term monitoring data have been critical to these scientific advancements. Sustained monitoring will be needed to continue to improve scientific understanding and tackle emerging scientific issues surrounding climate change and the effects of nonnative species and other threats and perturbations that interact with processes that govern ecosystem responses to atmospheric deposition.

- It has been established that Hg methylation and biomagnification in fish and wildlife are partly controlled by atmospheric Hg deposition. It has also been established, however, that watershed cycling of C and S are important drivers of Hg accumulation, especially in piscivorous predators. At many locations in New York, C and/or S cycling are likely more important than Hg deposition in this regard. Better information is needed to describe the influence of ongoing deacidification on Hg cycling in New York watersheds. In particular, scientists and policymakers need to know how Hg levels in fish will respond to continued decreases in S inputs and increases in C mobilization in watersheds that have relatively high Hg concentrations in fish.

- The concept of critical and target loads has not yet been successfully applied to atmospheric Hg deposition in New York. Scientists and policymakers need to know the levels of Hg input that lead to unacceptably high concentrations of Hg in fish and wildlife and the interactions between such critical Hg levels and watershed characteristics that control Hg cycling. If they exist, the tipping points need to be identified of S deposition below which Hg methylation becomes limiting for Hg biomagnification.
- Identification of ecosystem services that are impacted by atmospheric deposition and the extent to which these ecosystem services are influenced by emissions controls are at very early stages of development in New York and elsewhere. Similarly, valuations of ecosystem services that may be lost or recovered in response to changes in atmospheric pollutant emissions have not been well quantified. Further research is needed at the interface between environmental science and policy to determine the values to human society that are expected to be lost or gained in response to existing and future emissions and controls on those emissions.
- It is well known that the effects of atmospheric S, N, and Hg deposition are modified by climatic conditions, especially temperature, soil moisture, stream flows, drought, and snowpack dynamics. It is also well known that the regional climate is changing and that conditions in the coming decades and centuries may be quite different from the climate of today. More work is needed to quantify these linkages, allowing improved incorporation of climate change into mathematical models of ecosystem responses to air pollutants.
- As lake and stream chemical conditions continue to improve in response to emissions controls and decreases in S, N, and Hg deposition, aquatic conditions may become increasingly hospitable for fish and other aquatic life. More work is needed to determine the effects of this chemical recovery on Hg biomagnification, the recovery of biological communities, and the extent to which human intervention will be needed to reintroduce species to habitats from which they were extirpated in previous decades.

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