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OPINION

Acid rain recovery may help to mitigate the impacts of climate change on thermally sensitive fish in lakes across eastern North America

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Abstract

From the 1970s to 1990s, more stringent air quality regulations were implemented across North America and Europe to reduce chemical emissions that contribute to acid rain. Surface water pH slowly increased during the following decades, but biological recovery lagged behind chemical recovery. Fortunately, this situation is changing. In the past few years, northeastern US fish populations have begun to recover in lakes that were historically incapable of sustaining wild fish due to acidic conditions. As lake ecosystems across the eastern United States recover from acid deposition, the stress to the most susceptible populations of native coldwater fish appears to be shifting from acidification effects to thermal impacts associated with changing climate. Extreme summer temperature events – which are expected to occur with increasing frequency in the coming century – can stress and ultimately kill native coldwater fish in lakes where thermal stratification is absent or highly limited. Based on data from northeastern North America, we argue that recovery from acid deposition has the potential to improve the resilience of coldwater fish populations in some lakes to impacts of climate change. This will occur as the amount of dissolved organic carbon (DOC) in the water increases with increasing lake pH. Increased DOC will reduce water clarity and lead to shallower and more persistent lake thermoclines that can provide larger areas of coldwater thermal refuge habitat. Recovery from acidification will not eliminate the threat of climate change to coldwater fish, but secondary effects of acid recovery may improve the resistance of coldwater fish populations in lakes to the effects of elevated summer temperatures in historically acidified ecosystems. This analysis highlights the importance of considering the legacy of past ecosystem impacts and how recovery or persistence of those effects may interact with climate change impacts on biota in the coming decades.

Keywords: acid deposition, acid rain, acid rain recovery, brook trout, climate change, coldwater fish, lake stratification, *Salvelinus fontinalis*, thermocline, water clarity

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Introduction

Current deliberations to address climate change through limits on fossil fuel emissions, as proposed by the U.S. EPA's Clean Power Plan, are reminiscent of the 20 years of political debate that stalled efforts to reduce acid deposition long after a scientific consensus had been attained. Air quality regulations ultimately reduced emissions of chemicals that contributed to acid deposition across North America and Europe, and these actions have worked. Chemical recovery of surface waters from acid deposition began in the northeastern United States soon after passage of the Clean Air Act Amendments of 1990 and reductions in Canada and Europe yielded similar declines (Stoddard *et al.*, 1999; Garmo *et al.*, 2014; Driscoll *et al.*, 2016). Now that the biological recovery has begun to catch up to the more rapid chemical recovery observed within acidified waters, the trajectory is clear and encouraging. Today, while native fish populations are in decline throughout much of the world, in eastern North America fish survival and reproduction are improving in montane forest regions as a result of improving surface water chemistry conditions (Josephson *et al.*, 2014; Sutherland *et al.*, 2015). This trend suggests that we are entering an important stage in the ecological recovery of aquatic ecosystems from acid deposition. In this paper, we describe how regulation of sulfur dioxide and nitrogen oxide emissions in recent decades is

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affecting a bellwether aquatic species, native brook trout (*Salvelinus fontinalis*), in a region that was heavily impacted by acid deposition, the Adirondack Mountains of New York. We explore how the direct and indirect effects of emission reductions may influence brook trout populations in a future of changing climatic conditions.

Brook trout are a native salmonine fish dominant in thousands of small lakes and streams throughout the eastern United States and Canada (MacCrimmon & Campbell, 1969; Power, 1980). This species is ecologically important, thermally sensitive, and carries great societal value in its native range. Thus, brook trout have become an important indicator species in studies evaluating the effects of acidification on freshwater ecosystems (Baker *et al*., 1996; Wigington *et al*., 1996; Nislow & Lowe, 2003) and in studies assessing the impacts of climate change on coldwater fish populations (Warren *et al*., 2012; McDonnell *et al*., 2015; Wood & Fraser, 2015; Bassar *et al*., 2016).

Acid rain in North America

Acid rain in the northeastern United States occurred primarily as a result of sulfur dioxide and nitrogen oxide emissions from industrial and energy-producing activities in the middle of the continent. In the absence of emission control measures, fossil fuel emissions (primarily energy production from coal) foster the formation of sulfuric and nitric acids in precipitation as well as the dry deposition of acid gases and particles, causing acidification of lakes and streams in sensitive regions (Driscoll *et al*., 2001). Anglers first reported the loss of fish from Adirondack lakes as early as the 1950s, although the absence of regular assessments of pH in Adirondack NY lakes and streams until the late 1950s obscured any connection between fishery declines and increasing acidity in surface waters (Schofield, 1976a,b). The term 'acid rain' was not widely used until it was coined by scientists in the early 1970s, when declines in pH were clearly documented as a regional landscape-scale phenomenon with adverse effects for plant and animal life across broad acid-sensitive regions (Likens & Bormann, 1974; Schofield, 1976a). These observations were followed by a decade of political denial and scientific investigations before acid rain became the focus of government regulation in the 1990s and beyond (Driscoll *et al*., 2010).

In the United States, the Clean Air Act and subsequent rules such as the Nitrogen Budget Rule, Clean Air Interstate Rule, and the Cross State Air Pollution Rule led to reductions in sulfur dioxide and nitrogen oxide emissions from coal-fired power plants. Together with similar actions in Canada, these legislative actions led to reductions in acidic deposition across the eastern United States and Canada (Stoddard *et al*., 1999; Lehmann *et al*., 2005; Driscoll *et al*., 2010). Reductions in both sulfur dioxide and nitrogen oxide resulted in a recovery of pH, acid neutralizing capacity (ANC), and harmful concentrations of inorganic monomeric aluminum in many lakes and streams in eastern North America (Driscoll *et al*., 2003, 2016; Garmo *et al*., 2014). In addition, signs of an initial recovery in forest soils have also begun in some eastern forest ecosystems (Lawrence *et al*., 2015).

In some oligotrophic lake ecosystems, chemical recovery has progressed to the point where fish populations that were reduced or locally extirpated by acidification can now persist as stocked or wild, naturally reproducing, populations. For example, in Honnedaga Lake, where a Cornell research program has worked for over 50 years, we observed improvements in the wild brook trout population between 2002 and 2012 that coincided with changes in water chemistry (Josephson *et al*., 2014). And in recent years, we have seen substantial increases in brook trout spawning activity that align with ongoing recovery of Honnedaga Lake chemistry. Further, in the past 2 years, our research program has terminated liming in eight Adirondack lakes where $CaCO_3$ additions were implemented as an acid rain mitigation practice for 20–40 years. Also, we have successfully re-established stocked brook trout populations in two unlimed lakes from which they had been extirpated for more than 50 years. Beyond our study systems, a number of other Adirondack lakes are experiencing improvements in water chemistry that allow for fish population recovery, which has led to subsequent changes in aquatic resource management. Chemical recovery in Brook Trout Lake in the southern Adirondack Mountains, for example, prompted the New York State Department of Environmental Conservation (NYSDEC) to restock that system. Now, after decades of a fishless condition due to acidification, Brook Trout Lake has re-established a self-sustaining wild brook trout population (Sutherland *et al*., 2015). Similarly, the NYSDEC has restocked fish in at least 12 unlimed lakes in other areas of the Adirondack Park where a recovery from acidification has created conditions suitable for the persistence of stocked brook trout populations and may allow self-sustaining wild brook trout populations to develop (Jonathan Fieroh, NYSDEC, Personal communication).

The potential for these formerly fishless or formerly limed lakes to sustain wild fish populations does not indicate the end of acid rain impacts (Likens & Buso, 2012). Observed trends are promising, but they only signal the *start* of a biological recovery associated primarily with decreases in sulfate and nitrate deposition.

Many aquatic ecosystems still remain chronically or episodically acidified as a result of the legacies of historic acid deposition. And while surface waters and some forest soils are showing signs of recovery, the long-term consequences of acid deposition on base cation loss in soils are likely to persist for decades if not centuries (Likens & Buso, 2012).

With continued surface water recovery, the next few decades will provide an opportunity for the restoration of native brook trout in many lakes in which populations were reduced or extirpated in the late 20th century. However, while recovery from one major anthropogenic stressor is progressing, an even more widespread anthropogenic stressor is emerging – climate change.

Thermal stress in lake ecosystems

Climate models for eastern North America project increases in average temperature and, importantly for coldwater fisheries, increases in the frequency and severity of hot summers (Hayhoe *et al.*, 2007). Persistently elevated temperatures during summers are projected to alter the thermal structure of lakes in the northeastern United States and other north temperate ecoregions (De Stasio *et al.*, 1996; Keller, 2007). The potential for changing climate conditions to affect lake thermal conditions and therefore impact the habitat of coldwater fish has been recognized for decades (Magnuson *et al.*, 1990). The thermal profile of a lake during hot periods is particularly important in establishing the potential impact of elevated temperatures. Many lakes of adequate depth 'stratify' with a zone of warmer water at the surface (epilimnion) and cooler water below (hypolimnion) separated by a region of rapid temperature range (thermocline). Coldwater fishes such as brook trout generally prefer water temperatures cooler than 16 °C (and warmer than 8 °C) and become stressed when temperatures exceed 20 °C (MacCrimmon & Campbell, 1969; Lund *et al.*, 2003; Robinson *et al.*, 2010). In a stratified lake, these fish can often find thermal refuge in deep cool hypolimnia during the hottest time of year. However, in unstratified (shallow) lakes, the full profile of the lake warms in summer and deep water thermal refuge is limited. Coldwater fish are particularly susceptible to the effects of a hot summer in unstratified or weakly stratified lakes (Robinson *et al.*, 2010; Warren *et al.*, 2012).

Unstratified lakes receive little attention because they tend to be small, but are common across many regions of north-central and northeastern North America (Eilers & Selle, 1991). Fortunately, the physical and chemical properties of nearly 1500 Adirondack lakes were surveyed by the Adirondack Lake Survey Corporation (ALSC) in the mid-1980s in conjunction with fisheries surveys. Many of these lakes are small with mean depths and mean maximum depths of 2.6 ± 2 and 6.5 ± 5.6 m, respectively (mean $\pm$ SD). Forty-seven percent were classified as 'unstratified', and an additional 29% were considered to be 'weakly stratified' (Schofield *et al.*, 1993). Even if a small lake stratifies, areas of thermal refuge may be limited during hot summers when thermoclines extend to greater depths (Schofield *et al.*, 1993).

Lakes that are sensitive to the effects of severe summer temperatures (and potential loss of stratification and associated thermal refuge) often have large surface area to depth ratios. However, thermocline depth and the degree of stratification are not defined by lake morphology alone. Water clarity is also an important factor influencing lake thermal characteristics (Gunn *et al.*, 2001). All else being equal, the thermocline is established earlier and is shallower throughout the summer in lakes with water that transmits less light; by contrast, the thermocline will develop later and be deeper in lakes with greater water transparency. Consequently, processes that change lake clarity can alter the timing and extent of lake stratification, which influences the presence or amount of thermal refuge habitat available for coldwater species. Our experience with Adirondack lake fisheries suggests that projections of climate change impacts on fish need to take into account the trajectory of other ongoing changes in lake environmental conditions, particularly the physical properties associated with lake thermal structure.

Interaction of acidification and climate change on lake thermal structure

With a reduction in lake acidification, we often see concurrent declines in lake water clarity, which can create conditions that enhance thermal stratification in small lake ecosystems (Snucins & Gunn, 2000; Gunn *et al.*, 2001; Driscoll *et al.*, 2003). Water clarity in oligotrophic lakes increases during acidification as pH declines due to associated reductions in the supply and concentration of dissolved organic carbon (DOC) in the water (Gunn *et al.*, 2001; Driscoll *et al.*, 2003). Increasing water clarity leads to deeper light penetration, which results in a deeper thermocline in stratified lakes and therefore a smaller volume of cool thermal refuge in deep hypolimnetic water (Schofield *et al.*, 1993). By contrast, when pH increases (with recovery from acid rain) – as is occurring across many Adirondack lakes – DOC increases and water clarity is reduced. This process leads to a shallower thermocline and a larger volume and longer period of thermal refuge for coldwater fish. Lakes with low water clarity (high DOC) can also

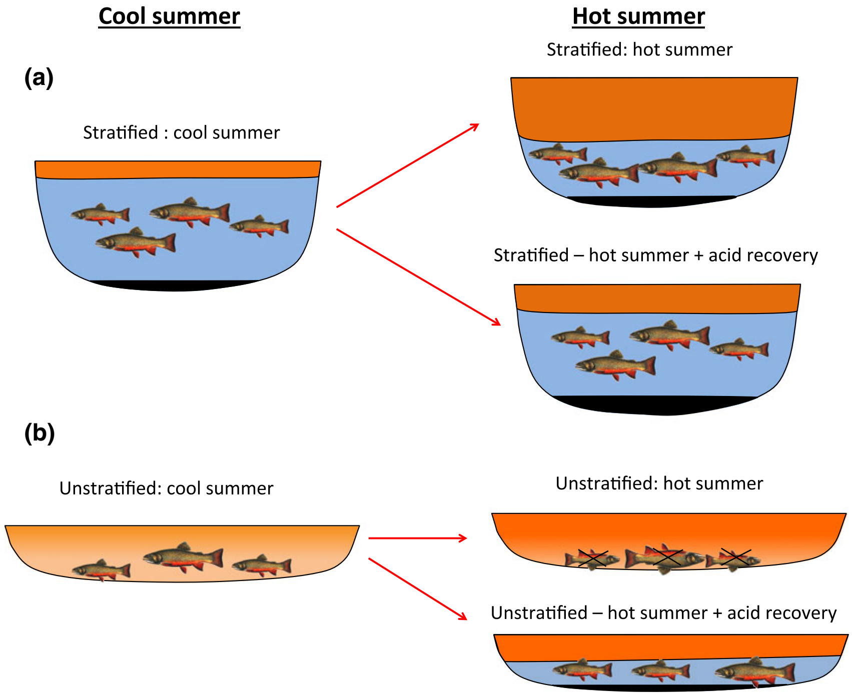

Fig. 1 Conceptual framework for how an increase in summer temperatures could affect fish in oligotrophic lakes that are (a) stratified and (b) unstratified. In stratified lakes, thermoclines will be deeper during a hot summer, thereby reducing coldwater refuge habitat for trout. With acid recovery and a decrease in water clarity, we expect a shallower thermocline and therefore greater coldwater habitat relative to the nonrecovery condition. In unstratified lakes, fish persist in a cool summer but are likely to experience high mortality in a hot summer. With acid recovery and a decrease in water clarity, however, we expect that these lakes may develop thermal stratification, which could create cooler refuge habitat in hot summers and thereby allow for persistence of coldwater fish. The tan coloration at the top of the lakes (or throughout the lake in the unstratified cases) represents the epilimnion, and blue coloration represents a hypolimnion. Darker gray at the bottom of the lakes indicates an area of low dissolved oxygen, which can develop in some stratified lakes.

establish stratification earlier in the season, which can lead to colder hypolimnetic waters and greater persistence of coldwater refuge habitat in lake ecosystems during hot summer (Snucins & Gunn, 2000). In addition to changes in overall DOC concentrations, increasing lake pH and associated reductions in inorganic monomeric aluminum can increase phosphorus supply and phytoplankton production, which also decreases water clarity and leads to shallower thermoclines (Tanentzap *et al.*, 2008; Gerson *et al.*, 2016).

Explicit links between changing pH, water clarity, and thermocline depth in an oligotrophic lake ecosystem were well illustrated in a series of lake liming studies completed in the Adirondacks during the mid-1980s when this region was subject to elevated acid deposition. Schofield *et al.* (1993) found that adding calcium carbonate to lakes increased pH and DOC, which reduced water clarity and reduced the thermocline depth. Increasing DOC and lake productivity can also lead to localized anoxic areas in the deeper waters, but overall, lake liming increases the volume of suitable brook trout thermal habitat in these lakes. We anticipate a similar response in lakes with improved chemical conditions, where decreases in acid deposition may increase brook trout thermal refugia in shallow Adirondack lakes (Fig. 1). This benefit of reduced acid deposition in mitigating potential climate impacts on native coldwater fish populations is not likely to protect these populations indefinitely from the long-term impacts of changing climate, but increasing pH and decreasing clarity can enhance resistance to thermal stress anticipated from hot summers in the coming decades. Increasing thermal refuge is likely to manifest most clearly in weakly stratified lakes in forested basins with thin, acidic soils. These systems are therefore recommended target areas to begin to explore trends in DOC, trout abundance, and thermal profiles of temperature and dissolved oxygen.

Conclusions

Long-term assessment of climate change impacts must take into account not only future alterations to temperature, precipitation, and natural disturbance regimes, but also the ongoing and historic legacies of other environmental impacts. Continued improvement in the acid neutralizing capacity of lakes and streams across the Adirondack Mountains during the past 25 years, and more recent progress in the recovery of biota, show that with careful foresight and thoughtful discussion, policy actions can effectively address and mitigate large-scale environmental impacts to aquatic ecosystems. Our experience in the Adirondacks provides an encouraging example of how forward-thinking legislation and patience in recovery has yielded measured improvement in lake habitat conditions, and fortunately, these improvements have the potential to mitigate against some of the negative influences of climate change predicted by Magnuson *et al.* (1990). Ultimately, across much of North America and Europe, the future of oligotrophic lakes – and the coldwater fish that inhabit them – will be affected by both climate change and acid recovery. Understanding the direct and indirect responses of these ecosystems to reduced anthropogenic acid deposition will be important to successfully manage lake resources under new climate regimes.

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