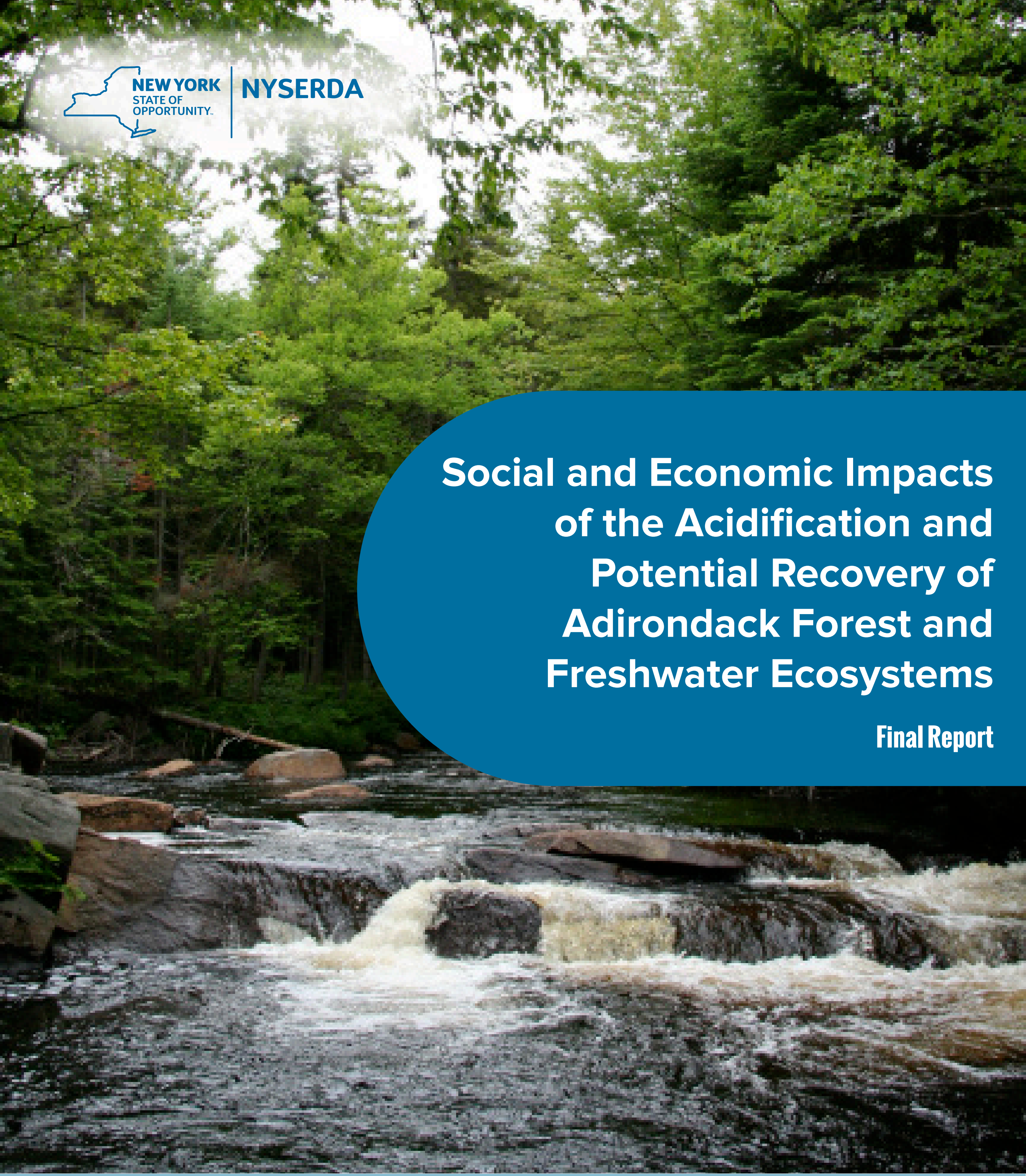

Social and Economic Impacts of the Acidification and Potential Recovery of Adirondack Forest and Freshwater Ecosystems

Final Report

September 2016

Report Number 16-26

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Social and Economic Impacts of the Acidification and Potential Recovery of Adirondack Forest and Freshwater Ecosystems

Final Report

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NYSERDA Report 16-26 NYSERDA Contract 33072 September 2016

Notice

Preferred Citation

New York State Energy Research and Development Authority (NYSERDA). 2016. "Social and Economic Impacts of the Acidification and Potential Recovery of Adirondack Forest and Freshwater Ecosystems" NYSERDA Report 16-26. Prepared by Colin Beier and Jesse Caputo (State University of New York College of Environmental Science and Forestry, Syracuse NY). nyserda.ny.gov/publications

Acknowledgments

The authors (Colin Beier and Jesse Caputo, SUNY ESF) are grateful to many organizations and individuals that made this work possible. This study was sponsored by NYSERDA, who also initiated and supported several of the Adirondack studies that our analyses were directly based upon. We wish to thank Greg Lawrence, Tim Sullivan, Charles Driscoll and Jon Erickson for serving on our expert advisory committee, and Greg Lampman for project oversight and management support. Greg Lawrence at USGS and Tim Sullivan at E&S Environmental Chemistry were essential collaborators on the forest components of the study, and data provided by the Adirondack Lake Survey Corporation was essential to the lake / fisheries component. We also extend our thanks to Doug Burns and Barry Baldigo at USGS for their input and advice.

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Executive Summary

Purpose

Sustaining progress in mitigating acid rain will require continued reductions in emissions that will inevitably give rise to real or perceived tradeoffs between healthy ecosystems and inexpensive fossil energy. Because most impacts of acid rain affect ecosystem functions that are poorly understood by policy-makers and the public, research is needed to explicitly identify and quantify how these functions benefit society in many ways. Our study used an ecosystem services (ES) approach—which quantifies the benefits that ecosystems provide to society—to assess how chronic acidification of ecosystems has potentially affected human well-being, in both material and monetary terms. We focused on the Adirondack region of northern New York State (USA), which is globally recognized as a 'hot-spot' for acid pollution of forests, lakes and streams. We focused on biological 'receptors' of deposition in forests and lakes that are acid-sensitive, that represent economically and culturally important resources, and that are relevant for regulatory efforts such as the identification of critical loads. We provide a 'snapshot' estimate by comparing present-day ecosystem conditions and their potential benefits along continuous gradients (or among categories) of acid impairment. Ecosystem dynamics and human interactions such as potential future recovery from acidification, or the long-term outcomes of management practices such as timber harvesting and fish stocking, were also addressed.

Key findings

- Acid pollution in the Adirondack region of New York has resulted in substantial losses of the potential economic benefits provided by its forest and lake ecosystems.
- We estimated that today's hardwood forests on culturally acidified soils will yield on average ~ \$10,000 less per hectare in potential value than forests on well-buffered soils. Below a threshold of 36% base saturation, net present value decreased by ~ \$440 per hectare for every percent decrease in base saturation, mostly due to lower timber value.
- Soil acidification poses a major obstacle to sustainable forestry in impaired Adirondack sugar maple stands, where simulations of harvesting the existing overstory result in dramatic long-term losses in value approaching \$200,000 per hectare over a century.
- In lakes, we estimated a loss of recreational fishing value between \$15 – 25 per angler per day for every unit of decrease in pH, while accounting for effects of fish stocking.

- Sport fishery value is expected to increase marginally with increases in lake pH, although lags are likely. Stocking with trout has a greater potential for improving the value of recreational fishing in acid-impaired Adirondack lakes compared to gains that would be realized via a complete cessation of acid pollution, under current deposition levels.
- Management efforts can partially mitigate—or greatly exacerbate—the loss of ecosystem services and potential values of Adirondack forests and waters caused by acid rain.
- Lime (calcium carbonate) additions may enable and/or accelerate recovery of economic and cultural values associated with target species such as sugar maple and trout.

1 Introduction

Acid rain is one of the iconic environmental problems of the post-industrial age. Resulting from pollution emitted by coal-burning power plants, the deposition of acids in precipitation has led to the chronic degradation of forests and aquatic ecosystems. However, acid rain is also one of a scant handful of environmental success stories—in which sound science informed an effective policy that has achieved positive outcomes. Emissions are rapidly declining, rainwater pH is increasing, and some ecosystems show evidence of small steps towards potential recovery.

Sustaining progress on acid rain mitigation requires continued declines in emissions that will inevitably give rise to real or perceived tradeoffs between healthy ecosystems and cheap energy. Because most impacts of acid rain affect ecosystem functions that are poorly understood by policy-makers and the public, an ecosystem services framework can help to explicitly identify and quantify how these functions benefit society in many ways. Otherwise, ecosystem recovery will seem to have few tangible impacts on our economy, health or quality of life—and political support for current and new regulations may dwindle.

1.1 Sustaining Progress in Acid Rain—What are the Benefits to Society?

Passage of the 1990 Clean Air Act Amendments (CAAA) by the U.S. Congress resulted in dramatic reductions in the emissions and deposition of acidifying pollutants—or acid rain—across North America. Title IV of the CAAA established regulations on nitrogen (N) and sulfur (S) emissions, primarily from coal-burning power plants, which cause the acidification and biological degradation of surface waters and forests (Driscoll et al., 2001). The largest reductions in deposition have been observed in the most acid-sensitive areas, including New England and the Adirondack region of northern New York. Since Phase I of CAAA (known as the EPA Acid Rain Program) was implemented in 1995, estimated reductions in sulfur emissions have been over 75% (based on 2011 data). Sulfate and nitrate concentrations in rainwater have declined by roughly 40% and 50% in the U.S. Northeast since 2000, respectively (Strock et al., 2014). In the last decade, lower deposition of acids and increased pH of rainwater across the U.S. Northeast (Kahl et al., 2004) has prompted early signs of chemical recovery in surface waters (Strock et al., 2014) and, more recently, chronically acid-impaired forest soils (Lawrence et al., 2015).

Despite progress in curtailing emissions since 1995, ongoing EPA regulatory efforts to further reduce SO_x emissions from power plants are regularly challenged in federal courts. In 2015, a measure to reduce transport of acid pollution across state boundaries, known as the Clean Air Interstate Rule, was vacated by the U.S. Court of Appeals, following a lawsuit by several states and power authorities. It is likely that such opposition will continue because of compliance costs as well as concerns about federal oversight over state authorities and private entities.

While the technical and political costs of CAAA regulations have been defined and debated, relatively little is known about the benefits of reducing acid pollution for human well-being. Early cost-benefit studies of 1970 Clean Air Act regulations, which included toxic pollutants, carcinogens, ozone and particulate matter, as well as NO_x and SO_x emissions, suggested that economic and health benefits outweighed implementation costs by U.S. $22 trillion vs. $0.5 trillion, respectively (U.S. EPA 1997). However, this analysis was almost entirely based on avoided costs of health risks associated with toxics and particulates, and dealt little with acid pollution impacts, which were still a nascent topic of scientific study at the time (1970–1990).

1.2 What are ecosystem services? Measuring benefits and estimating value

Ecosystem services (ES) are the benefits that nature provides to society, which categorically include the 1) *provision* of goods, raw materials and energy feedstocks, 2) *regulation* of life support systems (including water, climate, air, pollination and nutrient cycles), and 3) *cultural* benefits of human relationships with natural environments (including spiritual and educational). An assessment of ES can be used to measure the many ways in which ecosystems benefit people, and can highlight how specific human impacts on ecosystems may feedback onto different aspects of human well-being in ways that can be more easily considered in decision-making.

Ecosystem services may be measured in a variety of ways and the science and practice of ES is rapidly evolving. Current research incorporates a *supply* component, via the ecosystem providing the benefit, often defined as ‘natural capital’; and a *demand* component, which represents human needs for benefits, or conditions conducive to ‘social capital’, including physical well-being, economic prosperity, and cultural identity. Services may be measured in both material and monetary units for informing decisions based on the fiscal ‘bottom line’ of costs versus benefits. In this way, it is hoped that decision-makers can better internalize some of the negative environmental outcomes that have been historically dealt with as externalities.

Box 1. Lost in translation: How does acid rain relate to human well-being?

To date, it has been difficult to understand and communicate the importance of mitigating acid pollution for human well-being. The most common indicators of acid pollution and its ecosystem impacts—e.g., sulfate, nitrate, divalent base cations, inorganic aluminum, pH, acid neutralizing capacity (ANC), and dissolved organic carbon—are largely unrelated to human health and well-being, or tend to be poorly understood by lay audiences. Chemical and biophysical indicators are monitored to gauge the status of the ecosystem (Kahl et al.,2004), often in reference to benchmarks such as critical loads (e.g., McNulty et al.,2007).

Measuring an ecosystem service, however, requires that we identify a measurable human benefit (or beneficiary) associated with the biophysical factor (Beier et al.,2015). In some cases, such as trout fisheries and sugar maple forests of the Adirondacks, our biophysical indicators also happen to provide significant and tangible benefits to people. Yet many other biological indicators may be of little or no direct relevance to human needs, such as bacteria, plankton, invertebrates, etc. In addition, even if an indicator is directly relevant to human well-being—such as the nitrate concentration of a drinking water source—the magnitude of change in that indicator may not be sufficient to negatively affect beneficiaries (based on safe drinking water standards). Therefore it is often the case that biophysical indicators are more sensitive—but often less relevant to the average member of the public—than measures of ES, their benefits, and their potential monetary value.

2 Study Objectives and Approach

We used an ecosystem services (ES) approach—which quantifies the benefits that ecosystems provide to society—to assess how chronic acidification of ecosystems has potentially affected human well-being, in both material and monetary terms. We studied the Adirondack region of northern New York State (USA), which is globally recognized as a 'hot-spot' for acid pollution of forests, lakes and streams. A largely undeveloped and protected 'wild' landscape of forests, lakes and mountains, located downwind of power plants and heavy industrial operations in the U.S. Midwest, the Adirondack region is inexorably tied to acid rain science and policy. Our analysis drew upon on the Adirondack region's extensive and long-term lake and stream surveys, soil and vegetation inventories, and atmospheric monitoring programs. For both forest and aquatic ecosystems, our data encompassed a gradient of acidification—from heavily acidified to well-buffered against the effects of acid rain—that reflects differences in both geology (Driscoll et al., 2001) and geographic patterns of deposition across the Adirondacks (Ito et al., 2002).

We focused on biological 'receptors' of deposition in forests and lakes that were acid-sensitive, economically and culturally important resources, and relevant for regulatory efforts such as the identification of critical loads (Sullivan and Jenkins 2014). We provide a 'snapshot' estimate by comparing present-day ecosystem conditions and their potential benefits along continuous gradients (or among categories) of acid impairment. Ecosystem dynamics and human interactions such as potential future recovery from acidification, or the long-term outcomes of management practices such as timber harvesting and fish stocking, were also addressed.

Lastly, we note the separation of ES quantification and valuation in our approach. Measures of the potential benefits of ES were first estimated in material units or as probabilities of service provision (based on statistical models). These metrics were then translated to monetary values using market prices and/or benefit transfer data from the scientific literature. These value estimates reflect the net present value and do not represent net revenues or profit margins.

3 Adirondack Forests

3.1 Acid rain impacts on Adirondack forest ecosystems

Although there have been dramatic declines in acid rain over the last few decades (EPA 2013), the effects of chronic pollution on Adirondack forests will last for a very long time—potentially several centuries or more. Forest soils that have become heavily acidified and depleted of nutrients—which has occurred across much of the southwestern Adirondacks—will be very slow to recover to their pre-industrial condition. In the most severely acid-impaired soils, where the supply of calcium has effectively been depleted, recovery may not be possible without the aid of practices such as liming (addition of calcium carbonate) to "jump-start" the nutrient cycle again.

A principal character in the story of acid rain in Adirondack forests is sugar maple (*Acer saccharum*, Figure 1) an ecological 'keystone' species, the official NY State tree, and an iconic species for its economic and cultural importance across much of the eastern and Great Lakes forests of the U.S. and Canada. Unfortunately, the long-lived sugar maple is particularly vulnerable to acid rain, because it has high demand for calcium, which becomes depleted from acidified forest soils. Sugar maple is one of the most valuable renewable resources in eastern North America, as it supports a multi-billion dollar syrup industry, and provides high-value wood products, as well as cultural benefits including attractive fall foliage. In working forests, managing for sugar maple is often a primary objective of northern hardwood silviculture, which has developed techniques that promote its regeneration over other competing species. Although sugar maple may suffer from nutrient limitation on naturally acidic soils, chronic acid pollution has driven soil chemistry beyond the natural range of variation where the tree is found, and therefore created a problematic and persistent stressor for today's sugar maples across much of their eastern and northern range.

3.2 Effects of acidification on net present value of Adirondack forests

We first assessed the ecosystem services (ES) of 50 existing sugar maple forests along a range of soil chemistry, with roughly half of the stands occurring on soils that had been culturally acidified (with base saturation < 12%) due to chronic acid rain. Potential benefits included forest products (sawtimber, pulp and biomass), potential sap yield for maple syrup production, carbon sequestration by trees, and an index of aesthetic quality of fall foliage.

Today's acidified Adirondack hardwood forests have roughly half the economic value of forests where acid rain has had little or no impact on soil chemistry or fertility

The estimated value of ecosystem services (ES) from Adirondack hardwood forests increased with increasing base saturation (decreasing acidity), from roughly $10,000 per hectare in heavily acidified soils to over $20,000 per hectare in moderate and well-buffered soils (Figure 2). Nearly all (>84%) of this value comes from the potential to harvest the stand for wood products (Figure 2). Lower ES values in acidified soils are due to lower total standing biomass and a much lower volume of high-value sawtimber available for harvest. Lower standing biomass also decreased greenhouse gas regulation value (mean = $1,992.22 ha^{-1} across all plots) in stands with more acidified soils. Acidified forests contain fewer and smaller SM trees, resulting in lower values for potential maple syrup production (mean = $374.50 ha^{-1} across all plots) and fall foliage (mean = $50.10 ha^{-1} across all plots), based on our assumptions about relative aesthetic value of SM foliage compared to other tree species present in Adirondack forests.

Figure 1. Estimates of ecosystem service value in Adirondack hardwood forests along a range of soil base availability

This plot shows how several potential economic benefits of today's Adirondack hardwood forests vary due to soil base saturation, which is depleted by acidic deposition. Forests below 12% base saturation (black dashed line) have become severely acid-impaired due to human activities and are roughly half the value, per hectare, than non-acidified forests. GHGR represents greenhouse gas regulation (carbon sequestration). Lines are smoothed means, grey shaded areas around lines indicate 95% confidence intervals.

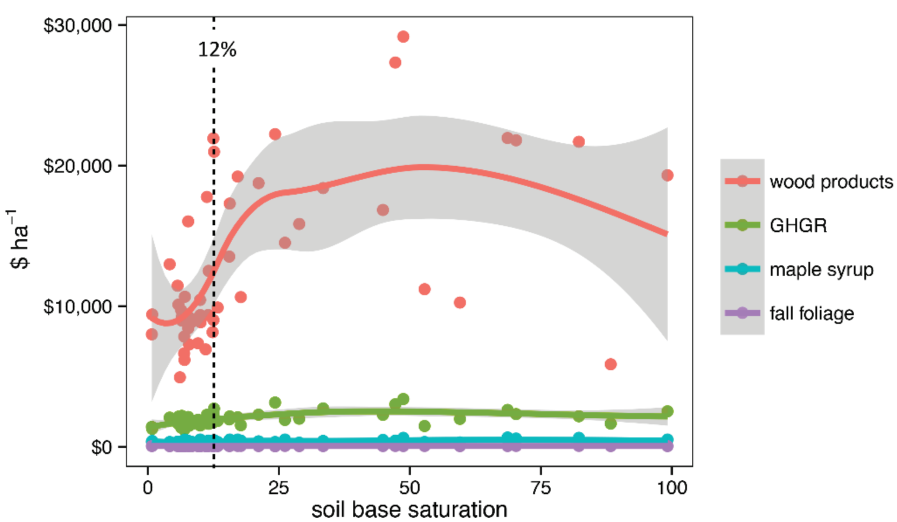
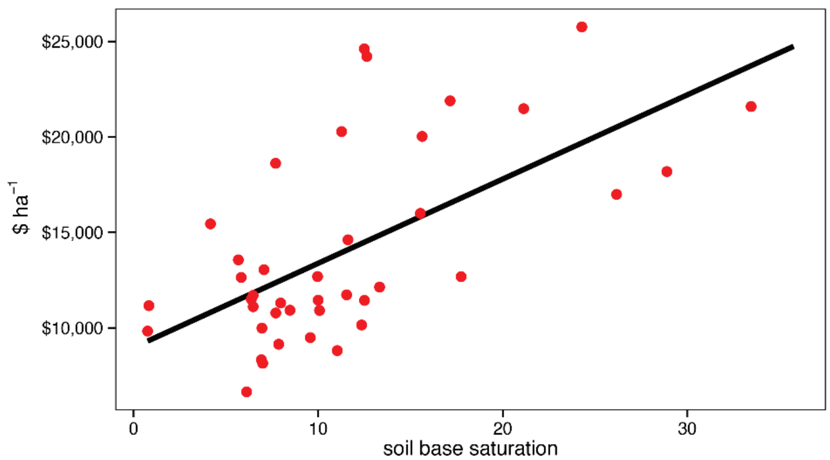


Figure 2. Effect of soil chemistry on total estimated net present value of acid-sensitive Adirondack hardwood forests



This plot illustrates the relationship between soil chemistry and estimated value of forests that have been historically sensitive to chronic acidic deposition. Note that the plot only depicts forests with base saturation of 36% or lower, which are the most sensitive to acid inputs. Below 12% saturation is considered to be acid-impaired due to pollution. Red dots are study sites, the black line is a regression model fit to the data. The model predicts a $440 per hectare increase in value for every percent increase of base saturation.

As Figure 2 shows, the relationship between soil acidification and potential economic value was not a simple linear relationship, but indicated the presence of a threshold at a base saturation level of approximately 36%. For forests with soils below this threshold, we estimated the potential value of each hectare increases by approximately $439.10 for each percentage point of increase in BS (Figure 1). Above the breakpoint, where base saturation is greater than 36%, our analysis found no consistent change in ES value with any further increase in soil base saturation.

3.3 The long-term Legacy of pollution in chronically acidified forests

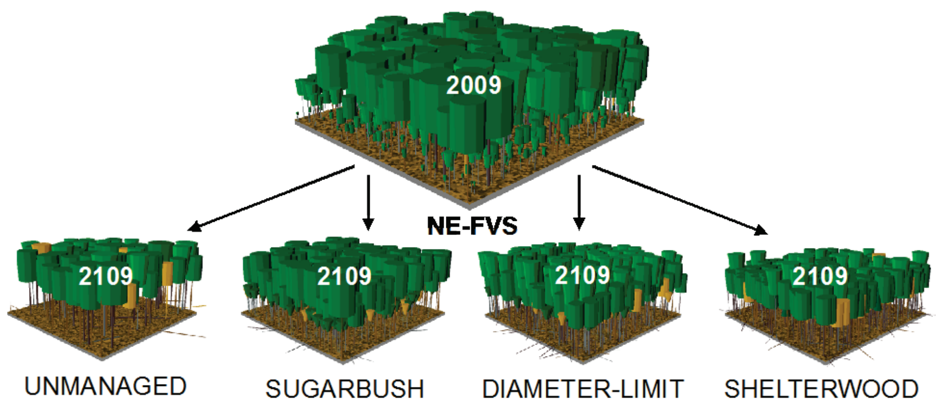
In 2013, an extensive study in the Adirondacks found that there was little or no regeneration of sugar maple in acid-impaired forests—i.e., where the soil chemistry indicated a human-caused degree of acidity. Without seedlings and saplings in the understory, where the young sugar maples normally persist and grow in deep shade for many decades, the study suggested that soil acidification—by effectively limiting the ability for sugar maple to regenerate itself—could shape the future composition of the forest. This observation was especially compelling because the study focused on forests dominated by sugar maple, where one would expect to find a dense 'carpet' of sugar maple seedlings and young trees occupying the deeply shaded forest floor.

Box 2. Simulating management outcomes in acid-impaired Adirondack forests

Managers of northern hardwood forests focus on regenerating certain tree species following a harvest operation, by ensuring there are enough young trees and ideal conditions to form a new canopy dominated by that species. Sugar maple is often the focus of such practices in working forests of the U.S. Northeast, because of its many economic and cultural values.

We used the Forest Vegetation Simulator (U.S. Forest Service) to project future conditions for 50 Adirondack hardwood forests, under four scenarios for a 100-year period:

- **Unmanaged**: stand is unaltered but will change based on ecological processes
- **Sugarbush**: stand is managed to maximize basal area of sugar maple
- **Shelterwood**: stand is harvested using best silvicultural practices designed to regenerate sugar maple as dominant species; multiple entries after the harvest may be made to remove competing species that interfere with maple regeneration
- **Diameter-Limit**: stand is harvested of all trees greater than 10cm in diameter; this is a common but relatively poor management practice for northern hardwood forests



Because the stands we simulated were occurring across a range of soil chemistry, our "experiment" could reveal interactions between management and acidification. We hypothesized that regeneration failure of sugar maple in acid-impaired forests would pose significant obstacles to sustainable forestry practices and their long-term economic benefits.

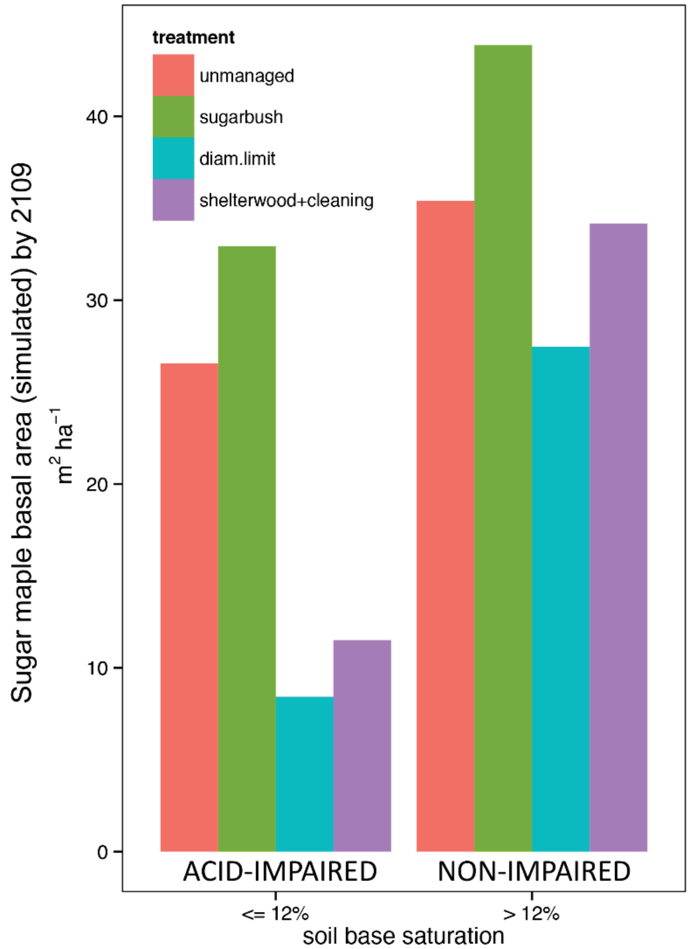
We hypothesized that sugar maple forests on acidified soils would lack the regeneration needed to establish a new sugar maple stand, if the existing trees were removed, either by harvest or another disturbance (such as an ice storm). We expected that removal of the sugar maple canopy in acid-impaired forests would result in a transition to red maple and American beech, which are already abundant in acid-impaired Adirondack hardwood forests, and are more tolerant of nutrient-poor soils than sugar maple. As a result, sugar maple may not recover to its previous dominance in the stand—and neither would the many benefits and values associated with sugar maple—even if forest management practices intended to promote SM regeneration are used.

To test this hypothesis, we conducted a model experiment to determine how interactions between forest management and the acid impairment of soils could shape long-term outcomes in northern hardwood forests. Model simulations were based on extensive field data from hardwood stands in the Adirondacks, using a group of study sites that collectively represented a regional gradient in acidification of soils due to acid rain. Stands were simulated in the model for 100 years under several management scenarios, including a shelterwood harvest, a diameter-limit harvest, a 'sugarbush' prescription (to maximize sap production), and an unharvested reference.

The legacy of chronic acidification in working forests of the Adirondacks likely means the loss of sugar maple as the dominant canopy species in future stands

Our model experiment revealed that the forest's future composition and economic values were largely dictated by a strong interaction between two factors: 1) the degree of acidification, and 2) use of management practices that involved harvesting the overstory. A summary of these results is provided in Figure 3. Overall, sugar maple failed to regenerate to previous dominance in acidified forests that were harvested, and the species was replaced by red maple and American beech in the century following harvest. By contrast, on well-buffered soils, models predicted that regeneration of sugar maple would occur regardless of which harvest method was used.

Figure 3. Effects of soil acidification on management outcomes in Adirondack forests



This plot summarizes the results of model simulations of forest management outcomes based on 50 Adirondack hardwood stands that occur across a range of soil chemistry We simulated how forest composition and stocking (basal area of trees by species) would change after a 100-year period following different management treatments being applied to each stand. Soils with base saturation less than 12% (left-hand group of columns) are considered to be severely acid-impaired due to pollution. In these stands, sugar maple (*A. saccharum*) failed to regenerate after harvesting, leading to its replacement in the overstory by other species, namely American beech and red maple. In non-impaired forests (right-hand group of columns), forest management resulted in regeneration of the sugar maple overstory.

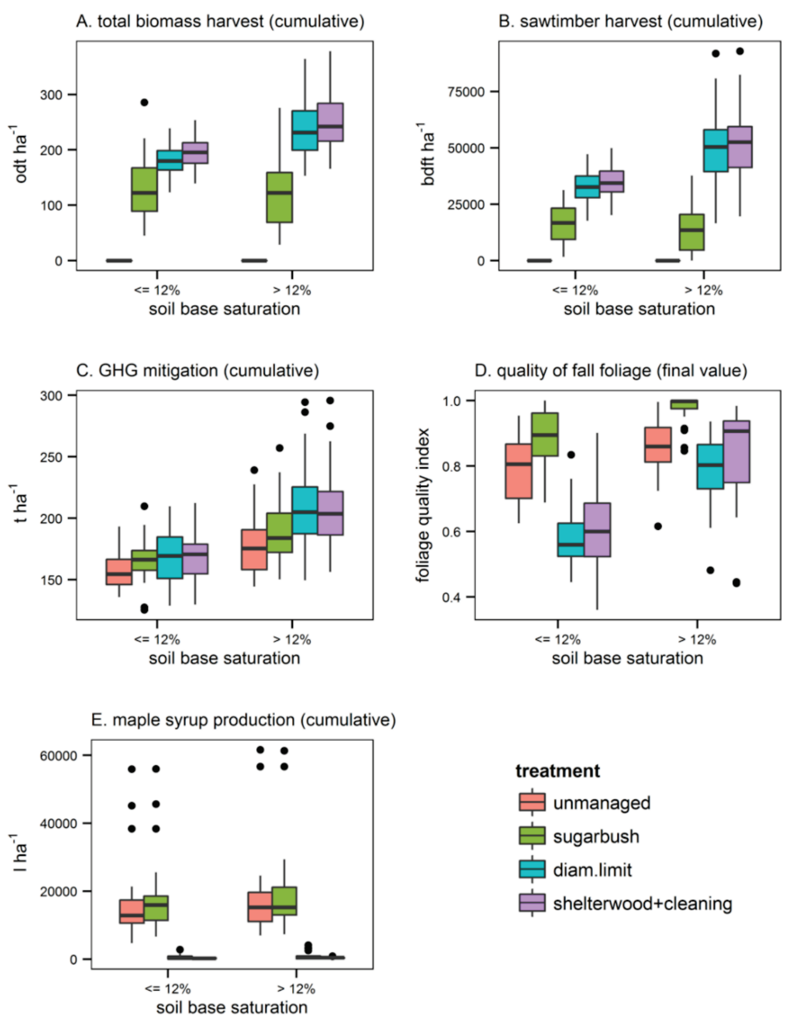
3.3.1 Implications for sustainable management of forest resources

We found that forestry practices that were developed to sustain high-value species such as sugar maple may no longer have successful outcomes in severely acid-impaired ecosystems. While the estimated value of today's acidified forests was marginally lower (~$10K per hectare) than well-buffered forests, the economic impacts of acidification were much larger when forest management activities harvested the existing sugar maple overstory. Since sugar maple is one of the most important commercial sawtimber species in the northern forest, this is a decision point that is often encountered in working forests of the Adirondacks and surrounding regions.

Acid rain impacts on sensitive Adirondack forest ecosystems have limited the options for their sustainable management, which in turn has reduced their potential economic and cultural values for both current and future generations

We assessed the model-simulated forests in the year 2109 for ecosystem services and their potential economic value. Our results highlight the tradeoffs associated with forest harvesting and long-term provision of multiple types of benefits, many of which are closely associated with the fate of sugar maple in the stand (Figure 4). Yet several benefits provided by sugar maple can also be provided by the other species that may replace it. For example, carbon sequestration (GHGR) and biomass production remained consistent across our simulations regardless of sugar maple. Fall foliage of other species, particularly red maple, may have equal or greater aesthetic quality than sugar maple. The foliage and greenhouse gas regulation benefits, as provided by other trees, are largely substitutable for those provided by SM. Although syrup may be produced from the sap of other trees, such as red maple, the much lower sugar content makes this practice very uncommon; and we did not consider syrup production by other trees to substitute for SM.

Figure 4. Effects of soil acidification on future ecosystem services of managed Adirondack forests



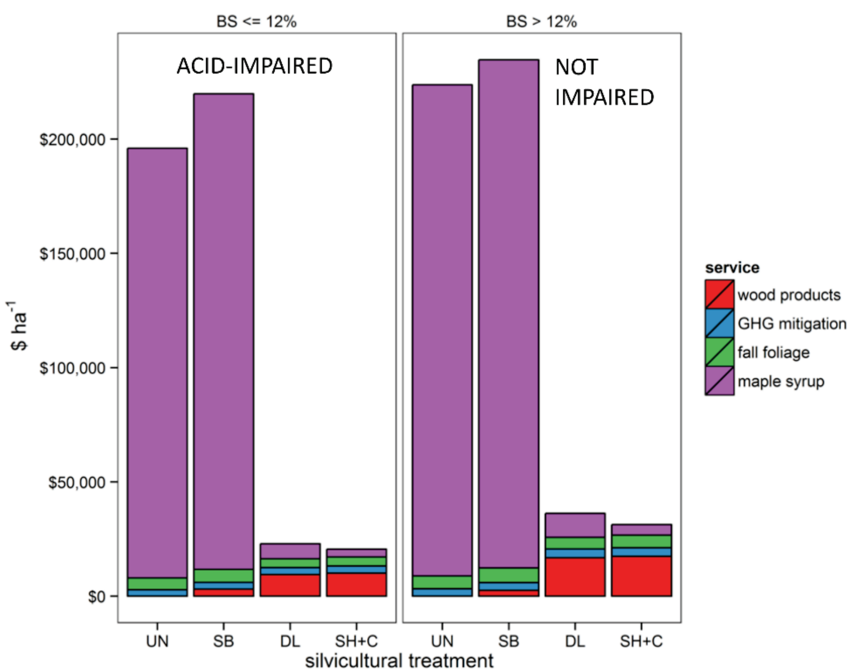
These plots summarize the results of model simulations of forest management outcomes based on 50 Adirondack hardwood stands that occur across a range of soil chemistry. Forest inventory data at the end of the simulation (in 2109) was assessed for five ecosystem services and their potential values. We found that harvesting acidified forests resulted in significantly lower future service provision for sawtimber, greenhouse gas (GHG) mitigation, and fall foliage quality, than when harvests were simulated for non-acidified stands. Any harvesting of the overstory strongly limited cumulative future syrup production. Box plots are shown to represent the variability in the simulation results - the center line of each colored box represents the average, vertical lines represent the range in which 95% of the data is found, and black dots are outliers. Boxes are color coded by treatment, with the left hand side of each panel representing acid-impaired forests and the right-hand side representing non-impaired forests.

Based on this analysis, we estimated potential losses between $172,999 to $199,191 per hectare, over a century, as a result of overstory harvesting in acid-impaired Adirondack forests, relative to the unmanaged forest and the sugarbush treatment, respectively (Figure 5). Over the 100-year rotation, most of this lost value is due to the cumulative potential revenue of annual syrup production, which is absent in harvested stands for most of the rotation, until mature SM of sufficient size are reestablished (according to the model simulation). In contrast with the net present value of the stand that is mostly in forest products (Figure 1), these products can only be harvested once in the rotation (by definition), while syrup production can occur each year.

Our results suggest that a landowner's decision whether or not to harvest the overstory in an acid-impaired stand represents a 'fork in the road' for the future forest (Caputo et al., 2016). Removal of a SM overstory may constitute the last commercial harvest before the stand becomes dominated by the much lower-valued red maple and American beech. Because acid-impaired soils are expected to take centuries to recover, this compositional shift—and its consequences for forest benefits and values—represents a long-term legacy of acid rain. During this period, liming can help to improve soil conditions (Lawrence et al., 2016), which should promote better regeneration of sugar maple (Sullivan et al., 2013; Battles et al., 2014).

Figure 5. Effects of soil acidification on simulated future economic values of managed Adirondack forests

These plots summarize the cumulative economic values (USD$ per hectare) at the end of model simulations (2109) of 50 Adirondack hardwood stands. Our model experiment subjected stands to different management treatments, including unmanaged (UN), sugarbush (SB), diameter-limit harvesting (DL) and shelterwood plus cleaning (SH+C), and simulated forest responses over a century. Future forests were then assessed for five ecosystem services and their cumulative monetary values, which are shown here. The left side of the panel depicts acid-impaired forests, the right side depicts non-impaired forests.



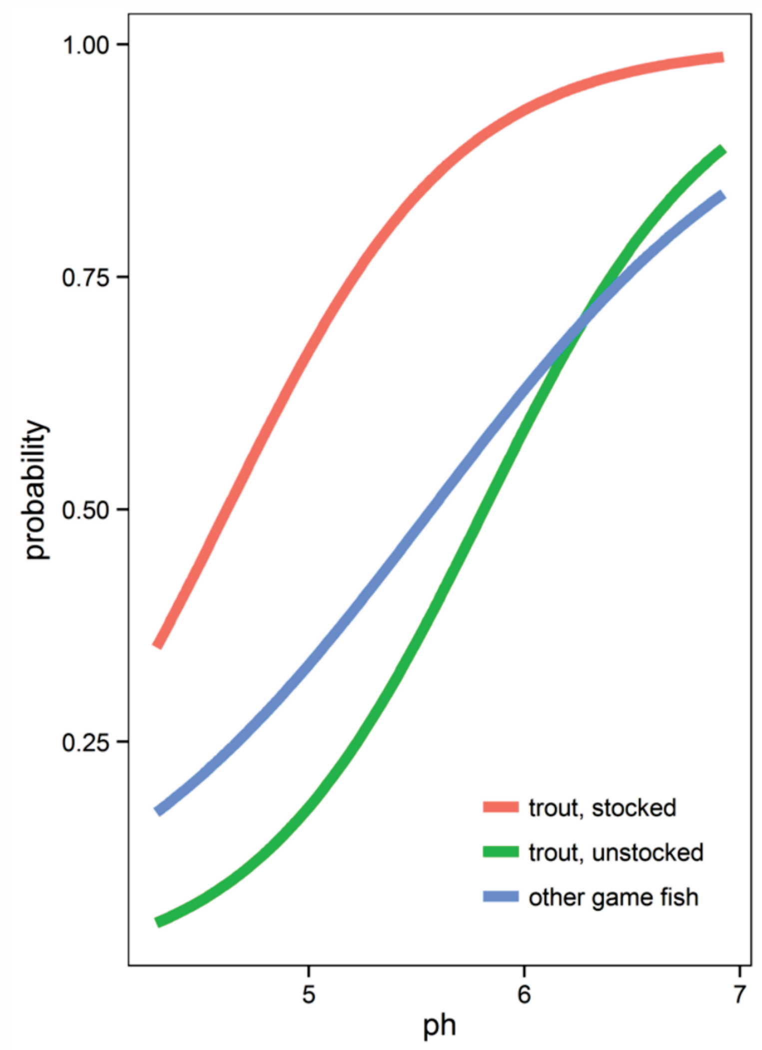
4 Adirondack Waters

Acidification of lakes resulting from acid pollution has caused adverse impacts to fish and other aquatic communities across the eastern United States, especially in the Adirondack region (Lovett et al., 2009, Driscoll et al., 2001). Although these impacts are well-known, many of the most sensitive species are small native cyprinids that are not typically targeted by recreational anglers. By contrast, brook trout (*Salvelinus fontinalis*)—a very highly sought-after game fish—have been shown to be somewhat tolerant to waters with low pH (Schofield and Driscoll 1987). Therefore, it is unclear whether acid pollution impacts on aquatic biodiversity necessarily translate into impacts on ES benefits associated with recreational fishing.

4.1 Acid rain impacts on sport fisheries in Adirondack lakes

Using fish species and water chemistry data from 52 lakes monitored by the Adirondack Lake Survey Corporation (ALSC), we determined the presence/absence of two broad groups: trout and other game fish (Figure 6). We also determined from ALSC records whether the lake had ever been stocked with trout species at any time prior to the most recent survey. Because of its close cultural associations, we included brown trout (*Salmo trutta*) amongst the true trouts (*Salvelinus* spp.). Water pH records for these ALSC lakes covered the time period 1984–2012. For each lake, we selected the pH value corresponding to the year of the most recent fish survey.

Figure 6. Effects of lake pH and stocking history on probability of game fish presence



This plot describes the statistical relationships between lake pH, fish stocking history and the probability that highly desirable fish species, mainly trout, are present in the lake. Curves are based on model predictions derived from data collected at 52 ALSC lakes from 1980-2002. As probability (vertical axis) approaches 1, the likelihood of trout presence nears 100%. Fish species groups are defined as:

Trout species
Salmo trutta
Salvelinus fontinalis
Salvelinus namaycush
Salvelinus namaycush X *fontinalis*

Other game fish
Ameiurus nebulosus
Lepomis gibbosus
Lepomis auritus
Esox lucius
Esox niger
Micropterus salmoides
Micropterus dolomieu
Salmo salar
Perca flavescens
Ambloplites rupestris
Semotilus corporalis
Osmerus mordax
Coregonus clupeaformi

We used statistical models to predict the likelihood of trout being present in a lake given its pH value (a continuous variable) and whether or not trout had ever been stocked in the lake (a binary or categorical variable). We used similar models to predict the likelihood of other (non-trout) game fish being present given the lake pH. The resulting regression equations allowed us to estimate the probability (of trout and/or game fish presence from lake pH and stocking history).

Lakes with lower pH are less likely to contain populations of desirable sport fish such as trout, but stocking of lakes with hatchery fish has offset some of these damages caused by acid rain

Among the 52 study lakes, the probability of the presence of trout and other game fish increased as pH increased (Figure 8), as expected. In unstocked lakes with pH > 6.5, there was greater than 75% probability that trout and other game fish would be present. Below pH 5.6, we estimated less than 50% probability that lakes contained any suitable game fish (Figure 7). Trout were more likely to be present than other kinds of game fish in lakes with pH > 6.3—and in lakes with pH < 6.3 the reverse was found to be true. In lakes where trout have been historically stocked, trout were more likely to be present than other game fish across the entire range of lake pH, and overall there was a greater probability of trout being present in stocked versus unstocked lakes. Above pH 6.9, the probability of trout presence in stocked lakes approached one (100%).

4.2 Changes in value of sport fisheries due to acid rain

For the valuation of recreational fisheries, we used estimates of the value of trout fishing ($32.85 per angler per day) and fishing for other game species ($11.70 per angler per day) in lakes from the meta-analysis by Boyle et al., (1999, as implemented by Loomis and Richardson 2008). To estimate monetary values of each lake's fishery, we multiplied the value estimates from Boyle et al., (1999) by probability (P) values derived from our statistical models using the equation:

Equation 1. $\$\ \text{angler day}^{-1} = (P(\text{trout})*\$32.85) + (P(\text{gamefish}|\sim\text{trout})*\$11.70)$

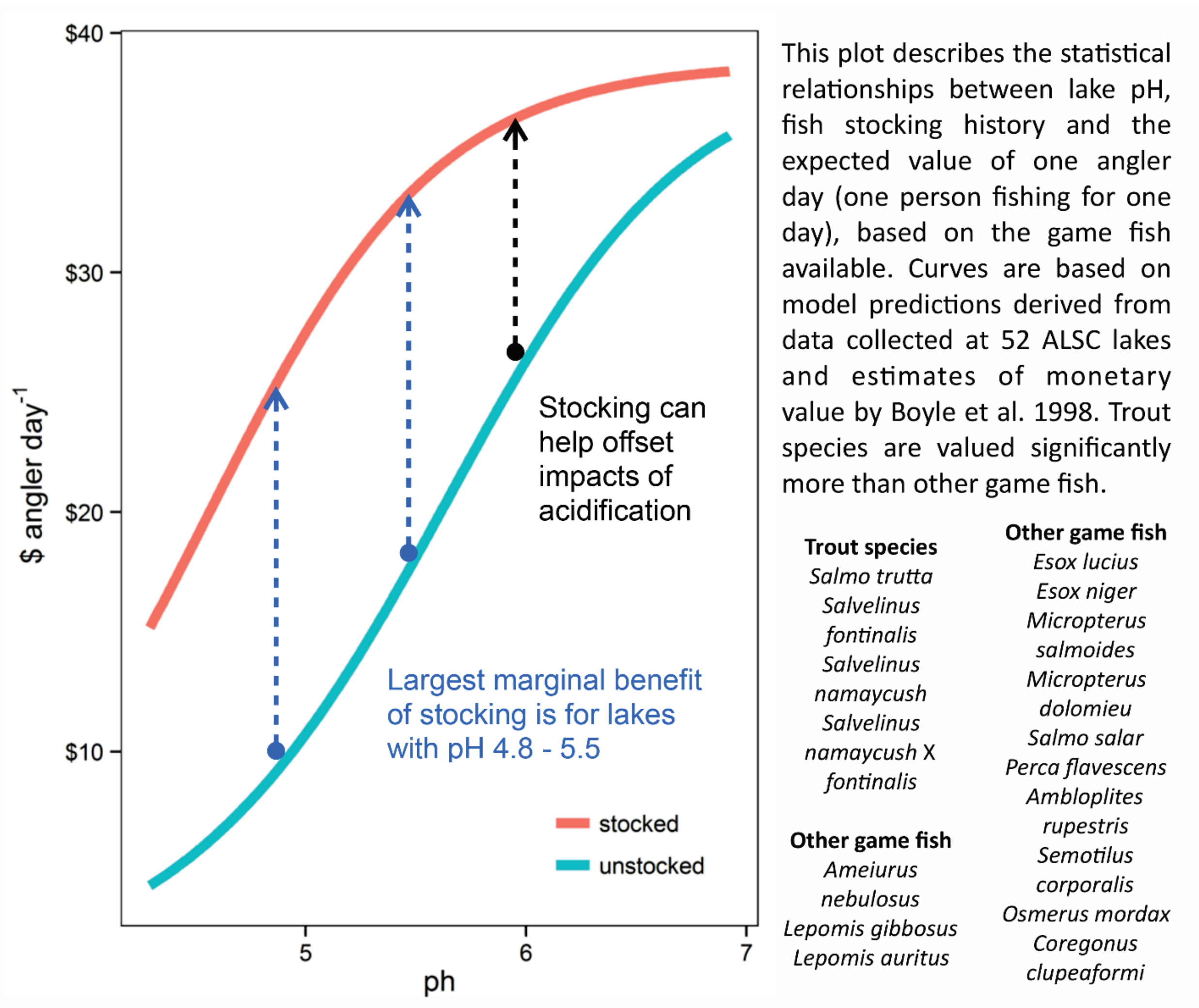
All values were converted to 2015 dollars using the U.S. Department of Labor Bureau of Labor Statistics inflation calculator (U.S. Dept. of Labor 2015).

The expected value of Adirondack sport fisheries is greatest in lakes with higher pH and a history of stocking, which both increase the probability of trout being present

We found that the expected value of recreational fishing increased with increasing pH, from a minimum of $4.41 angler day^{-1} in unstocked, acid-impaired lakes to a maximum of $38.40 angler day^{-1} in well-buffered lakes stocked with trout (Figure 7).

Stocking increased the expected value of recreational fishing relative to unstocked lakes by an average of \$11.50 angler day^{-1} across the entire pH range (Figure 7). This result was not surprising, given that reported values for trout fishing were almost three times higher than fishing for other freshwater species (Boyle et al., 1999). Models indicated the greatest marginal benefit of stocking, in terms of likelihood of trout presence, was between pH 4.8 and 5.5.

Figure 7. Expected value of recreational fishing in relation to pH and stocking history



4.3 Potential recovery of sport fisheries and their economic value

To estimate how the recovery of lake chemistry in response to decreasing acid rain could drive changes in the expected value of recreational fishing—via changes in composition of the fisheries in each lake—we used the models described above to analyze future projections of lake pH, based on model simulations from Fakhraei et al., (2014). We analyzed a number of emissions reduction scenarios produced by Fakhraei et al., (2014), based on hypothetical reductions of acidifying pollutants relative to current levels, from 0% (no change) to 100% (no pollution). Only three of these scenarios (0%, 50%, 100% reductions) are presented here for brevity.

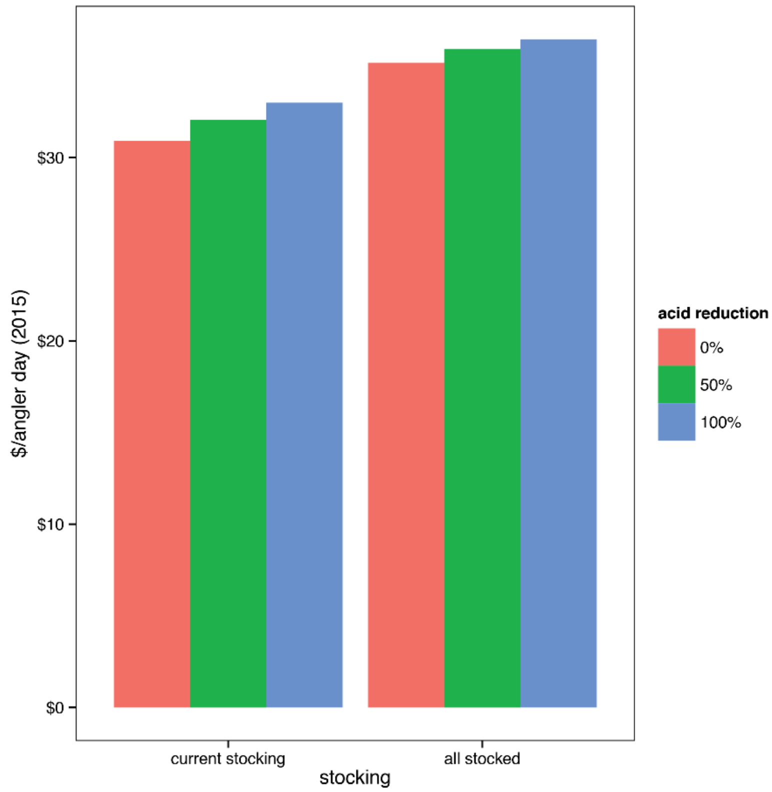
We then estimated changes in expected sport fisheries value based on the model-projected lake pH values for all five emissions scenarios combined with two fish stocking scenarios: 1) 'current stocking' —in which historical stocking was maintained and no additional stocking was assumed, and 2) ' all stocked'—in which all lakes were assumed to have been stocked with trout. In total we analyzed 10 scenarios for how recreational fishing value could change with a range of emissions reductions (including status quo) and fishery management efforts.

Recovery of pH due to emissions reductions will improve fishery value in many lakes across a vast region, but at the scale of individual lakes, stocking has a larger impact on fishery value

The expected value of recreational fishing increased over time in all scenarios in response to increasing pH (Figure 8). However, we probably overestimated the rate of this increase, because recovery of fish populations in the Adirondacks can lag behind chemical recovery for several decades (Josephson et al., 2014, Sutherland et al., 2015). Such lags could impact how anglers perceive the quality and availability of the resource, leading to lower demand and/or estimates of monetary value than our models suggest. In other words, while the lake ecosystem recovers, if Adirondack anglers have already decided that other lakes are more worth the trip, the benefit of re-establishing healthy trout populations may not be captured by its key beneficiaries.

Figure 8. Model-simulated future expected value of recreational fishing in Adirondack lakes by 2200 under three emissions scenarios x two fish stocking scenarios

This plot summarizes model projections of the future expected value of one angler day (one person fishing for one day) for 21 Adirondack lakes, based on two sets of scenarios: 0, 50 or 100 percent emissions reductions, and current stocking (including historically stocked lakes) versus all lakes stocked. The model used to make these predictions combined probabilities of fish presence based on pH and stocking history, with model simulations of future lake pH under different emissions scenarios. A 100% reduction in emissions implies a complete cessation in acid deposition by the year 2200.



Although expected fishing value increased over time in all scenarios, the mean difference in value among pollution reduction scenarios was relatively nominal (< \$1.00 angler day^{-1}) because of the slow recovery of pH predicted by Fakhraei et al., (2014). In 2000, the mean pH across the 21 ponds was 5.7. By 2200, the difference between the 0% reduction (pH 5.9) and the 100% reduction scenarios (pH 6.2) was less than 0.3 units of pH.

Overall, whether a lake was stocked with trout had a greater effect on fishery value over time than changes in lake pH. Throughout most of the simulated time series, expected value was approximately \$4 angler day^{-1} higher when it was assumed that all lakes had been stocked.

Simulated recovery also differed based on the underlying geology and acid sensitivity among lakes (Fakhraei et al., 2014). Seepage lakes (n=1) and lakes underlain by thin till (n=13) are more sensitive to changes in deposition than lakes underlain by medium or thick till (n=7). As deposition is reduced, thin till and seepage lakes increase in pH—and therefore expected sport fishery value—more rapidly than lakes characterized by medium-thick till.

In all scenarios, some lakes were expected to maintain relatively low-value fisheries after 200 years of recovery. The lakes that experienced limited or no improvement of sport fisheries are consistent with the 'unrecoverable' lakes, which were naturally acidic before acid rain became a problem, and therefore are not expected to respond to decreased pollution.

4.4 Acid pollution impacts on water quality regulation

We also estimated how acid rain affected the capacity of Adirondack lakes and streams to provide water suitable for drinking. Low pH and increased nitrate concentrations are two ways in which acid pollution can directly impact the suitability of freshwater resources for drinking and other human uses. Federal secondary standards in the U.S. and Canada require a pH range of 6.5 to 8.5 for drinking water. Nitrates are typically of concern because of their eutrophication potential, which has more direct impacts on human health and natural resources such as fisheries.

Using water chemistry data from the same 52 ALSC lakes used in our sport fisheries study, we determined whether these potential water sources met U.S. EPA drinking water standards for pH, nitrate, sulfate and chloride (U.S. EPA 2016). We incorporated lake geology into these statistical models to determine the effects of drainage type and till depth on drinking water quality. Using the same methods, but excluding geological factors, we estimated the expected value of drinking water in 201 streams and tributaries monitored in the *Western Adirondack Stream Study* (WASS, NYSERDA 2008). To estimate the value of drinking water within the appropriate pH range, we used an estimate of avoided treatment (i.e., liming) costs of $38 per hectare (Menz and Driscoll 1983) transformed to 2015 dollars ($93.48 per hectare). We multiplied the likelihood of meeting drinking water standards—as calculated by statistical models—by the cost of liming to provide a conservative estimate of the expected monetary value of drinking water provision.

Acid rain has had little negative impact on the capacity of Adirondack lakes and streams to provide clean water suitable for drinking, based on U.S. EPA secondary standards

For both lakes and streams, we found that effects of acidic deposition on water chemistry were not large enough to significantly reduce the likelihood that EPA regulatory standards would be satisfied. In other words, the capacity for Adirondack watersheds to provide clean water for drinking has not been exceeded by the impacts of N and S deposition. Land use policies in the Adirondacks promote the maintenance of continuous forest cover, which sequesters nutrients deposited in rainwater and reduces contamination of surface waters, providing a pollution remediation benefit to water-consuming populations (Beier et al., 2015; Caputo et al., 2015).

However, as we noted for the fisheries study, geologic factors played an important role in lakes. Lakes underlain by medium-thick till were approximately twice as likely to meet drinking water standards as lakes underlain by thin till. As a result, the expected value of drinking water quality was on average \$49.98 ha^{-1} for medium-till lakes versus \$7.22 ha^{-1} in lakes underlain by thin till. Lakes with thicker till tend to have greater capacity to buffer acid inputs (Jenkins et al., 2005).

4.5 Prospects for restoration and recovery in the post-acid rain era

Our study highlights a legacy of acid rain in heavily-impaired Adirondack forests, where nutrient supplies have been depleted from soils—and their replenishment via natural weathering processes will occur very slowly, if at all, relative to human time frames. In these severely acidified forests, we expect that management practices designed to regenerate high-value species such as sugar maple will probably be unsuccessful, which constrains their economic and cultural values for future generations. Put simply, we cannot wait for acid-impaired Adirondack forests to recover on their own—if we expect to manage them sustainably, we must give them some help.

Acidified forests will recover their value very slowly, if ever, without restoration efforts such as calcium addition via liming. Careful stewardship of acid-impaired forests is needed to sustain their value for present and future generations

Such help may come from a technique practiced for decades in Europe and North America (Lawrence et al., 2016)—the application of lime (calcium carbonate). Liming may be necessary to replenish nutrient supplies to a minimal level needed to enable regeneration of sugar maple and, in turn, the maintenance of sugar maple as the dominant species in future forests. However, there are major logistical and fiscal obstacles to widespread application of lime, which make the practice unfeasible across the vast acreage of the Adirondack forests thought to be acid-impaired. Even at small scales, forest landowners may be unable to make investments in liming to justify future returns, especially where discount rates are applied against future forest values in a cost-benefit analysis. In such cases, careful stewardship is needed to ensure that management actions, including those based on sound professional silviculture advice, do not lead to unintended and undesirable consequences that persist for many generations. Our study provides a basis for more robust assessment of the near- and long-term costs and benefits of managing acidified forests.

Lakes should recover more rapidly than forests, but fisheries may lag behind the chemical recovery. Fish stocking and lime application could help to shorten this lag period and hasten the restoration of the sport fishery as a valuable resource

Liming may also hasten the recovery of freshwater ecosystems and their benefits to society. Menz and Driscoll (1983) estimated that a 5-year liming program in the Adirondacks would cost between $93.00 and $1750.00 per hectare of lake surface (adjusted to 2015 dollars). Based on the approximate added benefit of $15 per angler per day that would be realized by increasing a lake's pH from 5 to 6, we estimate that a given lake would need to provide between 6 and 116 angler days ha^{-1} to offset the cost of liming. Where lakes are more easily accessible, liming costs are lower and also it becomes more likely that the lake will be utilized by a sufficient number of anglers to warrant the investment. At remote lakes, on the other hand, it is questionable whether enough fishing will take place to offset the much greater costs of liming.

Liming lakes and tributary habitats will probably be most effective in conjunction with management efforts that include, where appropriate, stocking of desirable game fish such as trout. Stocking has the potential to reduce the lag times associated with natural biological recovery, which may be on the order of decades; however, the practice of stocking fish is costly, limited in scope, and often needs to be repeated multiple times before a self-sustaining population can possibly become established. Despite these limitations, overall our analysis indicated that stocking with trout has a greater potential for improving the value of recreational fishing in acid-impaired Adirondack lakes compared to gains that would be realized via a *complete cessation* of acid pollution (based on model simulations; Fakhraei et al., 2014).

Although the benefits of stocking are apparent, the real cost of a successful hatchery stocking program is very difficult to estimate at the scale of an individual lake, for both biological and social reasons. Each lake's ecology poses a unique set of conditions that dictate whether a self-sustaining population can be established, while angler knowledge of stocking locations and timing can have a direct influence on fishing effort, which in turn creates a potential feedback to the biological outcomes of species reintroduction efforts. Due to this complexity, managers cannot predict whether stocking will be successful with much confidence. In addition, because public agencies (e.g., NYS DEC) typically bear most or all of the expense of stocking (i.e., using facilities and human resources that are also used for other purposes), isolating the actual cost to the organization (or taxpayer) of stocking a single lake is a tricky proposition.

However, if such cost estimates could be reliably obtained, our study provides a starting point for cost vs. benefit analysis for hatchery stocking. For instance, if we presume a stocking cost of $5,000 per year for an ‘average’ Adirondack lake, then based on the marginally higher expected value of fishing in stocked lakes (+$11.50 across the pH range), we could estimate that 435 additional angler days would need to occur each year for the benefit to offset the cost. Although there are many caveats to this basic calculation, it seems unlikely that fishing effort would increase sufficiently to offset stocking costs on a typical (small and remote) Adirondack lake. However, without baseline data on fishing effort (or creel records), we cannot estimate the relative increase in fishing pressure needed to offset the cost of stocking and whether such increases could be feasible. Of course, a sharp increase in fishing pressure in response to the stocking itself could directly undermine the long-term objective of a self-sustaining fishery.

Although our data indicates that stocking has more impact on fishery value than the recovery of pH, an important caveat is that our analysis was done at the scale of individual lakes. Yet hundreds of Adirondack lakes and ponds have been impacted by acid rain, and the vast majority of these surface waters should passively benefit from increases in rainwater pH and reductions in pollution loads. By contrast, liming and stocking must be actively performed on a lake-by-lake basis, often on a continuing basis, and not all water bodies are amenable to liming or stocking. Although both are well-established practices, liming and fish stocking are not in themselves a feasible or cost-effective solution for restoring fisheries across a remote landscape such as the Adirondacks. Eliminating all emissions sources that cause acid rain poses a categorically different challenge, but one that has largely been addressed through CAAA regulations and emissions caps, with the costs borne by the polluters and federal incentive programs.

Of course, continued reductions in emissions, the application of lime to promote chemical recovery, and the regular stocking of desirable game fish are not mutually exclusive objectives, but could be highly synergistic efforts leading to positive and sustainable outcomes for Adirondack fisheries. Making progress on the chemical recovery of surface waters, via both passive and active measures, should improve the outcomes of fish stocking, in order to restore and maintain self-sustaining Adirondack fisheries of significant economic and cultural value.

5 Conclusions

Today's acidified Adirondack hardwood forests have roughly half the monetary value of forests where acid rain has had little or no impact on soil chemistry. The legacy of chronic acidification in working forests of the Adirondacks likely means the loss of the highly-valuable sugar maple (Acer saccharum) as the dominant species in future stands. Acidification of Adirondack forests has limited the options for sustainable management and therefore reduced their potential economic and cultural values for current and future generations. Moreover, these acidified forests will recover their value very slowly, if ever, without restoration efforts such as calcium addition via liming. Careful stewardship of acid-impaired Adirondack forests is needed to avoid loss of sugar maple and sustain the many values of these forests for future generations.

Acid rain has had little negative impact on the capacity of Adirondack lakes and streams to provide clean water suitable for drinking, based on U.S. EPA secondary standards. However, Adirondack lakes with lower pH are less likely to contain populations of desirable game fish such as trout. Stocking of lakes with hatchery fish has offset some of these damages caused by acid rain. The expected value of Adirondack sport fisheries is greatest in lakes with higher pH and a history of stocking, both of which increase the probability of trout being present and therefore the expected value of the average fishing trip. Recovery of pH due to emissions reductions will improve fishery value in many lakes across a vast region, but at the scale of individual lakes, stocking has a bigger impact on expected fishery value. Lakes should recover more rapidly than forests, but fisheries may lag behind the chemical recovery. Fish stocking and lime application could help to shorten this lag period and hasten the restoration of Adirondack sport fisheries and their economic and cultural value.

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