Journal of Environmental Management 191 (2017) 19–27

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Loss of ecosystem services due to chronic pollution of forests and surface waters in the Adirondack region (USA)

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ARTICLE INFO

Article history:
Received 2 August 2016
Received in revised form
23 December 2016
Accepted 29 December 2016

Keywords:
Acidic Deposition
Clean Air Act Amendments
Ecosystem Services
Recreational Fisheries
Northern Hardwood Forests
Water Quality

ABSTRACT

Sustaining recent progress in mitigating acid pollution could require lower emissions caps that will give rise to real or perceived tradeoffs between healthy ecosystems and inexpensive energy. Because most impacts of acid rain affect ecosystem functions that are poorly understood by policy-makers and the public, an ecosystem services (ES) framework can help to measure how pollution affects human well-being. Focused on the Adirondack region (USA), a global ‘hot-spot’ of acid pollution, we measured how the chronic acidification of the region's forests, lakes, and streams has affected the potential economic and cultural benefits they provide to society. We estimated that acid-impaired hardwood forests provide roughly half of the potential benefits of forests on moderate to well-buffered soils – an estimated loss of ~ $10,000 ha^{-1} in net present value of wood products, maple syrup, carbon sequestration, and visual quality. Acidic deposition has had only nominal impact – relative to the effects of surficial geology and till depth – on the capacity of Adirondack lakes and streams to provide water suitable for drinking. However, as pH declines in lakes, the estimated value of recreational fishing decreases significantly due to loss of desirable fish such as trout. Hatchery stocking programs have partially offset the pollution-mediated losses of fishery value, most effectively in the pH range 4.8–5.5, but are costly and limited in scope. Although any estimates of the monetary ‘damages’ of acid rain have significant uncertainties, our findings highlight some of the more tangible economic and cultural benefits of pollution mitigation efforts, which continue to face litigation and political opposition.

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1. Introduction

Passage of the 1990 Clean Air Act Amendments (CAAA) by the US 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 US Northeast since 2000, respectively (Strock et al., 2014). In the last decade, lower deposition of acids and increased pH of rainwater across the US 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).

Sustaining progress in acid rain mitigation will require continued reductions in emissions that will give rise to real or perceived tradeoffs between healthy ecosystems and relatively inexpensive fossil energy. Early cost-benefit studies of clean air regulations under the 1970 Clean Air Act, which include toxic pollutants, carcinogens, ozone and particulate matter (as well as NO_x and SO_x emissions), suggested that the economic and health

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http://dx.doi.org/10.1016/j.jenvman.2016.12.069
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benefits outweighed implementation costs by an order of magnitude (US$22 trillion vs. $0.5 trillion; US EPA 1997). However, these benefits were almost entirely based on avoided costs of human health risks associated with toxics and particulates, and dealt little with acid rain impacts, which were still a nascent topic of scientific study at the time (1970–1990). Despite dramatic progress in curtailing emissions since CAAA Phase I was implemented in 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 US Court of Appeals, following a lawsuit by several US states and power authorities. It is likely that such opposition will continue because of compliance costs as well as federal oversight over state authorities and private entities (Kraft, 1998).

Because 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 tend to be poorly understood by non-scientists, it can be difficult to communicate the importance of acid pollution mitigation for human well-being. Chemical recovery does not necessarily translate to biological recovery of lakes (Nierzwicki-Bauer et al., 2010; Jeziorski et al., 2012; Sutherland et al., 2015), although the latter – especially when it involves a culturally or economically important species – may have more tangible benefits. In the US, monitoring programs have not emphasized biological receptors of acid pollution (Kahl et al., 2004) such as fisheries, which may be more relatable and interpretable by policy makers and the general public. As a result, the broader impacts of acid pollution on ecosystem functions and their benefits to society remain poorly understood.

In this study we use an ecosystem services (ES) approach – which measures 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. Our approach was to identify *final ecosystem services* (Boyd and Banzhaf, 2007) that were both 1) sensitive to effects of chronic acid pollution and 2) directly relevant to economic and cultural 'endpoints' for potential beneficiaries. We then estimated, using long-term environmental monitoring data and 'benefit-relevant indicators' (Beier et al., 2015), the capacity of forests and aquatic ecosystems to provide ES, and how this capacity varied along gradients of acidity, which are a function of both natural and anthropogenic factors. In other words, we assessed *potential benefits* of ES in material and monetary units of value, but did not explicitly measure how these benefits actually 'flow' to beneficiaries (i.e., *realized benefits*), which is an important consideration in applying ES in decision-making (Bagstad et al., 2014). To focus on how potential benefits have changed due to chronic pollution, we focused on the observed variation in potential benefits along the portions of acidity gradients that represent anthropogenic (pollution-mediated) degradation.

We present three case studies from the Adirondack region of northern New York State (USA), which is a globally known 'hotspot' for chronic acidification of forest soils and surface waters. A largely undeveloped and protected 'wild' landscape of forests, lakes and mountains, located downwind of power plants and heavy industrial operations in the US Midwest, the Adirondack region is inexorably tied to acid rain science and policy (Kraft, 1998; Jenkins et al., 2005). Case studies address whether acidified forests and lakes provide different amounts of potential benefits – including wood products, carbon sequestration, syrup production, recreational fishing, drinking water and visual quality – compared to similar ecosystems that have not experienced acidification. Estimates of potential benefits were calculated in raw units (or probabilities of service provision) and, as appropriate, converted to monetary units using market data and benefit transfer methods. Our objective was to highlight some of the tangible economic effects of acid pollution by focusing on 'endpoints' relative to human well-being, but not to place a definitive monetary value on Adirondack ecosystems or their broader cultural significance.

2. Methods

2.1. Approach

We used new methods for ES analysis (see Beier et al., 2015) that 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 – that largely reflects differences in surficial geology and parent material lithology (Driscoll et al., 2001), as well as geographic patterns of pollution inputs (S and N deposition) across the Adirondacks (Ito et al., 2002). Our analysis of ES focused on biological receptors of deposition in forests and lakes that were acid-sensitive, economically and culturally important, and relevant for regulatory efforts such as the identification of critical loads (Sullivan and Jenkins, 2014).

Here 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 such as potential future recovery from acidification were beyond our current scope. Similarly, inherent and long-term tradeoffs among potential benefits of managed forests, such as changes in carbon storage in a stand harvested for wood products (Caputo et al., 2016a) are not addressed here, but were investigated in a companion study (Caputo et al., 2016b). Where possible based on available data and historical records, we considered management activities that directly support ES provision, such as hatchery stocking of sport-fisheries. Lastly, we note the methodological separation of ES quantification and valuation in our approach. Measures of the potential benefits of ES were first estimated in material units or as model probabilities of service provision; these metrics were then translated to monetary units of value using market prices and/or benefit transfer data from the literature.

2.2. Northern hardwood forests

Adirondack hardwood forests have been inherently vulnerable to acid impairment, given both their sensitivity (due to base-poor parent materials that provide little buffering capacity; Driscoll et al., 2001), and their exposure to acid inputs, which have been among the highest in North America over the last century (Jenkins et al., 2005; Kahl et al., 2004). Observed effects of forest acidification include: the depletion of calcium and other base cations from soils (Sullivan et al., 2006); the mobilization of soil inorganic aluminum, which is toxic and inhibits calcium uptake by plants (Lawrence et al., 1995; Cronan and Grigal, 1995; Long et al., 2009); and lower abundance, health, growth and recruitment of calciphilic (calcium-loving) species such as sugar maple (*Acer saccharum* Marshall; Beier et al., 2012; Sullivan et al., 2013; Bishop et al., 2015). Although sugar maple (SM) experiences nutrient stress on naturally base-poor soils (Long et al., 2011), chronic acidification has driven soil chemistry beyond the natural range of variation found in hardwood forests where SM is found (Johnson et al., 2008), creating a chronic and severe stressor for extant SM populations in the Adirondacks and across northeastern North America (Duchesne et al., 2002; Long et al., 2009), where deposition inputs typically exceed critical loads (McNulty et al., 2007). Sugar maple is arguably one of the most ecologically, economically and culturally important species eastern North America (see Bishop et al., 2015). The effects of acid pollution on SM in extant Adirondack forests is the focus of this case study, which estimates changes in ES benefits along a regional gradient in soil base saturation.

2.2.1. *Data sources*

As described in Sullivan et al. (2013), a series of fifty 50 × 20 m (0.1 ha) forest inventory plots were established in the western Adirondack Mountain region in 2009. Sugar maple (SM) was the dominant or co-dominant canopy species in all plots. The study sites collectively represent the full range of soil pH and base cation saturation found in the region's upland hardwood forests, from poorly buffered and culturally acidified soils to well-buffered and calcium-rich soils (Sullivan et al., 2013). In each plot we sampled one complete soil profile down to the C horizon, and collected a 10 × 10 cm block of forest floor (Oe and Oa/A horizon) at five locations along a transect through the center of the 50 m plot length. Soil samples were analyzed for exchangeable cations and pH (0.01 M $CaCl_2$) as described in Sullivan et al. (2013). Base saturation was calculated as the sum of exchangeable base cations (Ca, Mg, K, Na) divided by total exchangeable cations (Ca, Mg, K, Na, H, and Al). In each plot we measured trees, saplings, and seedlings in nested quadrats and collected increment cores (two radii per tree) from mature ($\geq$30 cm DBH) dominant or co-dominant sugar maple trees (Sullivan et al., 2013; Bishop et al., 2015). Tree cores were used to estimate stand age structure and annual growth rates of SM trees.

Based on these data, we estimated potential benefits of four ES for each of the 50 hardwood forest plots, including: provision of wood products, provision of maple syrup, greenhouse gas regulation (carbon storage), and aesthetic value of fall foliage. To quantify the relationship between soil base saturation and total estimated ecosystem service value, we used segmented regression using the package ‘segmented’ 0.5.1.1 (Muggeo, 2008) in R 3.0.2 (R Core Team, 2013). All other analyses were also done using R 3.0.2 (R Core Team, 2013).

2.2.2. *Wood products*

Wood products provision includes the potential production of sawtimber as well as biomass for energy generation, wood chips, bio-based chemicals, etc. Using the forest inventory data, standing volume of sawtimber was estimated for each plot using tools in the Forest Vegetation Simulator (Dixon and Keyser, 2008). FVS measures sawtimber volumes in thousand board-feet (mbft), a unit widely used in North America (Caputo et al., 2016b). A board-foot is a unit of scaled timber 2.54 cm (1 inch) by 30.5 cm (1 foot) by 30.5 cm (1 foot); there is no exactly equivalent SFI unit. Stems unsuitable for sawtimber were assumed to be suitable for biomass production. Total biomass was estimated from stem diameter using Jenkins et al.'s (2003) allometric equation for mixed hardwoods.

2.2.3. *Maple syrup*

Maple syrup production was estimated from the standing tree inventory using the sustainable tapping guidelines of Heiligmann et al. (2006), in which all sugar maple trees over 25.4 cm (10 in) are tapped once and all maple trees over 45.7 cm (18 in) are tapped twice. The resulting number of taps in each stand was then multiplied by the average annual yield per tap in New York State, 0.86 L (0.23 US gallons), to estimate the total potential annual syrup yield per hectare. We estimated annual yield as the average of reported yields in 2012, 2013 and 2014 (USDA NASS, 2014).

2.2.4. *Greenhouse gas regulation*

To quantify carbon storage as a measure of greenhouse gas regulation, we used Jenkins et al.'s (2003) equation for all stems to estimate total standing biomass and then multiplied this value by a carbon:biomass ratio of 0.498:1 (Birdsey, 1992). Although our focus on this paper was on final ecosystem services, it can be argued that carbon storage in itself does not directly improve human well-being. Instead, the sequestration and storage of carbon in forest trees and soils is an integral component of a climate regulation service that directly benefits people. For this reason, it would be more correct to refer to our estimates of carbon storage (or greenhouse gas regulation) as an *intermediate* service (Boyd and Banzhaf, 2007).

2.2.5. *Aesthetic value of fall foliage*

Although anecdotal information suggests that sugar maple may be more highly valued for its fall foliage than other co-occurring trees in northern hardwood forests, such as American beech (*Fagus grandifolia* Ehrh.) and yellow birch (*Betula allegheniensis* Britton), we were unable to locate any studies that confirmed – or even attempted to measure – this social preference. Therefore, to account for foliage value we estimated a simple metric based on the assumption that sugar maple fall foliage was twice as preferable as that of other deciduous trees. To calculate this metric, we multiplied the proportion of stand basal area occupied by sugar maple by a preference weight of 1 and added to this value the proportion of basal area represented by other deciduous species multiplied by a preference weight of 0.5. Possible values of the metric ranged from 1.0 (i.e., entire stand is composed of sugar maple) to 0.5 (entire stand is composed of other deciduous species) to 0.0 (entire stand is composed of non-deciduous conifers). Sensitivity analysis of these parameters is discussed in Caputo et al. (2016b).

2.2.6. *Monetary valuation*

To estimate the economic values associated with these ES, we used a benefit transfer approach (Table 1). Sawtimber was valued using mean stumpage values for the Adirondack region as compiled by the New York State Department of Environmental Conservation (NYS DEC, 2014). Biomass was valued using average reported values for cordwood. Like the board-foot, there is no exact SFI analog for a cord; it is equivalent to a stack 122 cm (4 ft) by 122 cm (4 ft) by 244 cm (8 feet). A ratio of 1181 kg (3000 lb) $cord^{-1}$ was used to translate mass to volume. For the purposes of valuation, it was assumed that only 70% of potential cordwood could be harvested, with the remainder left onsite as residues (Lippke et al., 2011). The value of greenhouse gas regulation was taken from an estimate of the mean global price of carbon as reported by the World Bank (2014). The value of maple syrup production was estimated by averaging the unit value of maple syrup in 2011, 2012 and 2013 (USDA NASS, 2014). We could not find a specific estimate of the economic value of fall foliage viewing, so we derived a proxy value from Loomis's (2005) estimates of monetary values for U.S. recreational activities. Specifically, we used the average of Loomis's (2005) values for sightseeing, pleasure driving, and ‘general recreation’ for the northeastern USA, which are reported in terms of $USD per trip (as opposed to values per unit area). To reconcile these units with the other services measured in units of $ ha^{-1} $year^{-1}$, we assumed that each of the forest stands provided an average of one (1) recreational trip per hectare per year. Any alternative parameter value would linearly scale the valuation estimate. All monetary values were converted to 2015 dollars using the U.S. Department of Labor Bureau of Labor Statistics inflation calculator (U.S. Department of Labor, 2015).

Table 1
Monetary values of ecosystem services in the western Adirondack region of New York State, USA.

Ecosystem service	Value	Source
Sawtimber (by species)	\$55 – \$400 mbft^{-1}	NY DEC, 2014 (2014 dollars)
Fuelwood (by species)	\$5 – \$10 standard cord^{-1}	NY DEC, 2014 (2014 dollars)
GHG mitigation	\$4.9 $CO_2\text{-eq}^{-1}$	World Bank, 2014 (2013 dollars)
Maple syrup	\$11.38 L^{-1}	USDA NASS, 2014 (2011–2013 dollars)[a]
Fall foliage viewing	\$53.22 trip^{-1}	Loomis, 2005 (2004 dollars)[b]

[a] Average prices for 2011–2013 for New York State.
[b] Average of the per-trip values of sightseeing, pleasure driving, and “general recreation” for the northeastern USA.

2.3. Recreational fishing in lakes

Acidification of lakes has caused adverse impacts to fish and other aquatic communities across the eastern United States, and especially in the Adirondack region (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 fishermen (Schofield and Driscoll, 1987). In contrast, brook trout (*Salvelinus fontinalis*) – a 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 (Jeziorski et al., 2008) necessarily translate into impacts on ES benefits associated with recreational fishing.

2.3.1. Data sources

The Adirondack Lake Survey Corporation (ALSC) has collected data on 52 lakes across the Adirondacks since 1983 (Lampman et al., 2011), which are archived and publicly available. In this study, we used raw data pertaining to fish species presence and water chemistry. Fish surveys were conducted periodically at each ALSC lake from 1984 to 2005. For each lake, we examined the list of fish species that were found during the most recent survey and determined the presence/absence of two broad groups: trout and game species (Table 2). We also determined from ALSC records (Lampman et al., 2011) whether the lake had ever been stocked with trout species at any time prior to the most recent survey. There is no record of any of the study lakes being stocked by NYS DEC with any game fish other than trout, although some introductions of non-trout species have occurred in isolated incidents. Because of its close cultural associations, brown trout (*Salmo trutta*) was included amongst the true chars (*Salvelinus* spp.).

The complete ALSC lake water pH dataset covered the time period 1984–2012. Each lake was measured between 20 and 22 times during the full 29-year series. We used linear interpolation to fill in temporal gaps in order to derive a full time series for each of the 52 lakes from 1984 to 2005. For each lake, we then selected the pH value corresponding to the year of the most recent fish survey.

Table 2
Trout and other game fish found within 52 lakes in the Adirondack region, NY, USA.

Trout species	Other game fish
Salmo trutta	*Ameiurus nebulosus*
Salvelinus fontinalis	*Lepomis gibbosus*
Salvelinus namaycush	*Lepomis auritus*
Salvelinus namaycush X *Salvelinus fontinalis*	*Esox lucius*
	Esox niger
	Micropterus salmoides
	Micropterus dolomieu
	Salmo salar
	Perca flavescens
	Ambloplites rupestris
	Semotilus corporalis
	Osmerus mordax
	Coregonus clupeaformis

2.3.2. Analysis

We used logistic regression 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 categorical variable). We also used logistic regression 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 (P) of trout and/or game fish presence from pH and stocking status.

2.3.3. Monetary valuation

For valuation of recreational fisheries, we used estimates of the value of trout fishing (\$32.85 angler day^{-1}) and fishing for other game species (\$11.70 angler day^{-1}) 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 the regression models (§2.3.2) using the equation:

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

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

2.4. Drinking water in lakes and streams

Reduced pH and increased nitrate concentrations are two means by which acidic deposition can directly impact the suitability of freshwater resources for drinking and other human uses. Federal secondary standards in the US and Canada require a pH range 6.5–8.5 for drinking water. Nitrates are typically of greater concern because of their eutrophication potential, which has more direct impacts on human health and natural resources such as fisheries. Nitrate standards vary by state and federal authorities. We also included secondary sulfate and chloride standards in evaluating water quality. We note the analysis here addresses the *potential benefits* of this service, since the remote lakes monitored by ALSC and the tributary streams measured by WASS are not known to provide drinking water directly to local beneficiaries, although local consumption of lake and stream water is certainly possible, if not likely, on a small scale.

2.4.1. Data sources

In addition to lake pH, the ALSC provided data on concentrations of atmospheric acid anions – NO_3^- and SO_4^{2-} – for the same 52 lakes used in the recreational fisheries analysis. These acids are not commonly found in high concentrations in pre-acidified lakes and therefore can serve as a proxy for the intensity of deposition in the drainage of a given waterbody (Jenkins et al., 2005).

2.4.2. Analysis

For the 43 drainage lakes in the ALSC program, we calculated the mean pH and acid anion concentrations for the most recent year in the dataset. The remaining 9 lakes were primarily seepage lakes, which are largely independent of watershed processes and watershed chemistry and therefore not suitable for this analysis (Jenkins et al., 2005). We used logistic regression to predict the likelihood that pH would fall within drinking water standards based on atmospheric acid concentrations and lake geology. This last variable was a categorical variable with two levels: 'thin till' and 'medium-thick till'. Drinking water standards for pH (6.5–8.5) were derived from U.S. Environmental Protection Agency (EPA) secondary standards (U.S. EPA, 2016). We also analyzed whether – and how frequently – concentrations of nitrate, sulfate, and chloride exceeded New York drinking water standards (using methods from Caputo et al., 2016a).

2.4.3. Monetary valuation

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/ha (Menz and Driscoll, 1983) transformed to 2015 dollars ($93.48/ha). We multiplied the likelihood of meeting drinking water standards – as calculated through the regression analysis – by this estimate to determine the expected value of drinking water regulation based on atmospheric acid anion concentration and lake geology.

Using similar methods as above, we estimated the expected value of drinking water for 201 streams and tributaries monitored in the Western Adirondack Stream Study (WASS, Lampman et al., 2008). In this case, we used only the single predictive variable: atmospheric acid anion concentration. In the WASS protocol, water chemistry variables were measured at multiple points throughout the year. In our analysis, we exclusively used data collected in March to minimize the complicating effects of groundwater contribution to streams.

3. Results and discussion

3.1. Forest ecosystem services

Acidified forests have roughly half the value of forests where deposition has had little or no impact on soil chemistry. Estimates of the potential ES value of Adirondack hardwood forests increased in a non-linear trend along a gradient of soil base saturation (BS), from roughly $10,000 ha^{-1} at < 10% BS to over $20,000 ha^{-1} at >25% BS (Fig. 1A), with a mean value of $15,505.68 ha^{-1}. Nearly all (>84%) of this potential value comes from the potential to harvest the stand for wood products (Fig. 2). Reduced service values at low levels of BS 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 = $1992.22 ha^{-1} across all plots) in stands with more acidified soils. Acidified soils also 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).

The relationship between soil BS and potential economic value was non-linear (Fig. 1B). The segmented regression analysis indicated a breakpoint at BS = 36.3%. For values of BS < 36.3% (to the left of the breakpoint in Fig. 1B), the slope parameter of the first regression model (439.1) was significantly non-zero (95% confidence interval (CI): [210.6, 667.6]). In these acid-impaired forests, we estimated the potential value of each hectare increases by approximately $439.10 for each percentage point of increase in BS. Above the breakpoint (right of the dashed line in Fig. 1B), where BS is greater than 36.3%, the slope of the regression segment is negative but not significantly different from zero (95% CI: [-296.2, 63.1]), suggesting no consistent change in ES value with any further increase in soil base saturation.

Of course, soil base saturation is one of myriad factors that influence the condition of a forest stand. Land use history and past management practices, especially those that either inhibit or promote regeneration of high-value species such as sugar maple, have significant impacts on the stand conditions relevant for our present analysis. Legacy effects of forest management could explain the wide variability in stand conditions above the observed BS threshold where soil calcium availability is not a strongly limiting factor for SM growth and regeneration (Sullivan et al., 2013; Bishop et al., 2015). Although nearly all of the sampled forest stands have similar land use history – i.e., harvested for timber in the 19th century prior to incorporation in the NY State Forest Preserve in the early 20th century – we recognize that even minor differences in initial conditions, harvest practices and disturbance regimes (among other factors) can result in markedly different forests (with different potential economic values) decades later.

We note that these results reflect the forest ecosystem capacity to provide potential benefits at a single point in time (~2011). Also, because of tradeoffs associated with managing forests for wood products, not all of the benefits measured can be realized simultaneously. For instance, values of carbon storage and maple syrup production will be reduced or eliminated for a period of time after a stand is harvested (Caputo et al., 2016b). For this reason we have measured each potential benefit independently and aggregated them into a summary measure of potential value. Moreover, the current analysis does not take into account the effects of soil acidification or pollution reduction scenarios on the potential economic values of forests over several management rotations (for this analysis, see Caputo et al., 2016b). Lastly, benefits that are more species-specific (e.g., maple syrup), relative to those that are species-generic (e.g., carbon sequestration), will experience changes that are directly coupled with the future abundance, growth and health of the focal species, which may change in ways unrelated to acid pollution.

For example, Sullivan et al. (2013) observed significantly reduced sugar maple regeneration in Adirondack forests with less than 12% soil BS versus those above this threshold, which is approximately the level at which inorganic Al becomes mobilized in soil solution (and blocks Ca uptake by plant roots; Lawrence et al., 1995). A higher benchmark of 20% BS was also indicated as a secondary threshold for effective SM recruitment. Hence the thresholds of 12% and 20% BS may be more meaningful benchmarks for critical loads that ensure long-term production of the high-value benefits (e.g., production of sawtimber and maple syrup) in Adirondack forests that depend on SM dominance in the canopy. By contrast, our estimate of a 36% BS benchmark for ES production suggests where investments in ecosystem recovery, via reducing acid inputs and/or restoring base cation supply (e.g., by application of lime; Lawrence et al., 2016), could have their largest potential economic returns over the long term.

3.2. Recreational fishing in lakes

Among the 52 study lakes, the probability of the presence of trout and other game fish increased as pH increased (Fig. 2A), 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. Trout were more likely to be

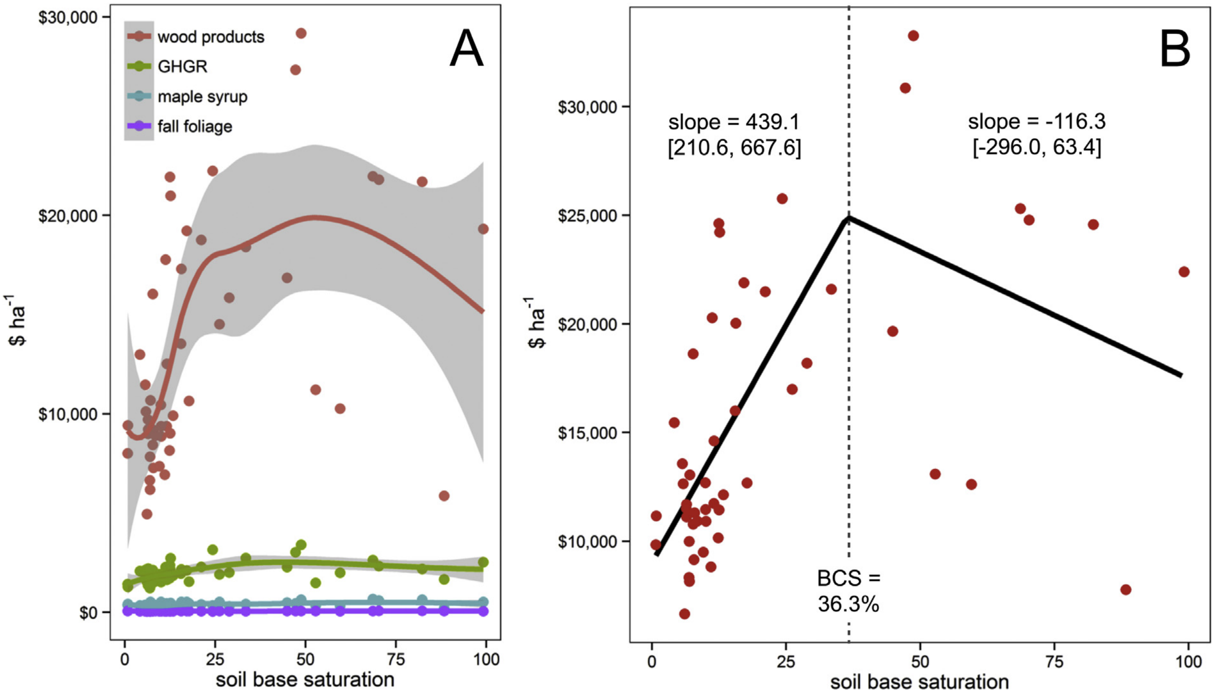

Fig. 1. Estimated value of forest ecosystem services (2015 USD$ ha^{-1}) as a function of soil base saturation. Panel (A) depicts the potential monetary value of wood products, carbon sequestration, syrup production and visual quality for each of 50 forest plots in the Adirondacks, using a loess smoother. Panel (B) depicts the segmented regression analysis that indicates a breakpoint between two linear models fitted to the total estimated ES value for each plot. Slope estimates and confidence intervals are given.

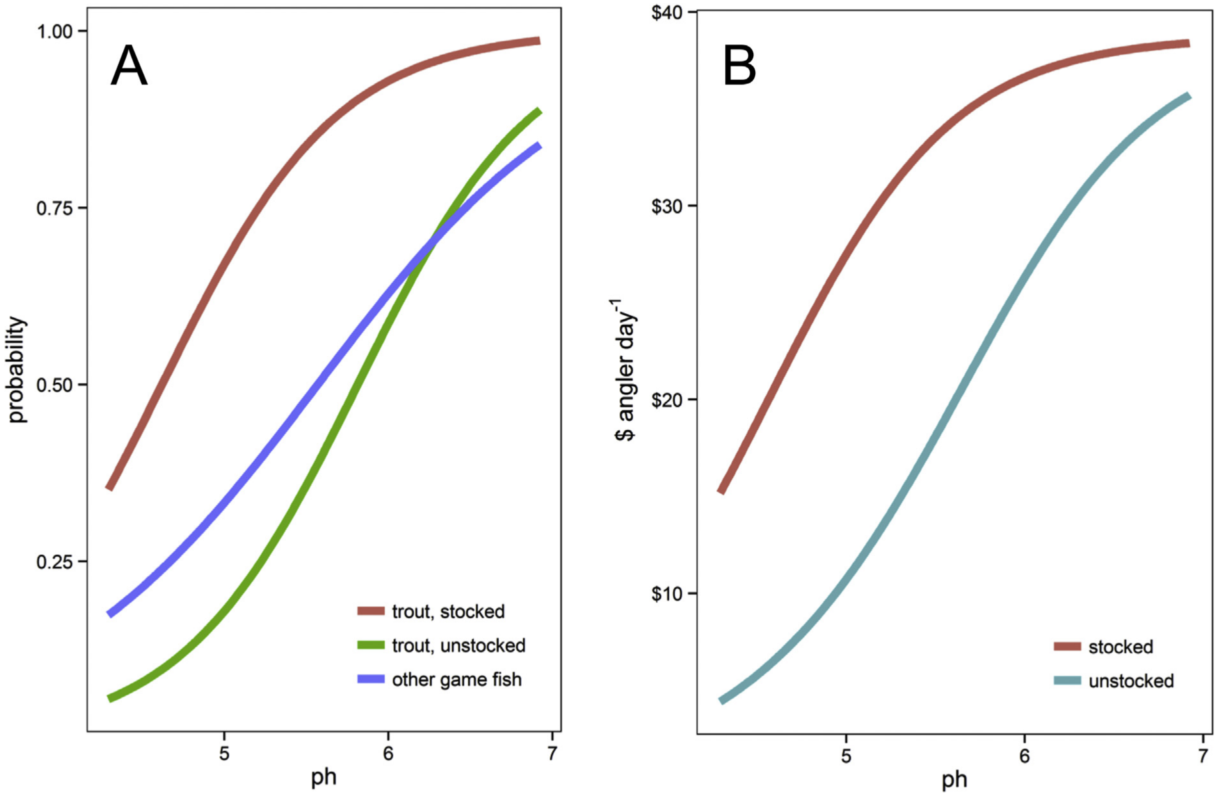

Fig. 2. Logistic models of recreational fishery composition (A) and estimated recreational fishery value (B) (2015 USD$ angler day^{-1}) as a function of lake pH and historical fish stocking practices in the Adirondacks (USA). To be counted as stocked, lakes may have been stocked only once or on a regular basis. Monetary values of fishing trips were based on Boyle et al. (1999).

present than other kinds of game fish in lakes with pH > 6.3; in lakes having 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 also as expected, we found 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 unity. All independent variables in the logistic models had low p-values ($p < 0.001$) and deviance tests for both models were not significant ($p > 0.4$), suggesting no evidence for lack of fit in either model.

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 that were stocked with trout (Fig. 2B). 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. This was not unexpected, given that reported values for trout fishing were almost three times higher than fishing for other freshwater species (Boyle et al., 1999). Like the previous analysis, these values refer to a single point in time. Caputo et al. (2016c) expand upon this analysis to investigate changes in the value of recreational fishing services across several scenarios of long-term ecosystem recovery.

3.3. *Drinking water in lakes and streams*

We found no significant relationship between atmospheric acid anion concentrations, which reflect direct pollutant loads into surface waters, and the suitability of water in Adirondack lakes (Fig. 3A) and streams (Fig. 3B) for potential human consumption. Deviance tests for both models were not significant at any reasonable α level ($P > 0.3$), suggesting no evidence for lack of fit. For both lakes and streams, any effects of acidic deposition on water chemistry were not large enough to significantly reduce the likelihood that regulatory water 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., 2016a).

In contrast to acid anion concentrations, there was a significant relationship ($p = 0.0061$) between geology and whether or not lakes met drinking water standards in terms of pH (Fig. 3A). Lakes underlain by medium-thick till were approximately 1.9 times 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 layers tend to have greater base cation supply and therefore greater capacity to buffer acidic deposition (Jenkins et al., 2005).

At no point in the data series did concentrations of nitrate or sulfate exceed NY drinking water standards in either lakes or streams. Chloride standards were exceeded on one occasion in a single stream, but never in any of the lakes. Taken together with the results of the logistic regression analysis, this suggests that historic levels of acidic deposition have had no effects on the drinkability of Adirondack waters relative to legal standards. Lastly we note that.

3.4. *Uncertainty and limitations*

Due to multiple sources of uncertainty and the scope of our assessment, our results reflect a partial estimate of economic damages due to chronic acid pollution in Adirondack ecosystems. Data limitations as well as a host of complexities inherent to our study – which are outlined below – precluded our ability to provide a robust extrapolation of valuation estimates to a broader area, such as the entire six million-acre Adirondack Park. Although the systems studied here are broadly representative of the Adirondack

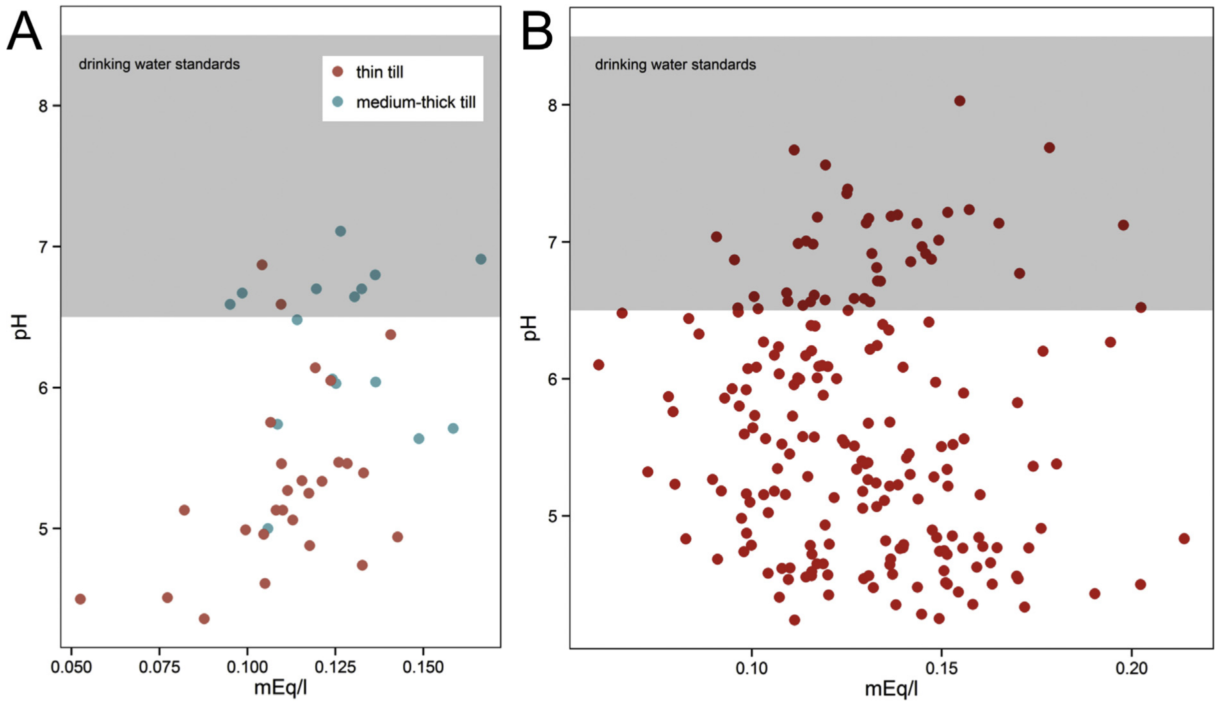

Fig. 3. Drinking water quality in lakes (A) and streams (B) of the Adirondacks (USA). Both panels depict pH as a function of acid anion (NO_3 and SO_4) concentrations in lake or stream water. Range of pH suitable for drinking water by US federal secondary standards is shown.

region, there exists more heterogeneity in both ecological provision of benefits and social demand or access to benefits, than we have captured in our analysis. We therefore caution against simple extrapolation of per hectare or per lake estimates of value without accounting for the significant uncertainties of such calculations.

First, our results are based on temporal ‘snapshots’ of ecosystem condition, which integrate effects over time, but do not capture dynamics of ecosystems and their anthropogenic stressors. Similarly, our methods for ES assessment and valuation do not account for how societal demands and preferences vary among demographic groups and over time. For instance, the most acid-impaired Adirondack lakes and forests were relatively acidic in their natural state prior to deposition impacts (Kahl et al., 2004), and therefore inherently have a lower baseline capacity to provide the focal ES of this study, even if they recover to pre-deposition conditions. As acidic deposition declines, ecosystems that can recover will mean that differences in ES provision between acidified and non-impaired systems could diminish. Recovery rates, trajectories and endpoints will vary fundamentally among different aquatic (Strock et al., 2014) and terrestrial ecosystems (Waller et al., 2012; Lawrence et al., 2015) and in complex ways depending on state factors including surficial geology, morphology and climate (e.g., Fakhraei et al., 2014). Moreover, ecological legacies associated with historic deposition, such as species loss and changes in community assembly (Nierzwicki-Bauer et al., 2010; Beier et al., 2012) may result in a lower capacity to provide ES that persists regardless of chemical recovery.

Second, management practices such as timber harvesting, fish stocking or the application of lime (calcium carbonate), could hasten, inhibit, or alter the recovery trajectories of ecosystems under pre-industrial deposition levels (Moore et al., 2015). Our results provide a reference point for the cost-benefit analysis of such actions. For example, a related study using stand-level model simulations found that acid-impaired Adirondack forests harvested for timber would retain only a small fraction of their value in future rotations due to loss of sugar maple (Caputo et al., 2016b).

Resource managers may also consider liming of acid-impaired ecosystems to hasten recovery (Battles et al., 2014; Lawrence et al., 2016), although this practice has potential detriments that must be considered alongside its benefits. Understanding the relationship between acidification and ES values is helpful for deciding whether or not the cost of liming – or other costly interventions, such as fish stocking – may be worth the potential benefits. In the Adirondacks, we estimated that the greatest marginal benefit of fish stocking, in terms of recreational fishery value, has historically been in those lakes with pH 4.8–5.5. Costs of maintaining these fisheries with hatchery stock can be partially avoided with ‘natural’ increases in lake pH resulting from reduced deposition inputs and higher rainwater pH. In all cases, operational costs, remoteness, and other factors will affect this cost-benefit calculus (Menz and Driscoll, 1983).

Lastly, we used a benefit transfer approach to translate measures of ES into monetary value ($USD). Although this approach is widely used in the ecosystem services literature (e.g. Farber et al., 2006), it has also received widespread criticism – especially in cases where there is low correspondence between the characteristics of the studies from which the values were derived and the characteristics of the study to which they were applied (e.g. Plummer, 2009). In our case, however, we were able to utilize values that were largely derived from the same setting (the Adirondacks) as our study. In other words, there is high correspondence between our case studies and the economic values that we used for valuation. In order to value recreational fisheries, we used a benefit function derived from a formal meta-analysis of a database of primary valuation studies (Boyle et al., 1999). Benefit functions are generally considered preferable to direct transfer of mean values in they include as independent variables many aspects of a study's characteristics – and therefore can achieve high correspondence (Loomis et al., 2008; Plummer, 2009). In our case, species (trout/other game fish) and venue (freshwater lakes) were included as independent variables in Boyle et al.'s (1999) function. Costs associated with lake liming, as well as the values associated with wood products and maple syrup, were all derived from the Adirondack region or New York State. The value of greenhouse gas regulation is derived from global averages, which is appropriate because the service benefits people across the entire planet. There is a lower correspondence for the valuation of fall foliage, largely due to the absence of primary research that provides a better estimate of these aesthetic/cultural benefits or value of tourism associated with fall foliage viewing. As fall foliage is widely touted as an important value of forests of the US Northeast, this is an area that should receive further attention.

4. Conclusions

Ecosystem services provided by acid-impaired Adirondack hardwood forests and lakes have roughly half the net present value of the same services provided by non-impaired ecosystems. We estimated that extant hardwood forests on anthropogenically acidified soils (base saturation < 12%) on average will yield ~ $10,000 ha^{-1} less in potential value than forests on well-buffered soils. Below a threshold of 36% soil base saturation, value of Adirondack hardwood stands is reduced by ~ $440 ha^{-1} for every one-percent decrease in soil base saturation, largely because of lower commercial value of the standing timber. For lakes, there was a significant loss of value in the recreational fishery for each unit of decrease in pH within the range 4–6, due to lower probability of trout being present. Results indicate that over half the maximum possible value of a fishing trip (angler day^{-1}) would be lost when a lake moves from a pH 6 to pH 5 due to acid inputs. Stocking of Adirondack lakes with hatchery-raised trout partially offset negative effects of acidification on the expected value of a fishing trip, with the largest marginal benefit of stocking within pH 4.8–5.5. Lastly, we found little or no impact of acid pollution on potential benefits of water quality regulation in Adirondack lakes and streams, although large differences in drinking water value were apparent based on lake geomorphic and hydrologic characteristics. Despite the uncertainty associated with ES assessment and valuation, our results illustrate the tangible negative economic and cultural externalities caused by acid rain and highlight the need to sustain progress made in emissions reductions and promoting ecosystem recovery.

Acknowledgements

This research was supported by the New York State Energy Research and Development Authority (NYSERDA) under contract agreement #33072. The authors also wish to extend thanks to Charles Driscoll, Jon Erickson, Myron Mitchell and the Adirondack Lake Survey Corporation (ALSC) for sharing their expertise and data.

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