15

Liming of Sudbury Lakes: Lessons for Recovery of Aquatic Biota from Acidification

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When the pH of lakes falls to less than 6.0, many plant and animal species suffer appreciable damage (see Fig. 5.2). Many species disappear (Schindler et al. 1989). In the 1980s, there were about 19,000 lakes in Ontario with a pH less than 6 (Neary et al. 1990). Roughly one-third of these lakes are near Sudbury. They were acidified by long-term emissions of sulfur dioxide from local smelters (see Chapter 3).

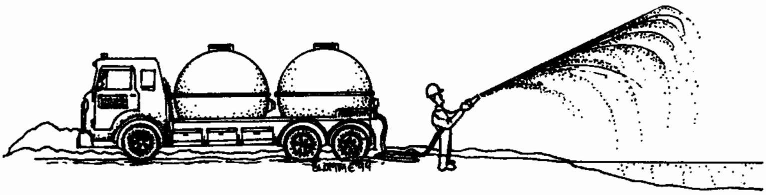
The solution to this problem is to generate less acid at the source (i.e., to reduce emissions of sulfur dioxide to the atmosphere). Neutralizing the acidity at the receptor by adding base to or "liming" entire lakes is not a solution to the acid rain problem for Ontario. It is impractical because of the large number and remoteness of the damaged lakes and the need for retreatment if inputs of acid remain elevated. Also, liming addresses only one of the problems attributable to an acidified atmosphere, the acidification of lakes.

Liming is considered a more effective part of the overall solution to the acid rain problem in other parts of the world where the problem is more advanced (Box 15.1). Those interested in the engineering and scientific aspects of liming as a management tool are encouraged to consult the recent books of Dickson (1988), Olem (1991), Olem et al. (1991), and Brocksen et al. (1992). However, this chapter has other purposes.

Although it is not a general solution to the acid rain problem, liming is warranted in some circumstances. It may be the only way to protect unique species or habitats threatened by acid rain. Chapter 11 provides an excellent example—the liming of the native habitat of the aurora trout, a unique color variant of the brook trout, *Salvelinus fontinalis*. Liming experiments can also contribute to our understanding of the factors that regulate the recovery of biota from acidification. This is particularly important at the moment because of the enormous magnitude of the programs designed to reduce sulfur dioxide emissions across North America over the next two decades (e.g., NAPAP 1993). This chapter provides a brief review of long-term liming experiments conducted in the Sudbury area, highlighting what they can teach us about the potential for the biota of acidified lakes to recover if water quality improves in response to lowered rates of acid input.

Given this objective, can liming experiments really be used in this larger context? What can the addition of base to a few polluted Sudbury lakes teach us about the future of the thousands of Canadian acidified lakes? For several reasons, liming experiments can teach us a great deal. First, liming produces water quality changes in lakes that are similar, although not identical, to those that accompany reductions in acid input (i.e., dramatic increases in lake

Box 15.1.



Lake or watershed liming studies have been carried out in many areas of the world, including Canada, the United States, Scotland, Wales, Norway, and Sweden (Olem et al. 1991); however, the largest operational liming program is in Sweden. Sweden had about 16,000 acidified lakes in the mid-1980s, most of them privately owned and accessible. Given the scale of the damage and with much pressure for solutions, it was decided to proceed with an operational liming program until the effective control of acidic deposition was achieved. Various methods are used to apply limestone directly to lakes, and in some cases, limestone is also applied to surrounding wetlands and watersheds or to streams. After lakes are initially neutralized, the strategy is to retreat them before they reacidify enough to cause damage to the biological communities that have become re-established. The Swedish government now subsidizes the repeated liming of about 6000 lakes and about 10,000 km of running water, a program that uses more than 150 million kg of limestone annually.

pH and alkalinity and decreases in toxic metals) (Yan and Dillon 1984). Second, the Sudbury liming experiments were conducted in lakes that varied widely in acidity. Because the biota of several of the limed lakes are representative of other Ontario lakes with similar acidity (Yan et al., under review), the experimental results should be broadly applicable. Finally, biological changes in limed and naturally recovering lakes have proved to be similar in the few cases in which such comparisons were possible (Keller et al. 1992a) (see Chapter 5).

Sudbury Liming Experiments

Eight whole-lake liming experiments have been conducted over the past two decades in Ontario. Seven of these lakes were in the large area (see Fig. 3.2) affected by the Sudbury smelter emissions. Between 1973 and 1976, staff of the Ontario Ministries of the Environment and Natural Resources limed Middle, Hannah, and Lohi lakes—three severely acidified, metal-contaminated lakes located close to the smelters—and Nelson Lake, an intermediately acidic, lake trout (*Salvelinus namaycush*) lake, located about 30 km from Sudbury. The objective of these experiments was to determine how the severity of damage would influence the rate of recovery of the lakes after water quality was improved (Scheider and Dillon 1976; Yan et al. 1977; Dillon et al. 1979; Yan and Dillon 1984; Gunn et al. 1988; Yan et al., under review). In the early 1980s, two new liming experiments were initiated by the Ontario Ministries of Natural Resources and Environment, with a focus on lake trout fisheries. Bowland Lake, 70 km from Sudbury, was limed in 1983 and restocked with lake trout to determine if this former lake trout lake could support a self-sustaining fishery after water quality and food web structure improved (Molot et al. 1986; Gunn et al. 1990; Jackson et al. 1990; Keller et al. 1990a,b; Molot et al. 1990a,b; Keller et al. 1992b). Trout Lake, near Parry Sound, was limed in 1984 to determine if a lake trout fishery that was threatened by acidification could be protected by liming (Howell et al. 1991). Finally, Whirligig Lake, one of the two lakes that comprise the entire native habitat of the aurora trout was limed in 1989, along with an upstream reference lake, Little Whitepine Lake, before restoring this unique trout into its native habitat (Snucins et al., in press) (see Chapter 11). Whirligig lake, 107 km north of Sudbury, was later relimed in 1993.

The eight experimental lakes spanned the full range of damage known in the Sudbury area. At one extreme were the acidic, metal-contaminated, fishless Hannah, Middle, and Lohi lakes, which had impoverished species assemblages at every level of their food webs (Dillon et al. 1979). At the other extreme were the slightly damaged Nelson and Trout lakes, which still supported fisheries at the time of liming, despite degraded water quality.

Calcium hydroxide and/or calcium carbonate were the neutralizing agents selected in all experiments. These materials are inexpensive, readily available, and for the latter agent, safe and easy to handle. They provide neutralizing substances that are normally important in the acid base chemistry of lakes. Finally, excellent dosage and treatment duration models exist for these materials (Sverdrup and Bjerle 1982; Sverdrup et al. 1984). In all cases, the base was added to the surface of the experimental lakes by boat or aircraft as a dry powder or a fine aqueous slurry (Fig. 15.1).

The investigators in each study wished to raise lake pH to near 7 and provide some residual buffering capacity. The dosages of base required to achieve these targets were calculated in various ways as the engineering of liming advanced between 1973, when Middle and Lohi lakes were limed, and 1989, when Whirligig and Little Whitepine lakes were limed. However, because the two most important parameters in the dosage calculations are the lake's volume and acidity, there is a strong negative relationship between application rate, expressed volumetrically, and the preliming pH of the study lakes (Fig. 15.2).

A detailed discussion of the changes in water quality that followed liming is beyond the scope of this review. In all cases, liming increased alkalinity and pH and decreased metal levels (e.g., Yan and Dillon 1984). The duration of effect varied dramatically from lake to lake and was influenced by the lakes' flushing rates, by input rates of acid, by rates of internal acid generation or consumption, and by any additional applications of limestone to the watersheds. For example, the pH of Nelson Lake, with its flushing rate of 10 years, is still greater than 6, 16 years after the addition of base (Fig. 15.3). By contrast, Lohi and Bowland lakes quickly re-acidified to pH less than 6, corresponding with their short flushing rates of 1 and 2.5 years, respectively. Like Nelson Lake, the pH of Middle Lake also remains greater than 6, 15 years after the additions of base, despite its short flushing rate of 1.5 years. In this case, the longevity of the treatment is mainly attributable to the liming of Hannah Lake in 1975, the lake upstream of Middle Lake, and to the liming of the catchments of Middle and Hannah lakes by the municipality of Sudbury in the early 1980s as part of land reclamation efforts (see Chapter 8).

Lessons of Liming

Viewed collectively, the liming experiments provide several general observations about biological recovery that follows reductions in the acidity of lakes:

1. rapid large elevations in pH are detrimental to the aquatic biota of acid lakes in the short term
2. rapid small increases in pH do no harm in the short term
3. biological communities can recover from excess acidity
4. rate of recovery of species is related in part to the severity of stress before liming
5. rate of recovery of species is also related to their fecundity and dispersal ability
6. several features of community recovery are directly attributable to improvements in water quality, but

FIGURE 15.1. Various lime application procedures used in Sudbury lakes: (**A**) Liming Hannah Lake in 1973 by boat and slurry pump. (Photo by Ontario Ministry of Environment.) (**B**) Liming Bowland Lake by fixed-wing aircraft in 1983. (Photo by B. A. R. Environmental.) (**C**) Liming Whirligig Lake by hand from a boat in 1989 (Photo by E. Snucins) and (**D**) by helicopter in 1993 (Photo by W. Keller.).

7. much of the recovery is only indirectly related to improvements in water quality, depending instead on a rebuilt food web

Each of these observations is discussed in turn.

Liming represents a stress to those organisms that have adapted to acid conditions. Therefore, it should come as no surprise that rapid large increases in pH are detrimental to some of the biota of acid lakes in the short term (observation 1). Yan and Dillon (1984) noted that after they raised the pH of Middle, Hannah, and Lohi lakes from 4.4 to near 7, algal biomass was depressed by an order of magnitude for several months. Further, they and Yan et al. (under review) noted that acid-tolerant zooplankton were decimated by the additions of base, leaving an extremely pecu-

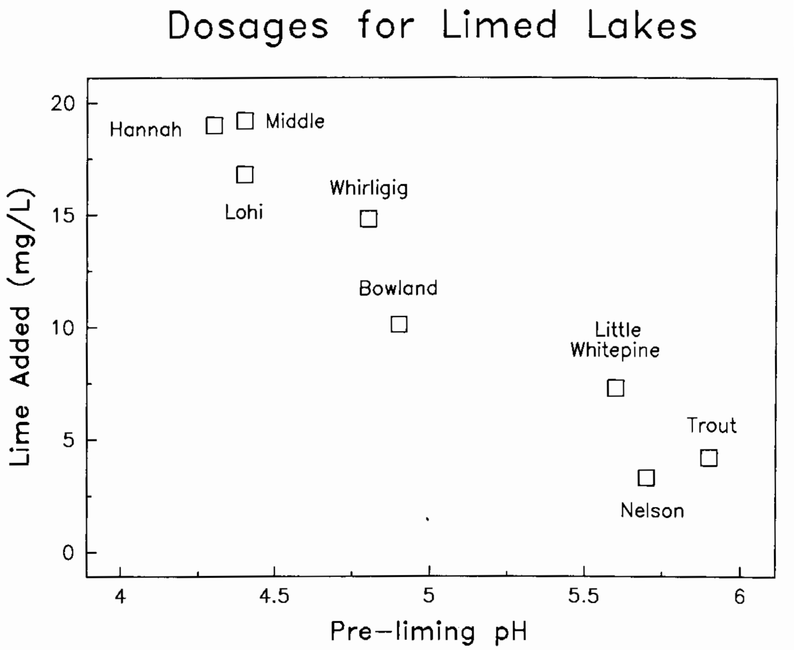


FIGURE 15.2. Scattergram of the dose of base initially applied to each lake versus the preliming pH. Note that the mass of material added per unit volume decreased with increases in pH.

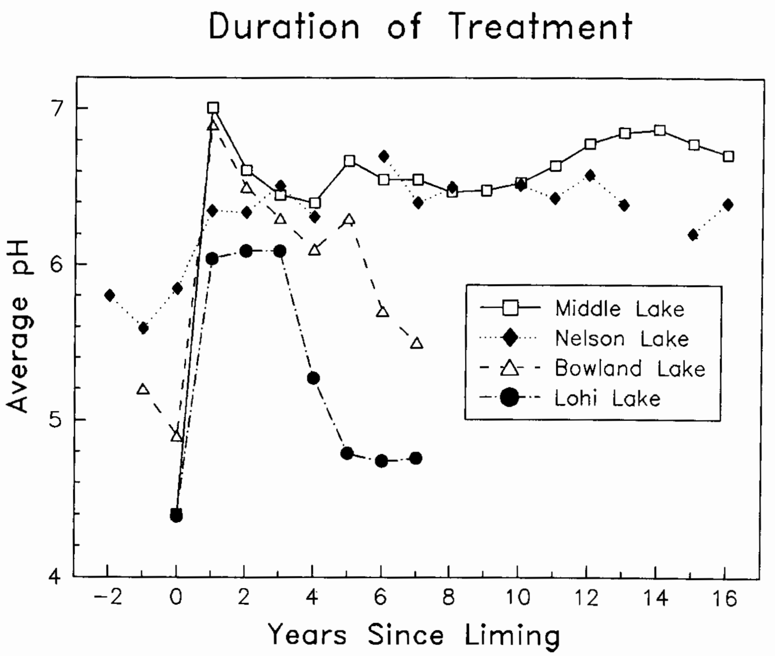


FIGURE 15.3. Changes in pH (annual average) of limed lakes before and after liming.

liar zooplankton community composed of littoral zone opportunists to dominate the lakes for almost a decade.

In contrast, smaller additions of base that produce smaller increases in pH do not harm aquatic communities in the short term (observation 2). Yan et al. (1977) raised the pH of Nelson Lake from 5.7 to 6.3 in 1975. This did not change plankton standing stocks or community structure. Molot et al. (1986) raised the pH of Trout Lake from 5.9 to 6.5 in 1984 with no discernable negative impacts on nutri-

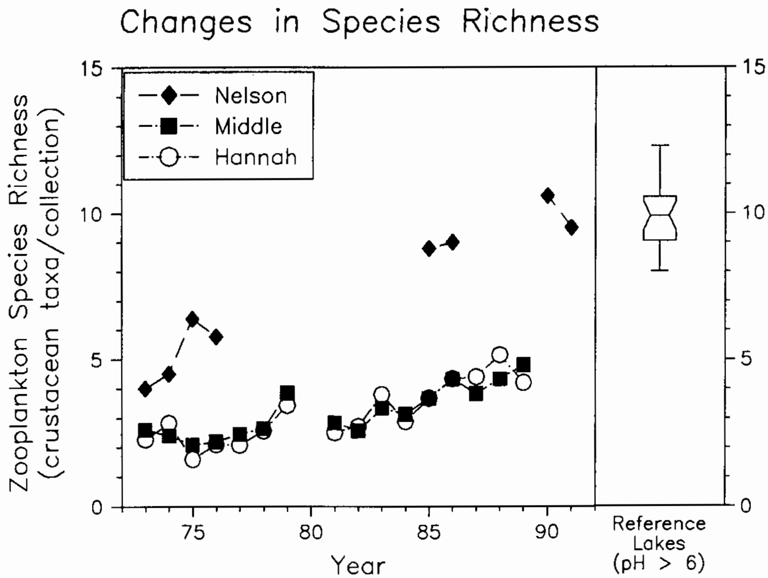


FIGURE 15.4. Recovery of zooplankton species richness in Middle, Hannah, and Nelson lakes in comparison with the expected richness in non-acidified lakes. The lakes were limed in 1973, 1975, and 1975, respectively, and have been non-acidic ever since. The notched box plot summarizes richness in the 22 reference lakes with pH greater than 6. The median richness is located at the narrowest part of the notch. The box encompasses 50% of the observations; the whiskers 99% of them.

ent regimes, phytoplankton, zooplankton, or fish (Howell et al. 1991). Finally, Yan and Dillon (1984) noted that the first liming of Lohi Lake decimated the phytoplankton, but subsequent additions that produced smaller changes in pH did not harm the community.

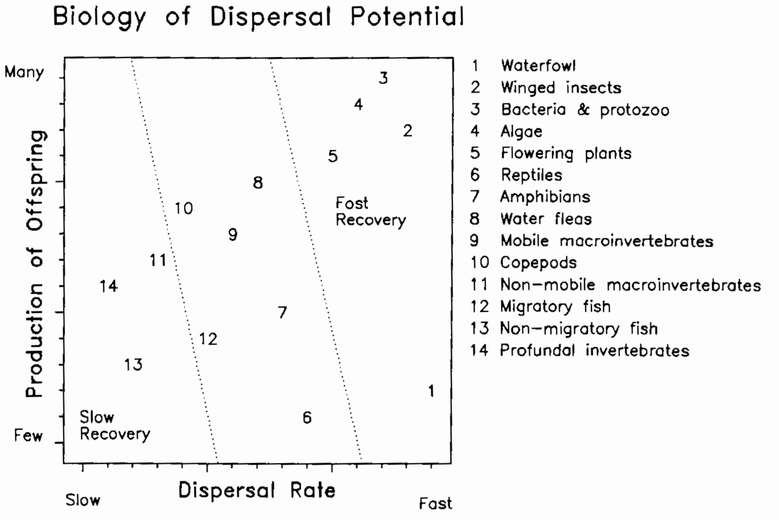
In the long term, the liming experiments clearly demonstrate that many aquatic biota can recover from acidity (observation 3). For example, in Whirligig Lake, re-introduced aurora trout are surviving and reproducing in their ancestral habitat (see Chapter 11). In Bowland Lake, stocked lake trout reproduced (Gunn et al. 1990), and communities of phytoplankton (Molot et al. 1990a), littoral algae (Jackson et al. 1990), zooplankton (Keller et al. 1992b), and some bottom-dwelling invertebrates (Keller et al. 1990b) changed in ways indicative of recovery.

The rate of recovery of aquatic biota in the liming experiments was related in part to the severity of preliming acidity (observation 4). In Nelson Lake, for example, the plankton communities returned to those characteristic of non-acidic lakes within 10 years of the addition of base. However, the zooplankton communities of the more severely stressed Middle and Hannah lakes remain impoverished in comparison with non-acidic reference lakes 16 years after the addition of base (Fig. 15.4).

The severity of acidity influences rates of recovery of biota for two reasons. First, fish exert a strong influence on the size structure and taxonomic composition of aquatic food webs. Hence, recovery of the ecosystem depends in part on the re-establishment of a normal fish community (Henrikson et al. 1985). This may take a very long time in severely acidified lakes, or it may never occur without the help of management agencies. Second, recovery must be delayed in severely acidified lakes, because many more species will have disappeared during the process of acidification (Yan and Welbourn 1990). In such cases, recolonization may be the rate-limiting step for recovery.

In fact, the liming experiments do provide evidence that the rate of recovery of different groups of biota is related to their fecundity and dispersal ability (observation 5). Educated guesses of the relative magnitude of these two parameters for various groups of aquatic and semiaquatic organisms allow estimation of the relative recovery rates of organisms from local extinction (Fig. 15.5). For example, aquatic insects with winged adult life stages should recover relatively quickly from acidification both because of the vast numbers of offspring they produce and because adult insects often fly tens of kilometers within a few days of emergence (Baldwin et al. 1975). Similarly,

FIGURE 15.5. Relative recovery potential of biota estimated from their fecundity and dispersal ability.



phytoplankton, littoral algae, bacteria, and protozoa are prolific, reproduce frequently, and disperse through the air (Maguire 1963; Parker 1970). These organisms should recover quickly as long as there are source pools in the vicinity (Cairns 1991). By contrast, non-migratory fish and profundal invertebrates such as the opossum shrimp, *Mysis relicta*, an important acid-sensitive macroinvertebrate predator (Nero and Schindler 1983), should recover very slowly from local extinction because they disperse so slowly. The distribution of the opossum shrimp in Ontario has not changed since the retreat of the glaciers (Dadswell 1974).

Although Figure 15.5 is consistent with colonization theory (Mooney and Drake 1989), the dispersal rates are so poorly known that the figure should be regarded mainly as an hypothesis generator. Nevertheless, data from the limed lakes support the ideas. In Middle and Lohi lakes, bacterial abundance increased and community composition normalized almost immediately after liming (Scheider and Dillon 1976). Phytoplankton community composition recovered many attributes of non-acidic lakes within a few years of liming (Yan and Dillon 1984). By contrast, although there are promising signs of recovery, zooplankton community composition remains unusual in the lakes 15 years after the addition of base (see Fig. 15.4). Similarly in Bowland Lake, filamentous algae responded immediately to liming (Jackson et al. 1990), rotifers responded within 1 year, but crustacean zooplankton communities did not resemble those of non-acidic lakes 4 years after additions of base (Keller et al. 1992b).

Some features of biological recovery in the experimental lakes were directly attributable to improvements in water quality (observation 6). Examples include the increase in abundance of the opossum shrimp in Trout Lake (Howell et al. 1991), the recruitment of stocked bass (*Micropterus dolomeiui*) in Nelson Lake (Gunn et al. 1988) and lake trout in Bowland Lake (Gunn et al. 1990), the reappearance of acid-sensitive plankton species in Bowland Lake (Molot et al. 1990a; Keller et al. 1992b), and the recolonization of Middle and Hannah lakes by the acid-sensitive (Keller et al. 1990c) water flea, *Daphnia galeata mendotae* (Yan et al., under review). Because changes such as these depend only on the restoration of water quality they augur well for the remainder of Ontario's acid lakes, as long as seed populations of the biota are available.

Other community changes in the limed lakes are not directly attributable to water quality improvements, rather they are indirect effects of changes in food webs, which may themselves be directly related to additions of base (observation 7). For example, Howell et al. (1991) thought that increased growth of lake trout in Trout Lake after liming was attributable to increased availability of invertebrate prey, which was itself directly attributable to liming. Although the appearance of new zooplankton species in Bowland Lake was probably a direct consequence of water quality improvements, changes in zooplankton abundance were a complex product of annual variability in vertebrate and invertebrate predation pressure and the water temperature (Keller et al. 1992b). These sorts of changes, which are dependent on complex interactions in food webs, are more difficult to generalize beyond the experimental lakes.

Conclusions

The recovery of organisms from stress is influenced by many factors. These include the severity and duration of stress, the condition of the habitat after removal of the stress, the presence of refuges, the availability of colonists, their productivity and dispersal ability, and barriers to their dispersal (Cairns 1990; Niemi et al. 1990; Detenbeck et al. 1992). Management agencies can also directly increase rates of recovery by re-introducing locally extinct species or manipulating damaged habitats. With such complexity, it is not surprising that restoration ecology is a science in its infancy. At the moment, rates or patterns of aquatic community recovery cannot be predicted with certainty, because of the complexity of the science, the paucity of theoretical frameworks, and the scarcity of experiments designed to test hypothetical regulators of recovery from long-term stressors such as acidification (Niemi et al. 1990). Studies of recovery of experimentally acidified lakes, such as those of Lake 223 in northwestern Ontario (see Box 5.1), will be extremely useful to this field in years to come if they are continued (Schindler et al. 1991).

The Sudbury liming experiments can contribute to the emerging discipline of restoration ecology in several practical ways. First, the liming experiments have provided approaches to setting recovery targets. For example, Keller et al. (1992b) and Yan et al. (under review) used reference data sets from non-acidified lakes to determine the normal temporal and spatial variability in zooplankton communities characteristic of "healthy" communities. Second, liming experiments provide insights about required durations of study. Two decades have not been enough for the zooplankton of Middle and Hannah lakes to recover but were adequate for the less severely affected community of Nelson Lake (see Fig. 15.4). Third, as previously discussed, these experiments provide insight about the role of the severity of the stress and dispersal ability of species for biological recovery. These are two of the hypothesized regulators of recovery. Finally, the experiments can identify predictable aspects of recovery. Those changes that we can attribute directly to improving water quality are probably most predictable, and they occur at the top and bottom of food webs. At the bottom, bacteria, phytoplankton, and littoral algae respond rapidly and directly to water quality improvements alone. At the top, the recruitment of piscivores (from relict adult or restocked populations) also responds directly to the improved water quality in spawning habitats. Changes in the middle of the food web are more difficult to predict because they are influenced by both direct and indirect regulators of recovery. Unfortunately, our understanding of the acid-sensitivity of most species is too poor (Locke 1991) and food web linkages are too complex to predict whether direct or indirect effects will predominate in the recovery of most biota in individual lakes.

The management of lakes in North America owes a great deal to whole-lake manipulation experiments. They have provided many insights into the impacts of pollutants on ecosystem function that smaller-scale experiments could not provide, and they have provided crucial tests of competing hypotheses with enormous management implications (e.g., Schindler 1990). It is expected that atmospheric emissions of sulfur dioxide will decline substantially in North America during the next 20 years, as Canadian and American governments attempt to reduce the acidity of our atmosphere. As we endeavor to predict the benefits of these programs, the Sudbury liming experiments of the 1970s and 1980s will provide some of the best models of the recovery of lakes from acidification.

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