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An Update on the Science of Acidification in the Adirondack Park

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RESOURCES FOR THE FUTURE

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Abstract

This paper provides a review of the science pertaining to all aspects of acidification in the Adirondack Park, updating an earlier review of the science (Cook et al. 2002). The review supports an ongoing social science investigation into the willingness to pay for ecological improvements that would result from reduced acid deposition. This paper builds a bridge between the physical science and social science by providing the background that will allow researchers to accurately summarize the crucial elements of ecological status and improvement in a stated preference survey.

Key Words: acid rain, acidification, stated preference, willingness to pay, benefit estimation

JEL Classification Numbers: Q51, Q53, Q57

Contents

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Introduction

In 2002 Cook et al. authored a review of the science of acidification in the Adirondack Park to provide a summary that could be used in social science research about public attitudes toward changes in the ecological status of the park. The review was developed to support a contingent valuation study of willingness to pay for ecological improvements in the park that could be expected to occur from a reduction in emissions that lead to acidification. A survey was administered to New York State residents from August 2003 through February 2004 and published by Banzhaf et al. (2006). Since that study, events have proceeded along two directions. New information about the science of the acidification in the park has entered the literature, and new methods for eliciting willingness to pay have found increasing application in environmental economics. This paper extends the previous review of the science by providing an updated summary that can be used to update and validate the previous estimates of willingness to pay. The new estimation will involve a revised contingent valuation survey and a new conjoint survey instrument.

The original *Summary of the Science* (Cook et al. 2002) contained information about general acidification science as well as specifics related to the Adirondack Park. In preparing this update we have reviewed recent publications and reinterviewed experts about the status of the park and scientific uncertainties described in the previous summary.

In general the recent literature reinforces the central findings of the previous *Summary*. Previous findings about the effects of acidification on aquatic ecosystems have been extended by additional evidence with respect to suspected relationships about the effects of acidification on

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terrestrial systems, surface water, and the methylation of mercury. A somewhat more clear characterization of the effects of future emissions scenarios also has emerged.

New information has further confirmed the direction of damages from acidic deposition. Uncertainties noted in the previous *Summary* are now more certain. Where uncertainties remain is not in the scientific understanding of cause and effect, which have been copiously documented, but rather the time scale on which damages occur. Because many factors affect high-elevation spruce-fir forests, one uncertainty that does remain is how nitrogen deposition in particular damages these forests, given that there are a lot of other factors also damaging these areas.

Forests

The effects of acidification on forests are organized into discussions about base saturation; calcium, mercury, and nitrogen; and effects on fauna. On net, emerging information in the literature suggests a strengthening of the link that Cook et al. (2002) suggested, but characterized as uncertain, between acidification and forest health. Biogeochemical relationships—measurements of the cycling of chemical elements through biotic components of the ecosystem—are increasingly considered indicators of the biotic health of forests. Nonetheless, quantification of the extent of damage remains difficult.

In the first *Summary of the Science*, Cook et al. speculated that acidic deposition was increasing morbidity and mortality of red spruce and other hardwoods, specifically sugar maple. Causal relationships between tree decline and acidic deposition are more compelling now, but this work is still being developed. Linkages to biogeochemical indicators are becoming more of a focus of research (Multi-Agency Critical Loads Workshop 2006). There is little new information about the magnitude of the impact of acidic deposition on trees, however.

A. Base Saturation

Many Adirondacks watersheds may have soil conditions affected by acidification that are unfavorable to forest health. Base cations in soil are important as nutrients as well as in neutralizing acid inputs. Base saturation (the measure of base cations in soil) in Adirondacks watersheds is calculated to have decreased by 50 percent between 1850 and 1984 with continuing declines (Chen and Driscoll 2005). Simulations of the Model of Acidification of Groundwater In Catchments (MAGIC) suggest that there was a rapid decline in Adirondacks base saturation between 1980 and 2000 that is likely to continue, although at a slower rate through the year 2100 (Sullivan et al. 2006). Similarly, a survey study of Adirondacks sites comparing 1984 and 2001 data found that decreased calcium availability and base saturation were significant in the period, accompanied by increased aluminum and acidity of soils (Warby et al. in review). Soils in acid-sensitive areas of the Northeast continue to acidify and show no signs of chemical recovery despite decreases in acidic deposition (Warby et al. in review).

A recent study revealed that three-fourths (n=990) of all Adirondacks watersheds draining to lakes larger than 1 ha, deeper than 1 m, and having an acid-neutralizing capacity (ANC) $\leq$ 200 μeq/L currently have base saturation less than 10 percent in the underlying mineral soils (as opposed to the organic layer on the forest floor that naturally contains higher concentrations of base cations because of decomposition) (Sullivan et al. 2006). A base saturation between 15 and 20 percent is thought to be an indicator of potential forest decline. Even if base saturation does not fall below this level, a general decrease may be enough to cause tree decline (Lawrence et al. 2005). There is naturally some variability between forest types, with soils under coniferous forests tending to have the lowest base saturation values and soils under hardwood forests the highest (Sullivan et al. 2006). This indicates that coniferous forests would be more at risk for forest decline due to base cation leaching from acidification but also that soils throughout the park have become depleted by acidic deposition.

This new information provides more concrete information with which to describe forest conditions in the survey (i.e., 75 percent of Adirondacks forests have soils deteriorated below the assumed threshold for optimum health and are expected to continue to degrade).

B. Calcium

New information in the literature supports liming as a mitigation of soil damage from acidic deposition. Mineral depletion from acidic deposition has been found to visibly deteriorate sugar maple canopies, increase winter injury to red spruce, and generally promote poor nutrient conditions in the average Adirondacks watershed. The base cation calcium is a particularly important nutrient for plant growth. Calcium depletion from forested watersheds is an early indicator of forest health because of its functional response to acidic deposition in many forests in North America (Fenn et al. 2006). Nutrient cations such as calcium are leached from soils at an accelerated rate with acidic deposition. The accelerated leaching is problematic in acid-sensitive areas where shallow soils and weather resistant bedrock are slow to replace the nutrients. The Adirondacks area has been depleted of large amounts of soil calcium due to acidic deposition over the last century. The depletion of nutrient cations fundamentally alters soils processes, compromises the nutrition of some trees, and hinders recovery of sensitive soils

(Cosby and Driscoll 2007). Increased mortality and decreased vigor of sugar maple in the eastern United States appears to be caused by deficiencies in calcium and magnesium in soils, coupled with stresses such as insect defoliation and drought (Horsley et al. 2000).

Results of an experiment mentioned in the first *Summary of the Science* regarding the effect of exchangeable calcium on tree growth have since been published. This experiment, performed at Hubbard Experimental Forest in New Hampshire, tested whether addition of calcium in the amount that had been depleted over the past 60 years because of acidic deposition would affect the northern forest ecosystem. Early results are positive; the calcium fertilization has resulted in visibly healthier canopy of sugar maples and an increase in the survival of sugar maple seedlings (Juice et al. 2006). These results reinforce the linkage between declines in sugar maple in the Northeast and anthropogenic effects on soil calcium status. In addition, the calcium treatment reduced winter injury of red spruce (Hawley et al. 2006). This experiment further links soil calcium depletion to tree decline, and gives hope that forests with soils depleted from acidic deposition will respond positively to increased sources of calcium (which on a biologic timescale can only occur through mitigation such as liming). Sugar maples are a common tree in the park and are valuable for their syrup, beauty, and timber.

Another biogeochemical indicator of forest health is the calcium-to-aluminum ratio of soils. A sample of watersheds statistically representative of 1,320 low-ANC watersheds has been found to have a mean calcium-to-aluminum ratio of 0.13 (Sullivan et al. 2006). A calcium-to-aluminum ratio in soils of less than 1 is believed to increase the probability of stress to forest ecosystems because it interferes with cation uptake (Gbondo-Tugbawa and Driscoll 2002).

This new literature provides more concrete information with which to describe forest conditions in the survey. Specifically, acidic deposition has led to mineral depletions that have been shown to 1) make visible changes to the canopy of sugar maple, 2) increase injury to red spruce, and 3) promote poor tree nutrition in the average Adirondacks watershed. Further reductions in soil calcium and increases in aluminum are likely and would result in additional sites of lower forest productivity and/or vulnerability to winter injury (Warby et al. in review).

C. Mercury

New information in the literature supports the conjecture of a tenuous link between acidification and the presence of mercury in terrestrial ecosystems. Mercury is relevant to the discussion of acidification for two reasons. First (as discussed in detail below), methylation of mercury is linked to the presence of sulfate. Second, mercury and sulfur are copollutants especially associated with coal for electricity generation, and postcombustion controls for sulfur dioxide tend to inadvertently control mercury emissions.

New findings show that biologically available mercury (methylmercury) is present in high levels in Bicknell's thrush in Northeastern forests. This is especially significant because previous evidence suggested that biologically available mercury was found only in inhabitants of freshwater ecosystems (Rimmer et al. 2005). Bicknell's thrush is a small song bird that breeds in high-elevation fir-dominated forests and is a strict insectivore and not piscivorous (fish-eating, and therefore not obtaining mercury through this route). Moreover, evergreen species of flora in these studied forests had higher total mercury and methylmercury concentrations in their foliage than deciduous species. It is not clear whether methylation is occurring within the leaf or if it results from direct deposition of methylmercury (Rimmer et al. 2005). The specialization of Bicknell's thrush in these forests suggests that it might be an appropriate bioindicator of the presence of available methylmercury in these forests (Rimmer et al. 2005), which are much different than the typical freshwater ecosystems most commonly considered as areas affected by mercury.

These new findings provide more concrete information with which to describe threats of the related pollutant mercury in the survey. Specifically, pollutant mercury has been found to have an effect on terrestrial birds as well as its already-recognized effect on aquatic species. Methylmercury has also been found in bats and spiders, but this work is still in progress (Driscoll 2007).

D. Nitrogen

Terrestrial threats from nitrogen deposition in the Adirondacks result from alteration of nutrient availability. Some plant species may initially experience increased growth due to "fertilization" when nitrogen becomes more abundant; however, trees in the park such as sugar maple are currently exhibiting reduced growth that could indicate a later stage of influence. Aber et al. (2003) note that acidic deposition has resulted in the accumulation of nitrogen in forest soils beyond what is needed by forest vegetation, and nitrogen now appears to be leaching into the surface waters of the Adirondacks. They conclude that nitrogen deposition is altering the nitrogen status of northeastern forests, most clearly indicated by stream nitrate concentrations. Both terrestrial and aquatic nitrogen saturation theories suggest that nitrate concentrations in surface water should be the primary indicator of nitrogen saturation status and should be expected to increase over time with chronic nitrogen deposition.

Using various biogeochemical response variable data from plots in Virginia and North Carolina dominated by sugar maple, yellow birch, and American beech, Boggs et al. (2005) discovered that chronic nitrogen deposition may be influencing the forest structure and chemistry of southern hardwood forests. Data from southern sites indicate that American beech and yellow birch are in later stages of nitrogen saturation due to deposition and are suffering negative influences, most obviously indicated by a relationship with basal area growth. At the same time, this study also found positive effects on sugar maple (indicating early-stage nitrogen saturation) that are inconsistent with the decline seen in northeastern sugar maple. This difference in response to nitrogen deposition could be explained by variations in soil conditions between the regions. Nevertheless, this study is relevant to the Adirondacks because it shows that in its later stages nitrogen saturation can cause reduced tree growth.

At the time of the first *Summary of the Science* in 2002, assumptions about the time until nitrogen saturation was achieved in a broad way throughout the park varied between 50 and 250 years, with some authorities believing it would never be reached. A 100-year saturation assumption is a more recently accepted time period for the Adirondacks (Jenkins et al. 2005). New biogeochemical modeling is underway to determine more precisely the status of nitrogen saturation in the park. Increased concentrations of nitrates in surface waters indicate that more nitrogen is being deposited to watersheds than can be retained.

This new evidence provides information with which to describe the terrestrial threats of nitrogen deposition (i.e., although some plant species may initially experience increased growth due to "fertilization" effects of some deposited materials, park trees such as sugar maple may currently be experiencing a later stage of influence that has reduced growth rates).

E. Fauna

New information in the literature supports the idea of a tenuous link between acidification and adverse effects on terrestrial fauna. Both snails and populations of a woodland bird in areas of the eastern U.S. are thought to be suffering due to forest changes associated with acidic deposition.

It remains difficult to establish and measure the effects on wildlife mortality or morbidity and biodiversity due to acidic deposition. One study determined that both land snail abundance and species richness were positively associated with soil calcium and pH at Maryland sites in the central Appalachian Mountains (Hotopp 2002). The author states that, because of the calcium–snail linkage found, temporal changes in soil calcium resulting from acid rain or timber harvest would be expected to affect the land snail community. Because land snails are low on the food chain it is possible that negative effects on them could in turn have negative effects on higher trophic levels.

In another study, available data were used to model adverse effects of acidic deposition on the breeding of wood thrush along the Appalachian Mountains (from New England to the Smoky Mountains). Hames et al. (2002) concluded that there is a highly significant negative effect of increased acidic deposition on the predicted probability of breeding by wood thrush; increased elevation, low pH soils, and habitat fragmentation increase the negative effect. Changes in forest cover, soil fauna, and lack of sufficient calcium for egg laying are effects of acidic deposition that have in turn been linked to loss of avian biodiversity in affected areas in Europe. Based on this study, these effects are thought to be contributing to the reduced breeding of wood thrush in the eastern United States (Hames et al. 2002).

These two studies show that, at least on a small scale, negative effects of acidic deposition are linked to terrestrial fauna effects.

This new evidence provides preliminary information that could be used to describe effects of acidic deposition on terrestrial animals, in addition to those described separately from mercury. Specifically, some land animals, such as snails and small birds, have been found to be adversely affected.

Link of Forest Effects to Aquatic Effects

The scientific literature is developing in a way to provide greater understanding of the interrelationship between terrestrial and aquatic systems.

Reaction times of aquatic and terrestrial environments differ and are important to consider along with future projections. Lakes in the Adirondacks may improve even while soils degrade. Lawrence (2002) identified depletion of exchangeable calcium in the forest floors as important in controlling episodic events: where calcium levels were high, stream ANCs remained >0 μeq/L even at high flows; where calcium levels were low, ANCs were negative and episodic acidification was severe. Acid episodes in surface water will continue until the base status of the mineral soil improves. Additionally, reacidification of the lakes with the lowest ANC levels would be caused by continued depletion of base cations from the lower soil horizon (Sullivan et al. 2006). Soils may continue to degrade, even if aquatic systems improve.

This information could be used to describe the interconnectedness of effects of acidic deposition in terrestrial and aquatic environments. Specifically, watersheds that have exhibited surface-water effects of acidic deposition also likely have soil effects, and vice versa. However, reaction times between the two environments differ; terrestrial systems respond more slowly and aquatic systems respond more quickly. Aquatic systems may improve even while soils continue to degrade.

Lakes

Although there have been improvements in Adirondacks lakes, ANC values remain at levels of concern and the small rate of recovery may not be maintained. To put current lake status in a historical context, new MAGIC model outputs extrapolated to regional lake populations suggest that the median ANC of 1,320 low-ANC lakes[1] in the Adirondacks had preindustrial (year 1850) values of 92 μeq/L (Sullivan et al. 2006). Maximum acidification was experienced between 1980 and 1990, with the same subset of lakes having a median ANC of about 61 μeq/L during that time. Values in the year 2000 showed limited recovery, with a median ANC of 67 μeq/L. Projections for the year 2100 estimate that the median ANC will be between 58 and 76 μeq/L depending on whether NO_x and SO_2 emissions remain capped on the basis of emissions controls enacted by January 2004 (prior to the Clean Air Interstate Rule [CAIR]) or are further reduced beyond CAIR. A CAIR scenario would result in median ANC levels between 58 and 71 μeq/L, possibly slightly worse or slightly improved from the year 2000.

This information is useful in describing the future of lakes without further emissions reductions regulations. Lakes have recently undergone some recovery, but it is very small compared to natural conditions. Lakes with ANC less than 20 μeq/L that have had recent gains in ANC are projected to reacidify after 2020 with emissions regulations no stricter than those enacted by January 2004 (Sullivan et al. 2006). Improvements in lake water chemistry will occur relatively quickly (5–10 years) after deposition reductions. However, after initial improvements lakes often reacidify, to a lesser degree than has occurred in recent history. This short-term improvement followed by reacidification is due to bedrock weathering and soil response. Permanent improvement and continued recovery would only occur with deposition at a very low

[1] Lakes larger than 1 ha, deeper than 1 m, and with ANC<200 μeq/L.

threshold, at which bedrock weathering can supply base cations to soil for neutralization; this is referred to as the “critical load.”

A. ANC

It is unclear how exactly the CAIR emissions legislation will affect ANC trends. Even with a much more aggressive control scenario, preindustrial conditions will still not be achieved by 2100. Driscoll et al. (2003) first reported a pattern of increasing ANC in Adirondack lakes in 2003. This finding was reiterated in the EPA’s report *Response of Surface Water Chemistry to the Clean Air Act Amendments of 1990*; both ANC and pH increased significantly in the Adirondacks during the 1990s (Stoddard et al. 2003). ANC increased an average of 0.23 μeq/L per year in the Adirondacks from 1984 to 2001 (Warby et al. 2005). Prior to the ANC increase a decline in base cations in surface water occurred caused by reduced leaching, accompanying reductions in acidic deposition, and limited improvements of ANC until sulfate concentrations declined enough to offset the balance (Kahl et al. 2004). ANC improvements in the following period reflect further reductions in sulfates; from 1990 through 2000, ANC trends reflect greater improvements in the Adirondacks, with increases of about 1 μeq/L per year (Stoddard et al. 2003).

Extrapolated ANC improvements in the Adirondacks were reported from a study of data from 1990 through 2000 that found that approximately one-third of the chronically acidic lakes (ANC<0 μeq/L) in the 1990s were no longer chronically acidic in 2000 (8.1 percent or 150 lakes, down from 13 percent or 240 lakes) (Stoddard et al. 2003).

Despite recent improvements in acid–base conditions as a result of deposition reductions, ANC values remain at levels of concern (Driscoll et al. 2003), and some lakes will continue to experience decreases in ANC and pH before any chemical improvements occur (Chen and Driscoll 2004). Estimates of the number of lakes affected by acid deposition in the Adirondacks were reported in the original *Summary of the Science* (Cook et al. 2002) as being between 40 and 48 percent of lakes with ANC<40 μeq/L. Jenkins et al. (2005) reported that between 20 and 40 percent of Adirondacks lakes are moderately acidic (pH<5.5; ~ANC<25 μeq/L). A more recent report from the New York State Energy Research and Development Authority (NYSERDA) (Sullivan et al. 2006) produced results representative of 1,320 low-ANC lakes (larger than 1 ha, deeper than 1 m, and with an ANC≤200 μeq/L). These findings are not directly comparable to the analysis of Cook et al., however, who examined 2,769 lakes larger than 0.25 ha. Sullivan et al. (2006) found that 30 percent (399) of low-ANC Adirondacks lakes had an ANC<50 μeq/L (e.g., 13 percent [175] with ANC<0 μeq/L and 21 percent [284] with pH<5.5) in the year 2000.

An additional 509 lakes larger than 1 ha and deeper than 1 m were excluded from modeling because of ANC>200 µeq/L; these lakes would not exhibit biologically significant changes in response to deposition scenarios. It is important to note that although many surface-water studies of Adirondacks lakes have been conducted, sampling and populations used vary greatly and are not necessarily comparable.

Cook et al. (2002) suggested a baseline in which ecological conditions were somewhat stable—not getting worse but not getting better on their own. However, Driscoll and Cosby (2006) think that with current deposition rates there will be a gradual worsening in lake conditions due to ongoing base cation depletion. This is supported by the newest MAGIC modeling, which suggests that "even under the small further decreases in acidic deposition that were expected under emissions control regulations in place in January, 2004" chemical recovery might fail to continue, and low-ANC lakes (ANC<20 µeq/L) will reacidify over the next two decades (Sullivan et al. 2006). The projections suggest that with this emissions scenario, very gradual chemical recovery will continue only for a subset of lakes currently having higher ANC values, with the lower 50 percent of lakes experiencing a reversal of ANC recovery by around the year 2020 without additional moderate-to-aggressive emissions control scenarios beyond those enacted as of January 2004 (although the number of lakes with ANC<0 µeq/L would remain stable) (Sullivan et al. 2006).

More restrictive emissions scenarios suggest future ANC improvements by 2100 but not to preindustrial distributions (Sullivan et al. 2006). Emissions controls under CAIR may affect the probability of reacidification (Sullivan et al. 2006). CAIR was not specifically modeled, but its emissions reductions are between the base case and moderate reduction scenario (Tables 1 and 2).

This information on the recent understandings of Adirondacks lake chemistry is very important to the development of the current and future scenarios in the survey. Specifically, this information indicates that absent intervention, lakes that are currently healthy or slightly harmed will remain healthy or very slowly improve through the year 2100. However, lakes of concern will continue to degrade.

B. Nitrogen

New information shows that an in-lake process in some watersheds is, at least temporarily, mediating lake acidification damages from continued nitrogen deposition. Unlike SO_2 emissions, total NO_x emissions have changed little since they peaked in 1990.

Concentrations of nitrogen in Adirondacks lakes have exhibited small but significant downward trends that do not reflect emissions or deposition trends (Driscoll et al. 2003; Kahl et al. 2004). Various time periods show different results for surface-water nitrate concentration trends suggestive of increased lake or watershed retention of nitrogen (Driscoll et al. 2003; Momen et al. 2006). Watershed retention of nitrogen is important because it prevents nitrogen from reaching surface water and contributing to its acidification. Momen et al. (2006) assert that an in-lake process, rather than terrestrial retention, may account for why changes in nitrogen deposition do not account for changes in lake nitrogen concentration in the Adirondacks. They found that an increase in chlorophyll A in lake samples suggests that an increase in phytoplankton activity may play a role in decreasing nitrogen in lakes; these preliminary results might suggest a response of nitrogen fertilization or eutrophication. The change in how increased nitrogen is affecting lakes complicates the use of lake chemistry as an index of terrestrial ecosystem processes (i.e., increased nitrogen concentrations in lakes as the indicator for nitrogen saturation of watersheds). A 2003 report that observed decreases in surface-water nitrate concentrations unrelated to nitrate deposition did not expect the decreases to continue; however, they did not include increased phytoplankton productivity as a possible cause (Stoddard et al. 2003). Climate variation or other nonpermanent changes in pH may be the cause for the fluctuations of nitrogen concentrations. Eutrophication is itself an adverse effect to aquatic ecosystems but is not generally included as a concern for lakes in this region.

Information on the recent understandings of Adirondacks lake processes is important to acknowledge when considering future lake status. Specifically, a mechanism has mediated increases in nitrogen concentrations from the continued nitrogen deposition to Adirondacks lakes; however, even without an increase in nitrogen emissions lakes may degrade, possibly through eutrophication or continued acidification.

C. Episodic Acidification

Recent information has identified sulfur as the major contributor to lake acidification. The baseline may gradually improve, since the primary effect of environmental policy is to reduce sulfur emissions, while nitrogen emissions have been less affected. Reduction of nitrogen emissions would reduce episodic acidification, but an overall improvement of water chemistry from sulfur reductions would be most beneficial in reducing both chronic and episodic acidification. Cook et al. (2002) expressed some uncertainty in *Summary of the Science* over whether reductions in sulfur deposition were important not only in reducing chronic acidification but also in reducing damage from the episodic acidification caused by nitrogen. Nitrogen is often important to occurrences of episodic acidification that result from spring snowmelt or large rain events in the spring or fall. The sudden pulse of acid anions (nitrates) that causes episodic acidification occurs when trees are dormant and cannot utilize the increased nitrogen. With the use of the PnET-BGC model Chen and Driscoll (2005) determined that a sulfate-reduction scenario rather than nitrate-control scenarios would be more beneficial in mitigating snowmelt acidification because it raises overall water quality, which results in lower spikes of episodic events.

This information on episodic acidification is helpful to understand the impact that emissions legislation may have. Sulfur has been the major contributor to lake acidification, and if that continues to be the case then policy aimed at sulfur emissions reductions will be the most fruitful for improvement of lakes both episodically and chronically, as Cook et al. (2002) previously acknowledged.

D. Aluminum

Recent findings suggest reduction in aluminum concentrations from surface waters is occurring and is correlated with decreasing acidic deposition and ANC trends. The median decline in total aluminum was approximately –1 μg/L per year between 1984 and 2001, as a result of increased ANC and pH (Warby et al. 2005). The decline in aluminum is statistically significant but small in terms of biologic importance. Low-ANC waters had even greater decreases in total aluminum, with a median decline of about three times the median per year (Warby et al. 2005). The decrease in aluminum exportation to surface water also is attributable to decreasing acidic deposition, and suggests a reversal of acidification.

The relation between ANC and pH improvement and reduced aluminum concentrations in surface waters is positive but should be taken in context. The possible reversal of ANC and pH improvements would be likely to lead to a reversal in aluminum improvements (i.e., aluminum in surface waters likely mirrors ANC trends).

E. Mercury

The Adirondacks have been found to be one of five biological mercury hotspots in the Northeast because of mercury deposition levels and landscape sensitivity. Recent mercury emissions reductions rules will not be sufficient to protect human and environmental health.

New information in the literature supports the link between acidification (specifically caused by sulfur inputs) and the availability of a toxic form of mercury in lakes. This would support a gradual recovery since the primary effect of environmental policy is to reduce sulfur emissions. The term “biological mercury hotspot” or simply “hotspot” is used to describe an area that, compared to the surrounding landscape, is characterized by elevated concentrations of mercury in biota that exceed established human or wildlife health criteria (Evers et al. 2007). Yellow perch and the common loon were the primary indicator species for a recent analysis of hotspots in the Northeast. Freshwater ecosystems are among the most sensitive to mercury pollution. The location of freshwater hotspots in the Northeast is not confined to locations of high deposition. Major mechanisms contributing to hotspots have been found to be 1) elevated deposition of mercury, 2) high landscape sensitivity, and 3) large water-level manipulation. The Adirondack Mountains of New York were among the five northeastern hotspots discovered by recent analysis (Driscoll et al. 2007a). The primary factors for the hotspot in the Adirondacks is the amount of mercury deposition received combined with landscape sensitivity characterized by shallow soils, abundance of wetlands, and acidified lakes (Driscoll et al. 2007a).

Current levels of mercury deposition in the Northeast are 4 to 6 times higher than levels recorded in 1900 (Evers et al. 2007) and 10 to 20 times higher than preindustrial conditions (Driscoll et al. 2007a). The 2005 Clean Air Mercury Rule (CAMR) is estimated to result in a 70 percent decrease in total United States mercury emissions from electric utilities, but would result in a decrease of only approximately 18 to 30 percent in the northeastern United States (Driscoll et al. 2007b). Decreases estimated to result from CAMR would likely produce significant ecological benefits in the Northeast but may not be sufficient to protect human and environmental health (Driscoll et al. 2007b). However, between 1999 and 2002 mercury levels in fish and loons indicate that biotic mercury levels can respond rapidly and proportionally to emissions reductions.

The previous *Summary of the Science* (Cook et al. 2002) provided evidence that acidification may create conditions that promote the transformation of mercury into a toxic form (methylmercury) that causes reduced reproduction rates in loons. Lab experiments and new field experiments show that sulfate additions are the likely mechanism responsible for increasing methylmercury concentrations. Sulfate-reducing bacteria are thought to be the primary converters of inorganic mercury to toxic methylmercury. Sulfur is likely the limiting factor in this process (Jeremiason et al. 2006). An implication of this observation, that sulfur is the limiting factor in mercury methylation, is that decreases in sulfur deposition could reduce damages from methylmercury.

The clarification that the mechanism responsible for increased methylmercury levels in lakes and fish is likely sulfate is important to understanding the impact that emissions legislation may have, because controlling sulfur emissions may be an effective way to control methylmercury.

F. Fauna

Biological recovery is inferred to occur after chemical recovery (Kahl et al. 2004), but may take decades (NAPAP 2005). The time and scale of biotic recovery is related to the extent and duration of the damage; recovery from a more severely damaged state takes longer and is less complete (Yan et al. 2003). This information supports the findings in the previous *Summary of the Science*.

Adirondacks lakes with chronically acidic conditions are generally fishless (Sullivan et al. 2006). Adirondacks lakes[2] with median ANC values had on average 4.6[3] fish species by 1990 (a decrease from 5.0 in 1850) and would gain no more than 0.3 fish species by 2100 with an aggressive emissions control scenario[4] or would lose 0.3 fish species with a base case scenario[5] (Sullivan et al. 2006). Lakes in the 20th percentile are estimated to have had an average of 2.0 fish species in 1990 (a decrease from 4.1 in 1850) but by 2100 would gain 1.5 species with the same aggressive control scenario.

A relationship between ANC and zooplankton species richness is also observed and likely to have been adversely affected in the Adirondacks by lake acidification (Sullivan et al. 2006). The median lake estimate for zooplankton species in 1850 is 21.9. A median loss of 1.9 species is estimated to have occurred between 1850 and 1990. Projections for 2100 are that the median number of zooplankton species will be between 19 and 21.0 depending on whether additional emissions controls are adopted.

This information on average fish and zooplankton populations is useful to describing past, current, and future lake conditions in response to acidification (i.e., the number of fish species and zooplankton species in lakes with median ANC may return to near preindustrial

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[2] Lakes >1 ha, >1 m deep, and with ANC≤200 μeq/L.

[3] Fractions of species are derived from averaging changes regionally and temporally.

[4] Aggressive additional control scenario: 2001 emissions levels and controls promulgated by January 2004 (not including CAIR) held constant through 2010, then 50 percent NO_x and 70 percent SO_2 reductions of 2001 levels from all sources by 2015 and held constant thereafter.

[5] Base case: continuation of 2001 emissions levels with additional controls promulgated by January 2004 (not including CAIR).

estimates by 2100 if aggressive emissions reductions beyond CAIR are adopted, or continue to decline with a base case emissions scenario).

Emissions

Continuation of Title IV emissions reductions would not produce complete recovery of acidified ecosystems. Recently legislated CAIR reductions will in all likelihood not be sufficient to lead to complete recovery. Many measurements show that improvements from acidification have occurred, but many scientists say that complete recovery will require further controls of sulfur and nitrogen emissions beyond Title IV of the Clean Air Act amendments (Gbondo-Tugbawa and Driscoll 2002; Jenkins et al. 2005; NAPAP 2005; Warby et al. 2005; Juice et al. 2006).

Recent MAGIC modeling suggests that an emissions control scenario more stringent than Title IV but less stringent than CAIR[6] would not prevent reacidification of low-ANC lakes. Continued chemical recovery was projected from this modeling with additional emissions controls that are moderately more stringent than CAIR.[7] It is unclear how the specific reductions from CAIR[8] and other legislation enacted since this recent modeling would affect Adirondacks lakes (Tables 1 and 2).

It is important to understand how current emissions controls map into the modeled scenarios for the construction of the survey. Modeling indicates that with Title IV emissions controls, plus all other emissions controls as of January 2004, further acidification is likely, but additional controls would further lake improvements.

Possible Changes to the Survey

Based on this review of the recent literature, several changes to the characterization of the ecological status of the Adirondack Park in the previous *Summary of the Science* (Cook et al. 2002) and in Banzhaf et al. (2006) seem appropriate. These changes are modest in nature, and

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[6] Base case scenario: controls enacted prior to January 2004. Total reductions by 2015 equal to 31 percent for NO_x and 11 percent for SO_2 from 2001 values from all sectors.

[7] Moderate additional controls scenario: total reductions by 2015 equal to 41 percent for NO_x and 53 percent for SO_2 from 2001 values from all sectors.

[8] CAIR reductions in Adirondacks according to Cosby: total reductions by 2015 approximately equal to 41 percent for NO_x and 35 percent for SO_2 from 2001 values from all sectors (Driscoll and Cosby draft).

generally suggest that the effects of acidification are at least as broadly occurring throughout the ecosystem as was previously suggested. Uncertainties described in Cook et al. are now more certain, with the exception of understanding how high-elevation spruce–fir forests are reacting to nitrogen inputs.

A. Lake Characterization

The current distribution of lakes described as healthy or as lakes of concern (defined as ANC greater than or less than 50 μeq/L, respectively) may be close to the 50/50 distribution described by Banzhaf et al. (2006). At the time of this writing, we cannot verify whether this assumption is consistent with the recent modeling without further consultation with experts to interpret recent modeling results from NYSERDA to our population of lakes. Banzhaf et al. (2006) describe an ecological baseline, and departures from that baseline, in their contingent valuation survey. In the baseline, the lakes were described as 50 percent healthy and 50 percent lakes of concern due to human-caused reasons. The healthy lakes include 10 percent of lakes that have no fish populations due to natural causes. The implications for the chemistry status of healthy lakes and lakes of concern are left vague; however, reduced or complete loss of fish populations is inferred to correspond to lakes of concern. According to literature of the time, a rough split of 50/50 occurs between lakes with ANC values greater than ~50 μeq/L (or that naturally have lower ANC) and those lakes with less than ~50 μeq/L due to human-caused reasons.

Two versions of the survey were administered using the same current lake description, but different projections of the future with and without future intervention. The scope survey indicated that absent intervention an additional 5 percent of the lakes would worsen over time, while a liming intervention program would result in all but 10 percent of the lakes being healthy (40 percent improvement). The base survey indicated that absent intervention there would be no change in lake status, while a liming intervention program would result in all but 30 percent of the lakes being healthy (20 percent improvement). This description was based primarily on expert opinions, which expected that a substantial reduction in deposition would lead to a recovery of 20 percent of lakes (from the current category of ANC between 0 and 40 μeq/L to >40 μeq/L). Literature of the time also projected an improvement of 20 percent but not to >40 μeq/L.[9]

[9] See Krupnick et al. (2007).

The most recent modeling estimated the status of 1,320 low-ANC lakes based on a study of watersheds containing lakes larger than 1 ha, deeper than 1 m, and with lakewater ANC$\leq$200 μeq/L (Sullivan et al. 2006). For these lakes it was estimated that 30 percent had ANC<50 μeq/L (13 percent <0 μeq/L) in the year 2000 (Table 3). An additional 509 were not modeled because of ANC levels sufficiently high to resist biologically significant ANC declines from deposition (ANC>200 μeq/L).

Depending on the interpretation of the recent NYSERDA modeling, the baseline condition of lakes of concern (ANC<50 μeq/L) should be between 14 and 48 percent of all Adirondacks lakes. The base case survey would describe a slight worsening of lake conditions, based most strongly on conversations with Charley Driscoll (Driscoll and Cosby 2006). According to Sullivan et al. (2006), approximately 33 percent of the modeled group is projected to have ANC<50 μeq/L in 2100 with a base case scenario. A scope case could describe improvements expected with the moderate or aggressive additional control scenarios in MAGIC modeling reported in Sullivan et al. (2006), that is, approximately 29 percent and 25 percent of modeled lakes with ANC<50 μeq/L in 2100, respectively (Table 3).

B. Fish Characterization

A new characterization of fish and lake ANC is a possible change to the survey. It would account for the gradual recovery not accounted for in the change in ANC classification that occurs due to improvements within each category. Current modeling literature projects very little further change based on the evaluation measure used in the last survey (movement between ANC categories). This is not because the ecosystems are fully recovered, or because further recovery is impossible. Rather, it is because very large deposition reductions (Title IV) have already been implemented and resulted in the most readily possible recoveries of lake chemistry (increases in pH and ANC).

An alternative improvement characterization that we might choose to explore further is the linear relationship of ANC and number of fish species (species richness) present (i.e., one additional fish species per 30-μeq gain in ANC regardless of the absolute ANC value). This relationship has been suggested by work in the Shenandoah National Park (NAPAP 2005). Additionally, coupling this with reported trends in median ANC values (Sullivan et al. 2006) would account for changes within ANC categories (reacidification as well as improvements). A problem that we would have to reconcile is that adopting this improvement characterization deviates from the ANC classification used in the Adirondacks survey, and thus it would be hard (if not impossible) to compare the results of the two surveys.

The most recent NYSERDA report did not report a linear relationship between fish-species richness and ANC in the Adirondacks (Sullivan et al. 2006). Instead it found a marked increase starting at ANC values around 0 μeq/L up to 100 μeq/L, with a modeled relationship approaching a maximum of 5.7 fish species per Adirondacks lake regardless of further ANC improvements.

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Table 1. Percent Reduction in Future Emissions (Relative to 2001)[a]

	2010	2015
Base case scenario		
SO_4	–8%	–11%
NO_2	–23%	–31%
NH_3	+2%	+5%
Moderate additional control		
SO_4	–8%	–53%
NO_2	–23%	–41%
NH_3	+2%	+5%
Aggressive additional control		
SO_4	–8%	–70%
NO_2	–23%	–50%
NH_3	+2%	+5%

[a]Sullivan et al. (2006).

Table 2. Percent Reductions in Future Emissions (Relative to 2001) under CAIR[a] for the Adirondacks[b]

CAIR	2010	2015
SO_4	–30%	–35%
NO_3	–34%	–41%
NH_4	0%	–1%

[a]Clean Air Interstate Rule.

[b]Driscoll and Cosby (unpublished data**).**

Table 3. Estimated Number of Adirondacks Lakes below Acid-Neutralizing Capacity (ANC) Criteria Values for the Population of 1,320 Adirondacks Lakes >1 ha with ANC<200 μeq/L[a]

	ANC								
Year[b]	≤0 μeq/L			≤20 μeq/L			≤50 μeq/L		
1850	0			93			191		
1900	93			109			216		
1980	204			279			519		
1990	204			263			581		
2000	175			217			399		
	Base	Mod.	Ag.	Base	Mod.	Ag.	Base	Mod.	Ag.
2020	175	159	159	229	191	191	437	407	398
2050	175	142	93	229	191	175	437	381	365
2100	175	125	93	243	191	175	437	381	336

[a]Based on MAGIC model simulations for 44 statistically selected lakes (Sullivan et al. 2006).

[b]Simulations for future years (2020, 2050, and 2100) are based on three scenarios of emissions controls: the base case (Base), which includes controls that have been or are expected to be enacted under existing regulations, and scenarios of moderate (Mod.) and aggressive (Ag.) additional emissions controls.