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Recovery of Acidified Lakes: Lessons From Sudbury, Ontario, Canada

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Abstract Over 7,000 lakes around Sudbury, Ontario, Canada were acidified by S deposition associated with emissions from the Sudbury metal smelters and more distant S sources. Air pollution controls have led to widespread changes in damaged Sudbury lakes, including increased pH and decreased concentrations of SO_4, metals and base cations. While chemical improvements have often been substantial, many lakes are still acidified, although water quality recovery is continuing. Biological recovery has been observed in some lakes among various groups of organisms including fish, zooplankton, phytoplankton and zoobenthos. Generally, however, biological recovery is still at an early stage. Lakes around Sudbury are also showing that the recovery of acid-damaged lakes is closely linked to the effects of other major environmental stressors such as climate change, base cation depletion and UV-B irradiance. Future studies of the recovery of acid-damaged lakes around Sudbury, and in other regions, will need to consider the interactions of these and other stressors.

Keywords acidification · lakes · recovery · Sudbury · sulphur · stressors · interaction

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1 Introduction

Metal mining and smelting began in the Sudbury, Ontario, Canada, area before the turn of the twentieth century, and the area grew into one of the largest metal-producing complexes in the world. Smelter emissions peaked during the 1960s, when the Sudbury area smelters constituted one of the world's largest point sources of SO_2 emissions. Thousands of tons of metal particulates have also been emitted from the Sudbury smelters over the years. Lakes in a large area of northeastern Ontario were severely affected by the atmospheric deposition of contaminants originating from the Sudbury smelter emissions. Over 7,000 lakes within a 17,000 km^2 area (Fig. 1) were acidified to pH<6.0, the point at which significant biological damage is expected (Neary, Dillon, Munro, & Clark, 1990). The lakes most severely damaged were those located within about 20–30 km of the smelters, where acid conditions were combined with very high concentrations of potentially toxic trace metals, especially Cu and Ni.

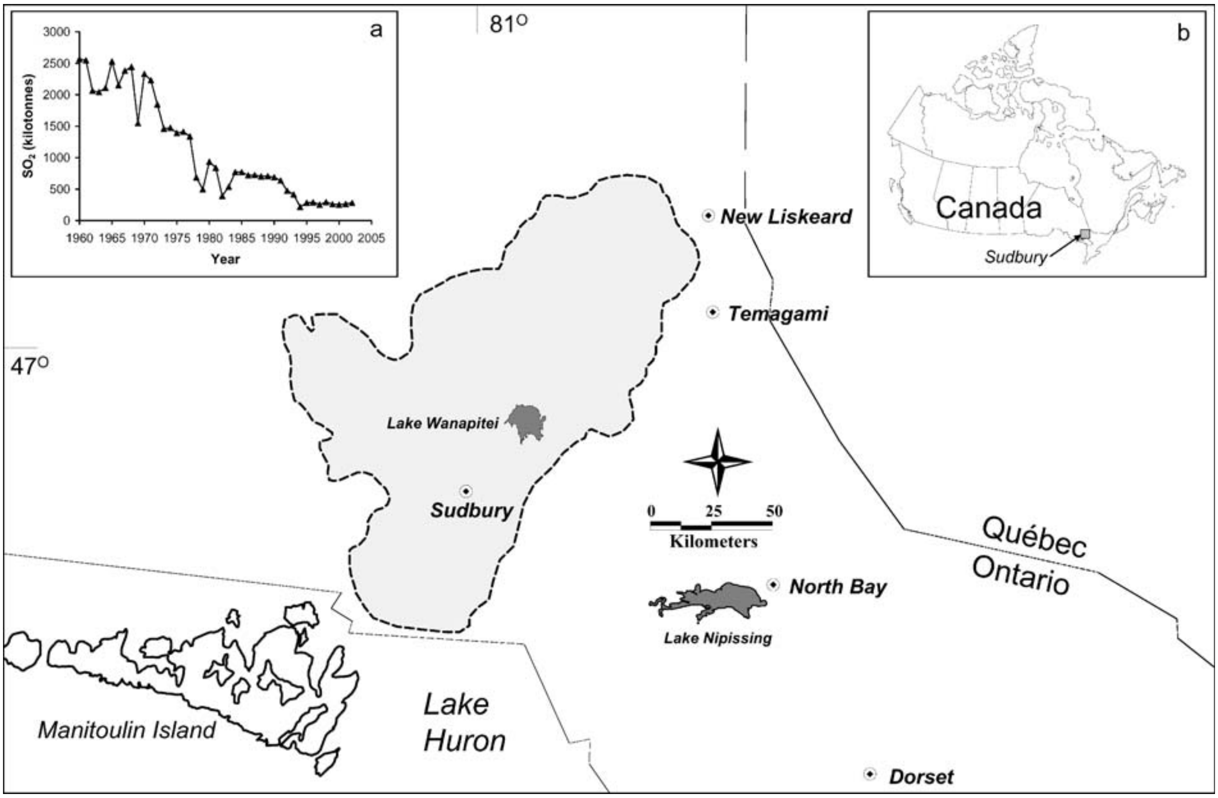

Fig. 1 The 17,000 km^2 zone of effect on lakes around Sudbury (*Inset* **a**, SO_2 emissions from the Sudbury area smelters; *Inset* **b**, the location of Sudbury, Ontario, Canada)

However, much has changed in the aquatic ecosystems around Sudbury. As emissions of SO_2 and metals were dramatically reduced during the 1970s (Fig. 1), large improvements in lake water quality were observed in the surrounding area (Keller & Pitblado, 1986; Keller, Pitblado, & Carbone, 1992) and biological improvements began to follow (Gunn & Keller, 1990; Havas et al., 1995; Keller & Yan, 1991). Large additional decreases in SO_2 emissions were achieved by 1994 (Fig. 1). Overall, reductions in SO_2 and metal emissions of about 90% have been achieved in recent decades. This paper presents long-term trends in the chemistry of Sudbury lakes and examines the physical, chemical and biological factors that may influence lake recovery processes.

2 Changes in Lake Chemistry

Large changes in lake chemistry followed the reductions of SO_2 emissions that occurred during the 1970s, including increased pH and alkalinity and decreased concentrations of SO_4, base cations and metals (Gunn & Keller, 1990; Keller, Dillon, Heneberry, Malette, & Gunn, 2001b; Keller, Dixit, & Heneberry, 2001a; Keller, Heneberry, & Dixit, 2003; Keller, Heneberry, & Gunn, 1999a; Keller & Pitblado, 1986; Keller et al., 1992). Changes continued in the 1990s, during which additional pollution controls were implemented at the Sudbury smelters. Sulphate concentrations declined greatly during this period, following substantial declines in earlier years (Keller & Pitblado, 1986). The strong relationship between SO_4 and distance from Sudbury observed in previous surveys (Keller & Pitblado, 1986) had become much weaker by 2004 (Fig. 2), and most Sudbury area lakes now have SO_4 concentrations similar to reference lakes near Dorset, ~200 km to the southeast.

In response to reduced S deposition, substantial increases in the pH of acidified Sudbury lakes have been observed. In a set of 44 acidic lakes monitored since 1981, the number of highly acidic lakes ($pH < 5.0$) declined from 28 to 6 by 2004 (Fig. 3). None of this set of study lakes were non-acidic in 1981; by

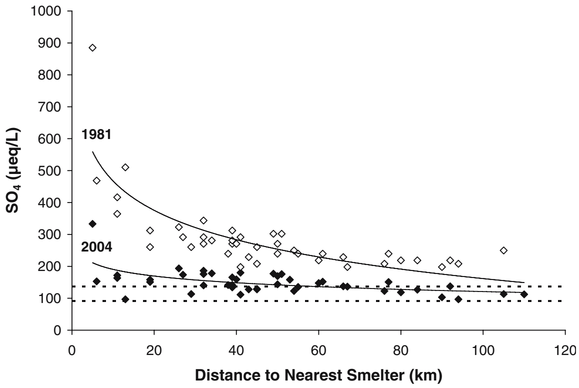

Fig. 2 Sulphate concentrations in lakes as a function of distance from Sudbury smelters in 1981 and 2004. The range of recent (1998–2001) SO_4 concentrations in 42 lakes near Dorset, ~200 km southeast of Sudbury, is indicated by the *dashed horizontal lines*

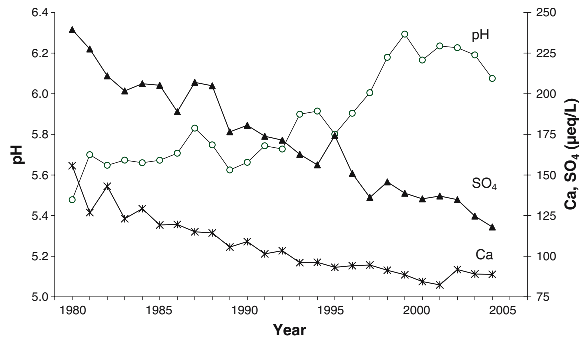

Fig. 4 Long-term changes in pH, SO_4 and Ca in Whitepine Lake, 89 km north of Sudbury

2004, 14 of the lakes had pH>6.0, a level sufficient for protection of most acid-sensitive aquatic biota (Neary et al., 1990). Decreases in SO_4 concentrations have, however, been partially balanced by decreases in base cation concentrations as well as decreased acidity. Examples of the temporal changes in SO_4, Ca and pH in one key long-term monitoring lake are shown in Fig. 4.

Substantial declines in concentrations of metals originating from the smelters (eg. Cu, Ni) and from acid-leaching of watersheds (eg. Al, Mn) have also occurred in Sudbury lakes. Concentrations of smelter-related metals, such as Ni, are now only substantially elevated in lakes within about 20–30 km of the Sudbury smelters (Keller et al., 1999a). Concentrations of metals related to watershed acidification, particularly Al, are still elevated in some lakes, notably the lakes that are still most acidic (pH vs. total Al: $r=0.77$, $p<0.05$; 44 lakes sampled in 2004; range in total Al 12–386 μg/l).

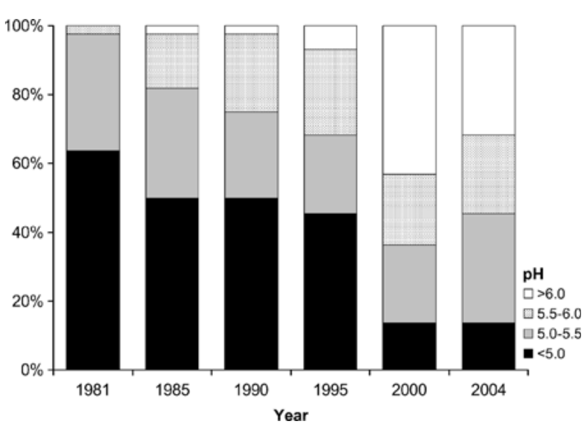

Fig. 3 Distribution of pH in 44 Sudbury lakes in surveys conducted between 1981 and 2004

While dramatic changes in lake chemistry have accompanied emission reductions, temporal patterns in lake chemistry cannot simply be attributed to the direct effects of pollution controls. Weather patterns have a profound effect on long term patterns in lake chemistry (Schindler, Curtis, Parker, & Stainton, 1996), as has been observed in the Sudbury area (Keller et al., 1992). Drought can lead to oxidation of stored S in lake catchments. When wet conditions resume, the release of this stored acidity can lead to lake re-acidification and many related physical and chemical changes including metal mobilization, changes in thermal structure, and increased UV-B penetration (Yan, Keller, Scully, Lean, & Dillon, 1996a). Such effects were observed in Sudbury area lakes following the 2-year drought of 1986–87 (Keller et al., 1992; Yan et al., 1996a) and had large impacts on zooplankton and phytoplankton communities in Swan Lake (Arnott, Yan, Keller, & Nicholls, 2001). Some of the recent changes in the chemistry of Sudbury lakes may still reflect recovery from this drought-induced acidification event. Recent changes may also, in part, still be a continuation of the general long-term recovery of lakes and watersheds that began decades ago in the Sudbury area.

3 Biological Recovery

Lakes in the large zone affected by the Sudbury smelter emissions are showing substantial evidence of biological recovery (Findlay, 2003; Holt & Yan, 2003; Keller, Gunn, & Yan, 1999b; Keller & Yan, 1998; Keller, Yan, Somers, & Heneberry, 2002; Snucins, 2003). Populations of a number of acid and/or metal-sensitive invertebrate species, including many common crustacean zooplankters such as *Daphnia mendotae*, *Skistodiaptomus oregonensis*, *Epischura lacustris*, and *Eubosmina longispina* have been observed to recolonize some lakes (Keller & Yan, 1991; Keller et al., 2002; Yan, Keller, Somers, Pawson, & Girard, 1996b). While zooplankton communities in some lakes have shown recovery, in most cases they are not yet completely similar to communities in non-acidic reference lakes (Keller et al., 2002; Yan et al., 2004; Yan et al., 1996b). Copepods appear to have recovered to a greater degree than cladocerans (Yan et al., 2004). Colonization by acid-sensitive benthic invertebrates, including amphipods and mayflies has also been observed in recovering lakes (Snucins, 2003).

The phytoplankton community of Clearwater Lake, one of the most highly affected Sudbury lakes in the 1970s, has now become similar to communities of near-neutral, more pristine lakes on the Precambrian Shield (J. Winter, unpublished manuscript). Evidence of recovery of phytoplankton communities has also been observed in other Sudbury area lakes (Findlay, 2003; Nicholls, Nakamoto, & Keller, 1992). Increased diversity and a shift away from dominance by dinoflagellates to increased importance of acid-sensitive chrysophytes has been a common pattern during the recovery of phytoplankton communities.

The process of biological recovery from acidification is very complex (Keller et al., 1999b; Keller & Yan, 1998; Yan et al., 2003). It involves the interplay of biological, chemical, and physical factors that control the arrival and success of colonists (Fig. 5). The rate and extent of biological recovery in Sudbury lakes appear to be related to both the initial severity of damage and continuing habitat limitations. Invertebrate community recovery in severely affected Sudbury lakes, even lakes that have maintained near-neutral conditions for many years, is still limited. Elevated lakewater concentrations of metals, and metal-contaminated sediments, undoubtedly still affect aquatic communities in some lakes close to the Sudbury smelters. For example, within ~20 km of Sudbury, concentrations of Cu and Ni often greatly exceed Ontario government water quality objectives for protection of aquatic life (5 and 25 µg/l, respectively), and severe effects guidelines for sediments (110 and 75 µg/g, respectively).

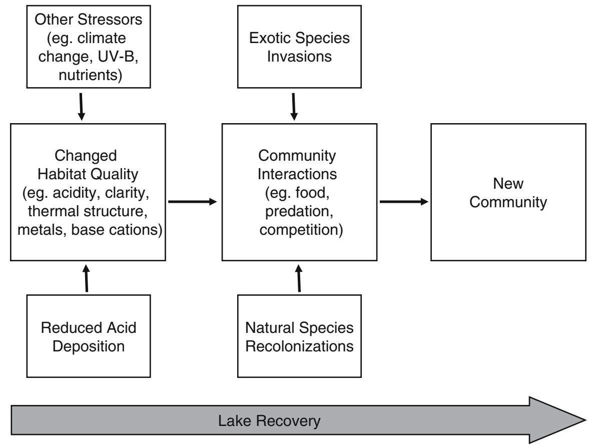

Fig. 5 Relationships between some factors influencing the recovery of lakes from acidification

Nickel, in particular, has been implicated as the contaminant most responsible for sediment toxicity to the amphipod *Hyalella* in lakes within the City of Sudbury (Borgmann, 2003). Elevated waterborne metal concentrations are a likely explanation for the lack of recovery of cladoceran zooplankton in Middle Lake, in Sudbury (Yan et al., 2004). In Middle Lake (Yan et al., 2004) and in Whitepine Lake (Keller et al., 2002) a number of new zooplankton species appeared sporadically, but did not become successfully established, suggesting that habitats had not sufficiently recovered at the time of invasion. These included *D. mendotae*, *Daphnia retrocurva*, and *S. oregonensis*, in Whitepine Lake and *Holopedium gibberum*, *Daphnia dubia*, *Daphnia longiremis*, *Daphnia pulex*, *D. retrocurva* and *Eubosmina tubicen* in Middle Lake.

Biological as well as chemical factors may have a large influence on the recovery of aquatic communities from acidification. For example, in cases where the elimination of fish has resulted in zooplankton communities controlled by invertebrate predators, zooplankton communities are not likely to recover without the re-establishment of planktivorous fish populations (Keller et al., 2002). Fish are also expected to have direct effects on community recovery as residual fish populations expand and new fish species become established through natural invasions, or through intentional or unintentional introductions. In particular, the ongoing northward expansion of smallmouth bass (*Micropterus dolomieu*) populations in Ontario, which will likely be enhanced under a warming climate, has large implications for aquatic systems (Vander Zanden, Wilson, Casselman, & Yan, 2004) and hence for the recovery of aquatic communities in Sudbury area lakes. Smallmouth bass are important predators on planktivorous fish, which in turn affect planktonic food webs. The simple fish communities occurring early in the recovery of some Sudbury lakes are often dominated by large populations of stunted yellow perch (*Perca flavescens*). Heavy predation by perch may be a factor inhibiting the recovery of cladoceran zooplankton communities (Yan et al., 2004).

The dispersal of species is also an important part of the recovery process. However, the eventual appearance of many common crustacean zooplankton species in long-term lake records (Keller & Yan, 1991; Keller et al., 2002; Yan et al., 2004; Yan et al., 1996b) suggests that dispersal will not be a major control on zooplankton recovery in the long term. Dispersal will also probably ultimately depend largely on time for many other invertebrates. With enough time many invertebrate species can reasonably be expected to naturally colonize recovering Sudbury lakes. This expectation is supported by a number of examples of effective dispersal by zooplankton, phytoplankton and benthic invertebrate species to lakes in the Sudbury area that did not have residual populations (Pollard, Colbourne, & Keller, 2003; Watson, Hunt, & Keller, 1999).

4 Factors Complicating Lake Recovery

The effects of large-scale stressors including climate change, UV-B irradiance, and acidification are linked (Yan et al., 1996a), and these and other ecosystem interactions will affect lake recovery processes (Fig. 5). Biological recovery will be affected not just by lake chemistry, but by the sometimes dramatic physical changes such as altered transparency and thermal regimes that accompany chemical recovery. Drought-induced re-acidification episodes may set back biological recovery (Arnott et al., 2001). Effects of climate change may interact with changes in acidity and resultant changes in lake clarity to affect lake thermal structure (Keller, Heneberry, & Leduc, 2005; Yan et al., 1996a). As well, expansions of some non-indigenous species may be promoted by climate change with resultant effects on recovering aquatic communities (Vander Zanden et al., 2004). Calcium declines could alter distributions of some Ca-rich biota, and increase the sensitivity of some organisms to acid, metals or UV-B (Keller et al., 2001a). These are just some of the ways that the recovery of lakes from acidification may be affected by stressor interactions. Future studies of lake recovery will need to be done within a multiple stressor framework.

5 Conclusions

Lakes in the Sudbury area provide one of the best examples in the world of the environmental benefits of SO_2 emission controls. However, despite dramatic water quality improvements, some Sudbury lakes are still acidic and metal-contaminated. Much evidence of biological recovery is emerging for many groups of aquatic biota including zooplankton, phytoplankton, benthic invertebrates and fish. However, severely damaged biological communities have often been slow to recover, in part reflecting continuing habitat quality limitations. Future recovery of Sudbury lakes from acidification and metal contamination will also be influenced by the effects of other regional (eg. arrival of invasive species) and global (eg. climate change) factors.

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