



## A new look at liming as an approach to accelerate recovery from acidic deposition effects



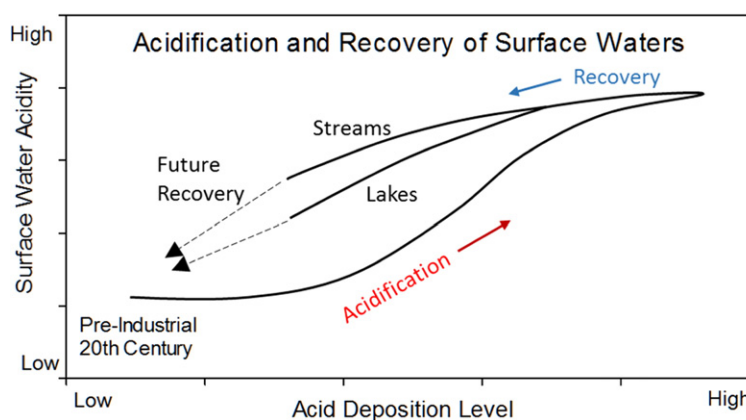
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### HIGHLIGHTS

- Liming is no longer needed to prevent further damage from acidic deposition.
- Liming may accelerate recovery in calcium-depleted landscapes.
- Whole-watershed liming can benefit both terrestrial and aquatic ecosystems.
- Clear remediation goals and full knowledge of the system being considered is needed.
- Lime should be applied judiciously to avoid damaging naturally acidic systems.

### GRAPHICAL ABSTRACT



Liming is no longer needed to prevent further damage from acidic deposition. However, recovery of calcium-depleted ecosystems is sluggish and the conditions of full recovery remain uncertain. Whole-watershed liming may accelerate recovery in terrestrial and aquatic ecosystems where recovery is being impeded by low availability of calcium.

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### ABSTRACT

Acidic deposition caused by fossil fuel combustion has degraded aquatic and terrestrial ecosystems in North America for over four decades. The only management option other than emissions reductions for combating the effects of acidic deposition has been the application of lime to neutralize acidity after it has been deposited on the landscape. For this reason, liming has been a part of acid rain science from the beginning. However, continued declines in acidic deposition have led to partial recovery of surface water chemistry, and the start of soil recovery. Liming is therefore no longer needed to prevent further damage, so the question becomes whether liming would be useful for accelerating recovery of systems where improvement has lagged. As more is learned about recovering ecosystems, it has become clear that recovery rates vary with watershed characteristics and among ecosystem components. Lakes appear to show the strongest recovery, but recovery in streams is sluggish and recovery of soils appears to be in the early stages. The method in which lime is applied is therefore critical in achieving the goal of accelerated recovery. Application of lime to a watershed provides the advantage of increasing Ca availability and reducing or preventing mobilization of toxic Al, an outcome that is beneficial to both terrestrial and aquatic ecosystems. However, the goal should not be complete neutralization of soil acidity, which is naturally produced. Liming of naturally acidic areas such as wetlands should also be avoided to prevent damage to indigenous species that rely on an acidic environment.

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## 1. Introduction

Acidic deposition caused by fossil fuel combustion has degraded aquatic and terrestrial ecosystems in North America and Europe for over four decades. The widespread recognition of consequences of ecosystem acidification has led to effective political and regulatory efforts to reduce emissions and corresponding deposition of acidifying substances (Burns et al., 2011). For example, in the northeastern U.S., wet deposition of sulfur in 2010 was approximately one-quarter of the level in 1980 (<http://nadp.sws.uiuc.edu/>; accessed Sept. 25, 2015). However, the lowering of emissions has been a gradual process and further reductions have been recommended to achieve recovery goals (Burns et al., 2011).

The only management option other than emissions reductions for combating the effects of acidic deposition has been the application of substances to neutralize acidity, most often lime, after the acids have been deposited on the landscape. Lake and stream liming was initially used as a fisheries management tool to neutralize acidic waters as a stopgap measure or in the earliest stages to simply improve water quality before acidic deposition was discovered (personal communication, H.A. Simonin, New York State Department of Environmental Conservation, retired). For this reason, liming has been a part of acid rain science from the beginning (Scheider et al., 1975) and has continued to be used for both experimental (Sterling et al., 2014) and operational purposes (Hesthagen et al., 2011; Moore et al., 2015).

With recovery of surface waters (Clair et al., 2011; Strock et al., 2014; Wright et al., 2005) and soils (Lawrence et al., 2015a) underway, and acidic deposition levels continuing to decline, liming is no longer needed to prevent further damage. The question has now become whether liming would be useful for accelerating recovery of systems where improvement has lagged. Slow chemical responses of surface waters and soils to decreasing emissions has been linked to Ca depletion from decades of elevated soil leaching by acidic deposition (Likens et al., 1996). The capacity of soils to replenish lost Ca under current and future emissions remains uncertain (Lawrence et al., 2012, 2015a).

Under these current conditions, liming remains a potential management option to boost the availability of Ca in aquatic and terrestrial ecosystems where Ca depletion limits the reversal of acidic deposition effects. Therefore, the objective of this review is to assess liming as a possible tool to accelerate recovery of ecosystems within the context of our current understanding of recovery processes. Because the current status of recovery is a key factor in the efficacy of liming, this article begins with a summary of the chemical recovery status of North American surface waters and soils. This assessment considers the treatment of both aquatic and terrestrial ecosystems to identify (1) the settings and application methods with the greatest likelihood of improving

overall ecosystem health, and (2) the remaining questions that need to be addressed to fully weigh the benefits and drawbacks of liming as a remediation tool.

The literature on the use of liming to combat acidic deposition effects in Europe and North America is extensive. For this review we have chosen North America as the geographic focus, but include European studies with high relevance to North American conditions.

## 2. The status of chemical recovery in North American surface waters and soils

### 2.1. Lakes

The most pronounced reversals of lake acidification have occurred in regions where peak acidic deposition levels were highest and where decreases were greatest. In the area surrounding Sudbury, Ontario, emissions of SO<sub>2</sub> from metal smelters decreased from 2500 metric kilotons per year in 1960 to <300 metric kilotons in 2002. In response, surveys of 44 lakes in this region showed that the number of lakes with pH < 5.0 decreased from 28 in 1981 to 6 in 2004 (Keller et al., 2007). However, only 14 of the lakes had a pH > 6.0 by 2004, the level considered sufficient for most aquatic biota (Driscoll et al., 2001). Large decreases in lake SO<sub>4</sub> concentrations occurred, but were partially offset by decreases in base cation concentrations.

In Atlantic Canada, where deposition levels are the lowest in eastern North America, but buffering capacity is also extremely low, pH did not show significant changes in any of 66 lakes from 1983 to 2007 (Clair et al., 2011). The difference between base cations and acid anions (calculated acid neutralizing capacity) did increase significantly over this time period in these same lakes due to decreases in SO<sub>4</sub> that were greater than decreases in Ca (Clair et al., 2011). Concentrations of Ca continued to decrease significantly through the periods of 1990 to 2007 and 2000–2007.

In the Adirondack region of New York State, arguably the region in the U.S. with the greatest impacts from acidic deposition, wet atmospheric SO<sub>4</sub> deposition declined by approximately three-fourths from 1980 to 2010 (<http://nadp.sws.uiuc.edu/>; accessed Sept. 25, 2015). In response, the number of lakes with acid neutralizing capacity (ANC) < 0 meq L<sup>-1</sup> decreased from 15.5% in 1991–1994 to 8.3% in 2006–2007 (Waller et al., 2012). Of 42 randomly selected Adirondack lakes, 35 showed ANC increases during this period and only one lake showed an ANC decrease, which was attributed to increased organic acidity. Similar to recovering lakes in other regions, the increase in ANC was limited because the decrease in SO<sub>4</sub> concentrations was partially offset by a decrease in Ca concentrations. In lakes in the Adirondacks and New England from 2000 to 2010 ANC increases continued, but base cation

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