# 5

# Lake Water Quality Improvements and Recovering Aquatic Communities

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In the remote areas to the northeast and southwest of Sudbury, the environmental damage is less visible than in the denuded landscapes near the smelters but is no less severe. These hilly forested areas, underlain by granitic bedrock (Fig. 5.1), contain most of the more than 7000 lakes estimated to have been damaged by smelter emissions (see Fig. 3.2).

Perhaps the most striking example of biological damage to these lakes is the loss of sportfish species, such as lake trout (*Salvelinus namaycush*), brook trout (*S. fontinalis*), walleye (*Stizostedion vitreum*), and smallmouth bass (*Micropterus dolomieui*) (Beamish and Harvey 1972; Matuszek et al. 1992). Most of Ontario's estimated sportfish losses from acidification occurred in this area (Matuszek et al. 1992). In fact, excluding the losses of Atlantic salmon (*Salmo salar*) from Nova Scotia rivers (Watt et al. 1983), almost all Canada's well-documented cases of fisheries losses from acidification are in the Sudbury area (Kelso et al. 1990). However, a century of industrial emissions has resulted in far more extensive biological damages than the loss of sportfish. Losses of acid or metal-sensitive species, leading to reduced community richness, occurred for organisms at various aquatic trophic levels, including zooplankton (Sprules 1975; Keller and Pitblado 1984), phytoplankton (Kwiatkowski and Roff 1976; Nicholls et al. 1992), and benthic invertebrates (Roff and Kwiatkowski 1977). Effects of acidification on waterfowl (see Chapter 16) and amphibians (Glooschenko et al. 1992) have also been reported for the area.

A simplified illustration of some of the biological changes that occur in a typical Sudbury lake between pH 5.0 and 6.0 is provided in Figure 5.2.

## A New Question—Reversibility

More than 35 years ago, Gorham and Gordon (1960) began scientific studies of lakes and ponds near Sudbury. Since then, a vast amount of information has been collected that clearly established the damaging effects of smelter emissions on the chemistry and biology of water bodies. This information has been widely used nationally and internationally in the debate for cleaner air. In recent years, research findings from studies of Sudbury lakes have been used to answer another controversial question: Are acidification damages reversible?

In the 1970s, there was uncertainty, which continues to some degree, whether acidified lakes would recover without the addition of lime or other artificial sources of alkalinity. It was assumed that the acid-neutralizing capacity of watershed soils, once exhausted, could not recover or that the renewal of buffering capacity through the geochemical weathering

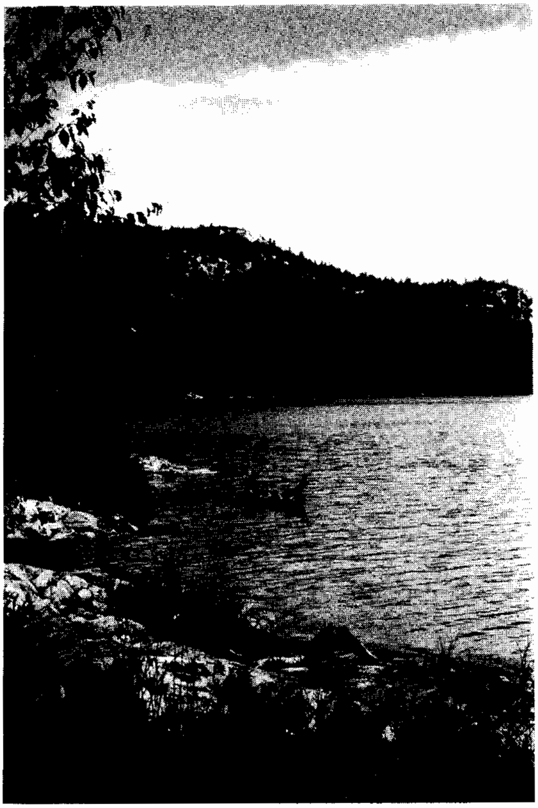


FIGURE 5.1. Acidified lake within the area affected by the Sudbury smelter emissions. (Photo by W. Keller.)

of watershed minerals would take a very long time (Barth 1987; Steinburg and Wright 1994).

Recent studies, however, have shown that some natural systems are highly resilient and can recover rapidly. It appears that the buffering capacity of many acidified aquatic systems was overloaded, not exhausted.

## Lake Chemistry

The condition of lakes around Sudbury has been improving in response to declining emissions (Fig. 5.3) at the smelters. Results from detailed studies of individual lakes (LaZerte and Dillon 1984; Hutchinson and Havas 1986; Gunn and Keller 1990) as well as extensive survey data (Keller and Pitblado 1986; Keller et al. 1992b) have demonstrated this trend. These observed chemical changes have provided probably the best direct evidence in the world that abatement programs not only protect sensitive systems but allow for the recovery of damaged ecosystems (Wright and Hauhs 1991). The box inserts in this chapter (Boxes 5.1 and 5.2) provide some experimental evidence from lake and watershed manipulation studies supporting the findings of lake monitoring programs in the Sudbury area.

Figure 5.4 illustrates some of the general chemical trends observed in remote Sudbury lakes since the mid-1970s. As emissions of sulfur dioxide declined (see Fig. 5.3), lakes have shown marked increases in pH and alkalinity and declines in sulfate. Reduced acidic deposition has also reduced the mineral leaching of watershed soils, resulting in reductions in calcium and magnesium concentrations in lake waters. Very similar results have been reported from a regional survey of lakes in southwestern Scotland (Battarbee et al. 1988) and from Nova Scotia and Newfoundland rivers (Thompson 1987) after reductions in acid deposition.

Reductions in the degree of metal contamination of lake waters (Keller and Pitblado

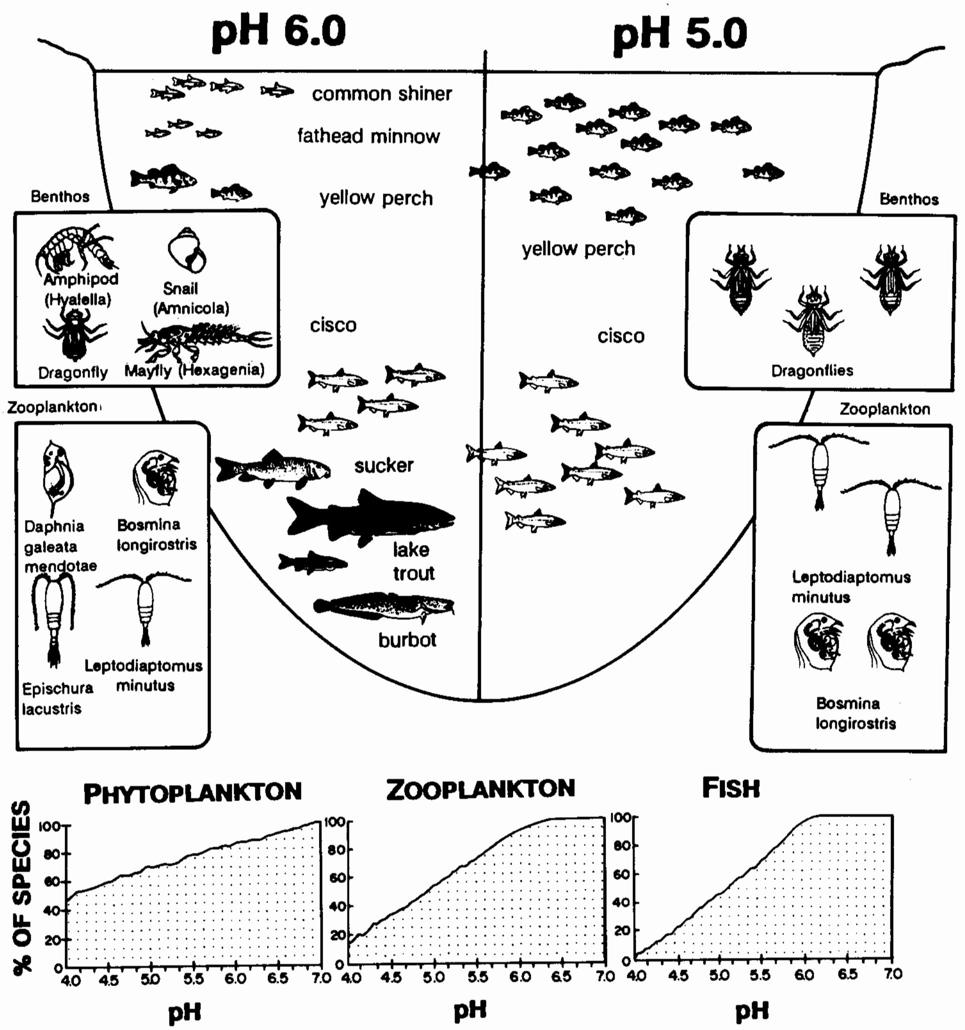



**FIGURE 5.2.** Simplified illustration of some of the biological changes that accompany lake acidification. Patterns shown are based on findings from Sudbury area studies and the general literature. The dominant trend is the loss of acid-sensitive species at various aquatic trophic levels, leading to an impoverished community.

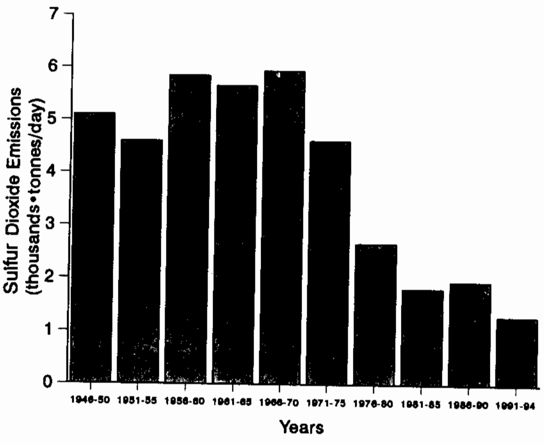
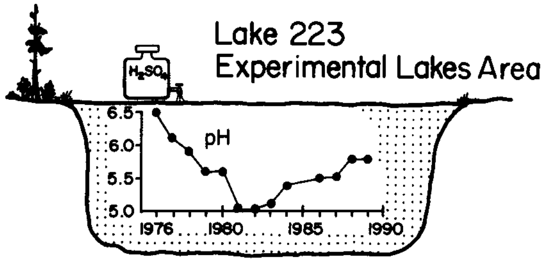



**FIGURE 5.3.** Average daily sulfur dioxide emissions for metal smelters in the Sudbury area for 5-year intervals beginning in the mid-1940s. The final interval is an average for 1991–1994 using projected emissions of 1000 tonnes/day for 1994.

*Box 5.1.*



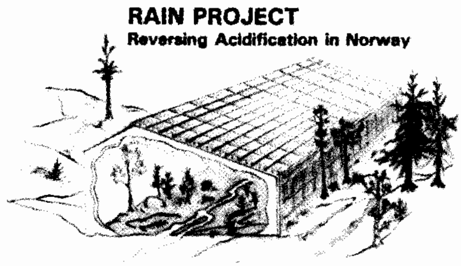

The whole-lake manipulation experiments at Canada's Experimental Lakes Area in northwestern Ontario have provided an important demonstration of acidification effects and the recovery potential of damaged lakes (Schindler et al. 1991). By direct addition of sulfuric acid to the water column of Lake 223, the pH of the lake was progressively reduced from 6.5 in 1976 to 5.0 in 1981. Since then, pH has been allowed to increase steadily. Researchers were initially surprised by the amount of acid needed to acidify the system. Significant internal alkalinity generation was occurring through the activities of sulfate-reducing bacteria. The experimental acidification produced biological responses that were remarkably similar to effects observed in Sudbury and other areas of high-acid deposition. Algal mats appeared, and sensitive species such as crayfish (*Orconectes virilis*), slimy sculpins (*Cottus cognatus*), opossum shrimp (*Mysis relicta*), and fathead minnows (*Pimephales promelas*) disappeared. Reproductive failure occurred among lake trout at pH 5.6 and white suckers at pH 5.0. The recovery part of the experiment continues, but preliminary results indicate that many of the adverse effects are being eliminated as the water quality improves (K. Mills, Canadian Department of Fisheries and Oceans, Winnipeg, Manitoba, *personal communication*).

1986; Fig. 5.4) and surficial sediments (Nriagu and Rao 1987) have also been reported. The changes in concentrations of potentially toxic metals deposited by the atmosphere have been most dramatic near the smelters, where concentrations of nickel and copper are highly elevated. Concentrations of aluminum and manganese, metals abundant in soils, have generally decreased in lake waters as the acid leaching of watersheds was reduced and the pH of acidic lakes increased (Keller et al. 1992b).

Although the general chemistry trends since the 1970s reflect improvement, these trends leveled off by the mid-1980s as emissions stabilized, confirming the link between pollution abatement and environmental recovery. In the late 1980s, many lakes actually showed a reversal of the pattern of recovery; a decline in water quality, probably caused by climatic factors, occurred after 1987 (Fig. 5.4; Keller et al. 1992b). It appears that extensive storage and oxidation of sulfur occurred in lake watersheds during the very dry years of 1986 and 1987. After abundant precipitation in 1988, lake pH values decreased somewhat as sulfate concentrations increased, apparently in response to high sulfur and acid exports from lake watersheds. Further details of the mechanism of sulfur storage and release are provided in Chapter 24.

Nevertheless, despite weather-related fluctuations and the stabilization of emissions, the overall chemistry pattern through the late 1970s and the 1980s demonstrates dramatic improvements in water quality. This greatly

*Box 5.2.*




Domed cities may be a far-fetched solution to survival in a contaminated atmosphere, but greenhouses or other such shelters are often used to conduct controlled experiments on the effects of acidic precipitation. In Norway, researchers conducted a unique experiment in which the greenhouses were moved to the site with the soil and plants rather than vice versa (Wright et al. 1988). In a long-term experiment funded by Norwegian, Swedish, and Canadian environmental agencies, scientists from the RAIN (Reversing Acidification in Norway) project altered the chemical composition of precipitation falling on small experimental watersheds. Using covered and uncovered watersheds, sprinklers, irrigation systems, and snow-making machines, a variety of experiments were conducted: (1) sulfuric acid addition to a pristine site; (2) 1:1 mixture of sulfuric and nitric acid addition to a pristine site; (3) acid removal from a contaminated site; and (4) control watersheds, with and without greenhouses. These experiments showed that acid precipitation led to the rapid leaching of base cations (e.g., calcium, magnesium) and toxic forms of aluminum from watershed soils. Reduction in acid inputs reduced these effects. The RAIN project continues to generate important findings on recovery rates and processes. A similar approach is now also being used to assess the effects of other atmospheric contaminants such as carbon dioxide.

expanded the potential resource base of acid-sensitive species such as lake trout (Fig. 5.5). However, the restoration of aquatic systems around Sudbury is still at an early stage. Many lakes remain acidic and metal-contaminated. Some lakes more than 100 km from Sudbury are still highly acidified, with pH less than 5.0. Highly elevated concentrations of copper and nickel are currently restricted to nearby lakes. However, within about 20 km of Sudbury, concentrations of these metals in most lakes exceed suggested safe values for the protection of fish and other aquatic life (see Chapter 20).

## Biological Recovery

Observations of biological improvements in Sudbury lakes have been steadily mounting (Keller et al. 1992a). These findings are very important, because the protection/restoration of aquatic communities is a major objective of emission abatement programs.

### Algae

Fossil records of algal remains in sediments provide clear evidence of the rapid recovery of planktonic diatoms and chrysophytes with increased pH and reduced metal levels in Sudbury lakes (see Chapter 3). Examination of the changes in phytoplankton community composition in lakes sampled in the mid-1970s or early 1980s, and again in the mid-1980s, also indicates that positive responses of phytoplankton communities have accompanied water quality improvements (Nicholls et al. 1992). Examples of the changes in phytoplankton community richness observed in several of these lakes are shown in Figure 5.6.

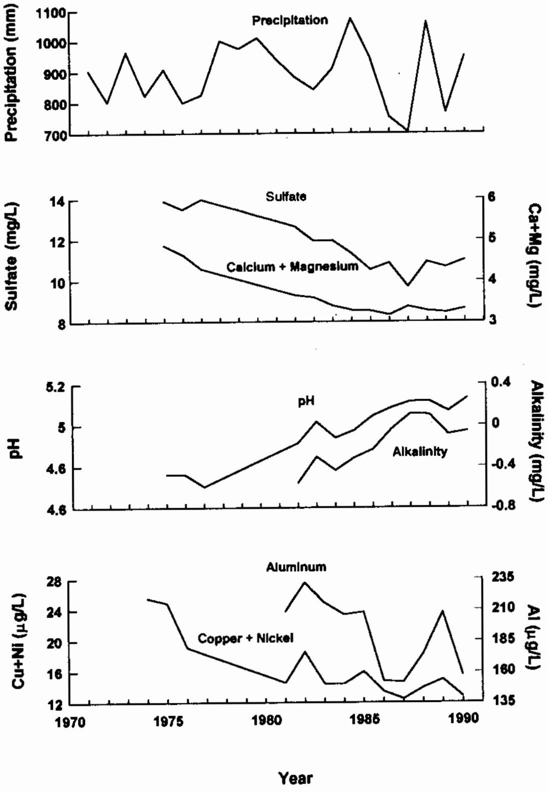



**FIGURE 5.4.** Time trends in lake chemistry as Sudbury area smelter emissions declined. Values for chemical characteristics are annual averages for a group of seven acidic lakes distant (48–105 km) from Sudbury but within the zone of smelter influence. Total annual precipitation is also shown.

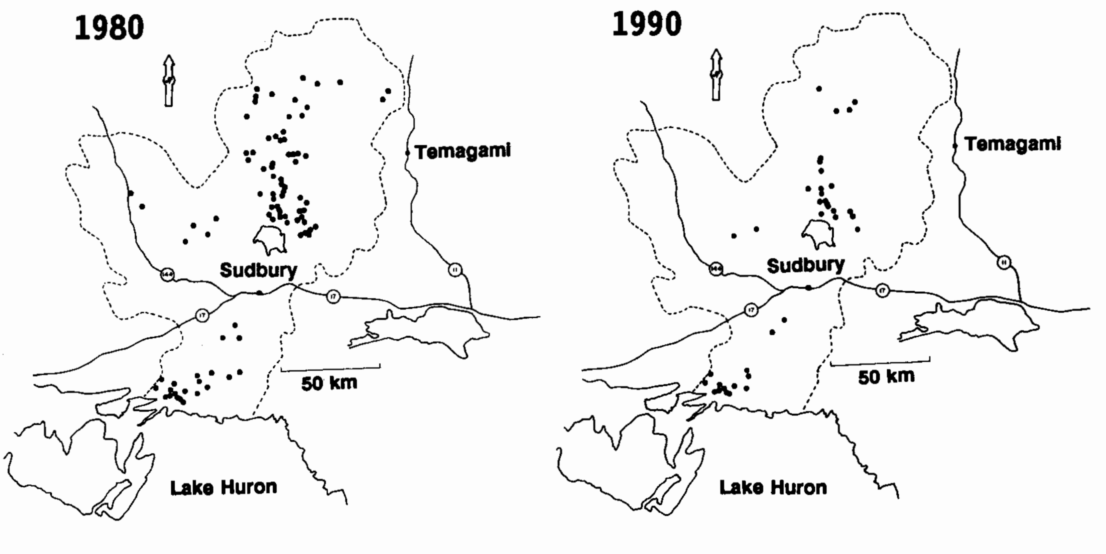
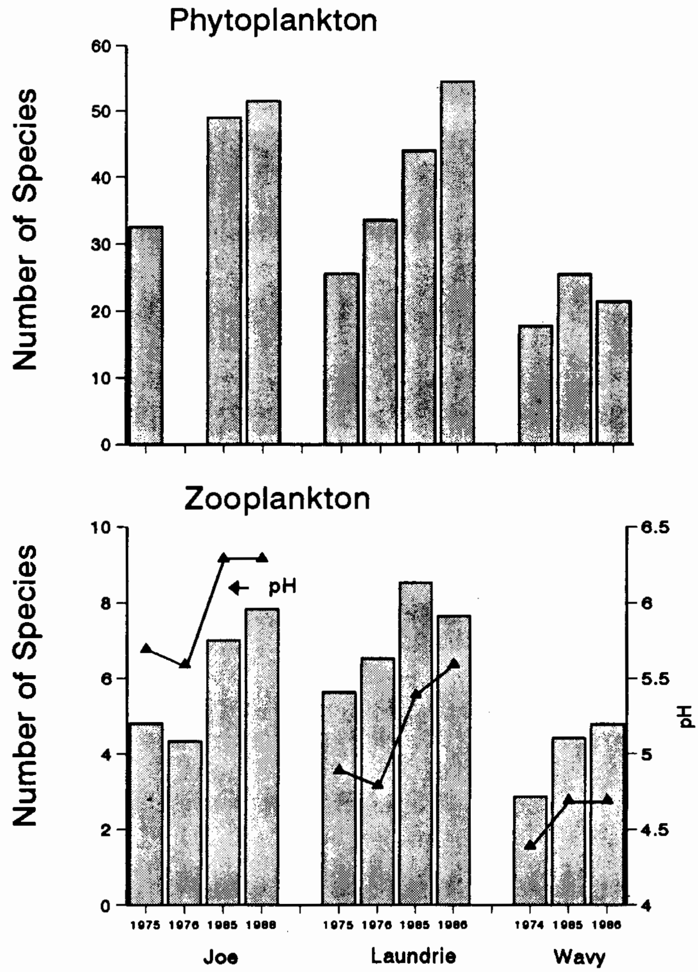



**FIGURE 5.5.** Number of lake trout lakes too acidic to support viable populations (*solid dots*) has declined from 86 in 1980 to 38 in 1990. Most of these changes occurred early in the 1980s.

**Figure 5.6.** Changes in annual average pH (*solid line*) and the richness (*shaded bars*) of phytoplankton (Nicholls et al. 1992) and zooplankton (Keller and Yan 1991) communities in three Sudbury lakes.




Many acidified Sudbury lakes have extensive benthic growths of filamentous algae, a response to acidified conditions (Fig. 5.7). During the natural recovery of Swan Lake from pH 4.8–5.4 (1982–1987), the community composition of benthic algae changed, and the extent of shoreline coverage declined greatly (Vandermeulen et al. 1993). As pH increased, the dominance of *Zygogonium* gave way to dominance by a mixture of *Spirogyra, Oedogonium,* and *Desmidium.*

## Zooplankton

Some natural recovery of planktonic rotifer communities was documented in Swan Lake, as pH rose from 4.0 in 1977 to 4.8–5.1 in 1982–1984 (MacIsaac et al. 1986). Dominance shifted from *Keratella taurocephala* to *Polyarthra* and other species as water quality improved. This change is consistent with survey results indicating dominance by a variety of species, particularly *Keratella cochlearis* and *Polyarthra,* in non-acidic lakes, and strong dominance by *K. taurocephala* and *Gastropus* in acidic lakes (MacIsaac et al. 1987).

Increased average species richness of crustacean zooplankton has been observed in many lakes (Locke et al. 1994), including Laundrie, Wavy, and Joe (Keller and Yan 1991; Fig. 5.6). These patterns followed the negative relationship generally observed between species richness and lake acidity (see Fig. 5.2). New species that became important in these lakes as chem-

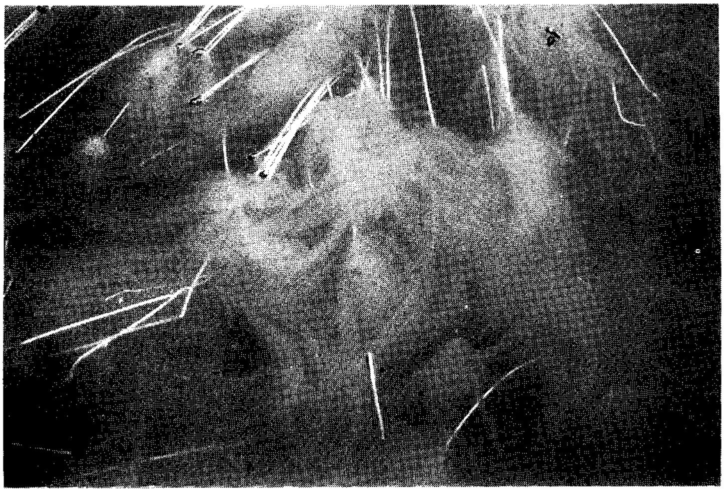


**FIGURE 5.7.** Filamentous green algae accumulation in the nearshore zone of an acidic lake. Such growths are widespread in acidified lakes and are a major concern for recreational users. (Photo by W. Keller.)

istry improved included *Holopedium gibberum*, *Eubosmina*, *Daphnia pulex*, *Skistodiaptomus oregonensis*, *Epischura lacustris*, and *Tropocyclops extensus*. With the exception of *H. gibberum*, which is metal-sensitive, these recolonists are considered acid-sensitive, and all are relatively common in northeastern Ontario lakes. Based on a comparison of species richness in these lakes and nonacidic southcentral Ontario lakes, natural recovery was not complete. However, recolonization by common widespread species made zooplankton community composition much more typical of natural Precambrian Shield lakes.

## Benthic Invertebrates

Recovery of the invertebrate communities that occupy the lake bottom has been reported for Whitepine Lake and Laundrie Lake (Gunn and Keller 1990; Griffiths and Keller 1992). In these lakes, as pH increased, the abundance and the number of species collected generally increased, suggesting higher survival under less acidic conditions. Acid-sensitive organisms first collected in the most recent survey included several mayfly species (*Hexagenia*, *Ephemerella*, *Caenis*) in Whitepine Lake and the amphipod *Hyalella azteca* in Laundrie Lake.

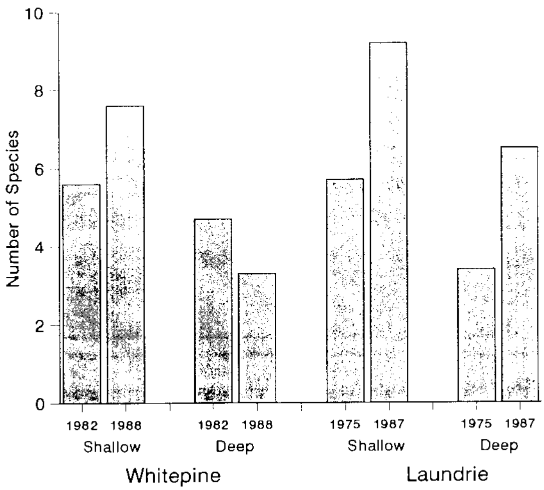



**FIGURE 5.8.** Changes in the average number of benthic invertebrate species per sample in littoral (*shallow*) and profundal (*deep*) soft-sediment habitats of Whitepine and Laundrie lakes (Griffiths and Keller 1992). Over the period, pH increased from about 5.4 to 5.9 in Whitepine Lake and 4.9 to 5.6 in Laundrie Lake (northern basin). Note that species richness did not increase in the deep areas of Whitepine Lake, where predation by an expanding lake trout population was intense.

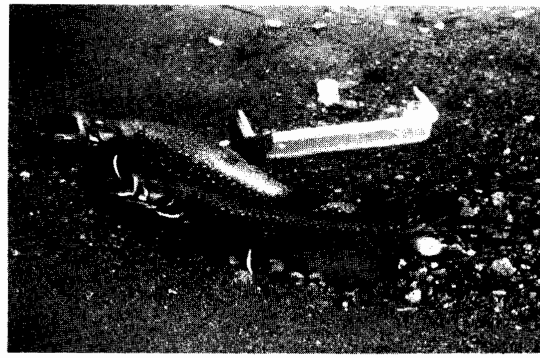


**FIGURE 5.9.** Spawning brook trout in Joe Lake, 28 km north of Sudbury. The historical trout population was eliminated from Joe Lake by acidification and metal contamination, but water quality improvements have allowed successful restocking and reproduction. (Photo by V. Liimatainen.)

Other acid-sensitive recolonists included the worms *Arcteonais lomondi*, *Stylaria lacustris*, and *Dero nivea*, the midge *Cladotanytarsus*, and the clams *Musculium securis* and *Pisidium*. Changes in the species richness of these lakes are shown in Figure 5.8.

## Fish

Improved water quality has allowed successful restocking of extinct fish species in several Sudbury lakes (Fig. 5.9). But there are relatively few cases of natural recovery among fish communities. The best-documented case is the resumption of successful reproduction by remnant lake trout after pH increased in Whitepine Lake (Gunn and Keller 1990). In this lake, the very abundant population of acid-tolerant yellow perch (*Perca flavescens*) decreased rapidly as lake trout populations were re-established. Not all residual populations, though, responded to improved water quality. The very sparse remnant populations of white suckers (*Catostomus commersoni*) and burbot (*Lota lota*) became extinct despite the pH increase.

# Expectations

It is expected that further chemical and biological improvements will result from the large-scale additional abatement measures being implemented by the Sudbury smelting industry. The ultimate environmental effect of these emission control programs cannot be predicted using present knowledge. Close monitoring of environmental responses will be required to assess the adequacy of control measures and determine the need for additional steps. Based on previous findings, the interpretation of monitoring data must carefully consider climatic fluctuations, which can greatly affect time trends in lake chemistry.

In time, under a regime of reduced deposition of atmospheric contaminants, many currently acidic Sudbury lakes should improve such that water quality conditions will no longer constrain aquatic biological communities. Other lakes may show less significant chemical changes, but even in these lakes, some improvement in biological communities is expected. Given suitable water quality conditions, biological improvements will be substantial, based on evidence from experimental neutralization studies (see Chapter 15) as well as observations of natural recovery. Benthic filamentous algae respond almost immediately to decreased lake acidity, through dramatically reduced abundance and shifts in community composition. Phytoplankton communities also respond rapidly to chemical improvements, with increased community richness and shifts to types considered more typical of near-neutral Precambrian Shield lakes. Many common zooplankton species and mobile species of benthic invertebrates show relatively rapid (within a decade, and often much less) recolonization rates.

# Complications

It has been suggested that the benefits of reduced acid emissions may be temporarily offset by corresponding decreases in calcium concentrations in lake waters, resulting from reduced leaching rates of watershed minerals (Henriksen et al. 1989; Skeffington and Brown 1992). Declining calcium is a concern because calcium reduces the toxic effects of acid and various metals in soft waters. Calcium limitation, although perhaps of concern for some Ontario lakes or in other regions with extremely dilute lakes such as southern Norway (calcium <1 mg/L), does not appear to be a major problem for Sudbury lakes or Precambrian Shield lakes in general, where calcium concentrations are usually higher. Of 250 lakes sampled within about 250 km of Sudbury, only 9 had calcium concentrations of less than 2 mg/L and the average for these lakes was 1.7 mg/L (Pitblado and Keller 1984). These values are well above the requirements for normal physiological functions in fish.

Communities in recovering Sudbury lakes are becoming more typical of those in nonacidic Precambrian Shield lakes, although it is impossible to demonstrate a return to the exact community that prevailed historically in individual lakes. The establishment of typical communities is expected, because species important in the natural restructuring of communities are residual acid-sensitive species that have persisted in reduced abundance and recolonizing species that are common in the area. Predatory and competitive interactions, as well as acid-sensitivity and recolonization sources, may, however, influence the recovery process (Fig. 5.10).

In the transition phase, between communities typical of acidic lakes and those typical of nonacidic lakes, community structure may be variable (Locke et al. 1994) and somewhat atypical. For example, based on both observations of natural recovery (Keller and Yan 1991) and experimental lake neutralization studies (Yan et al., under review), among crustacean zooplankton, some species normally considered characteristic of nearshore (littoral) habitats, including *Sida crystallina*, *Chydorus sphaericus*, *Orthocyclops modestus*, and *Simocephalus serrulatus*, may invade open water (limnetic) habitats early in the recovery process. These opportunistic invaders are ultimately eliminated when more usual open-water species re-invade the plankton (Fig. 5.10). The occurrence of such transition communities among other groups of organisms has not yet been documented for Sudbury lakes, but they may occur.

In some cases, the biological communities existing in acidic lakes may resist recovery to more typical communities, even under suitable water quality conditions (Fig. 5.10). In fishless lakes, high abundances of predatory invertebrates such as larvae of the phantom midge *Chaoborus*, which are normally controlled by fish predation, may prevent or retard the re-establishment of normal invertebrate communities (Nyberg 1984; Stenson et al. 1993). In particular, zooplankton in small, nutrient-rich, fishless lakes with high *Chaoborus* abundance may be affected by invertebrate predation (Yan et al. 1991). In such lakes, the recovery of natural invertebrate communities may depend on the re-establishment of fish communities that will control invertebrate predators. In the case of fish communities themselves, it appears that in lakes with high abundances of acid-tolerant fish species, interspecific competition may inhibit the successful re-establishment of some species. Examples of this type of negative competitive interaction between acid-sensitive and acid-tolerant species include brook trout and yellow perch and lake trout and cisco (*Coregonus artedii*). Expanding fish populations may limit the recovery of some invertebrate prey species (see Fig. 5.8).

Many species, if given suitable water quality and sufficient time, are undoubtedly capable of re-establishing themselves in aquatic ecosystems. Other species are much less mobile and may not be able to recolonize former habitats. For many fish species, natural recolonization may depend on the existence of connections with unaffected water bodies or other refuge areas (Bergquist 1991). The re-establishment of recreational fisheries will, in many cases, require restocking and the development of protective management strategies. For some nonmobile invertebrate or small fish species, re-introductions may also be necessary to achieve a desired aquatic community structure within a reasonable period of time.

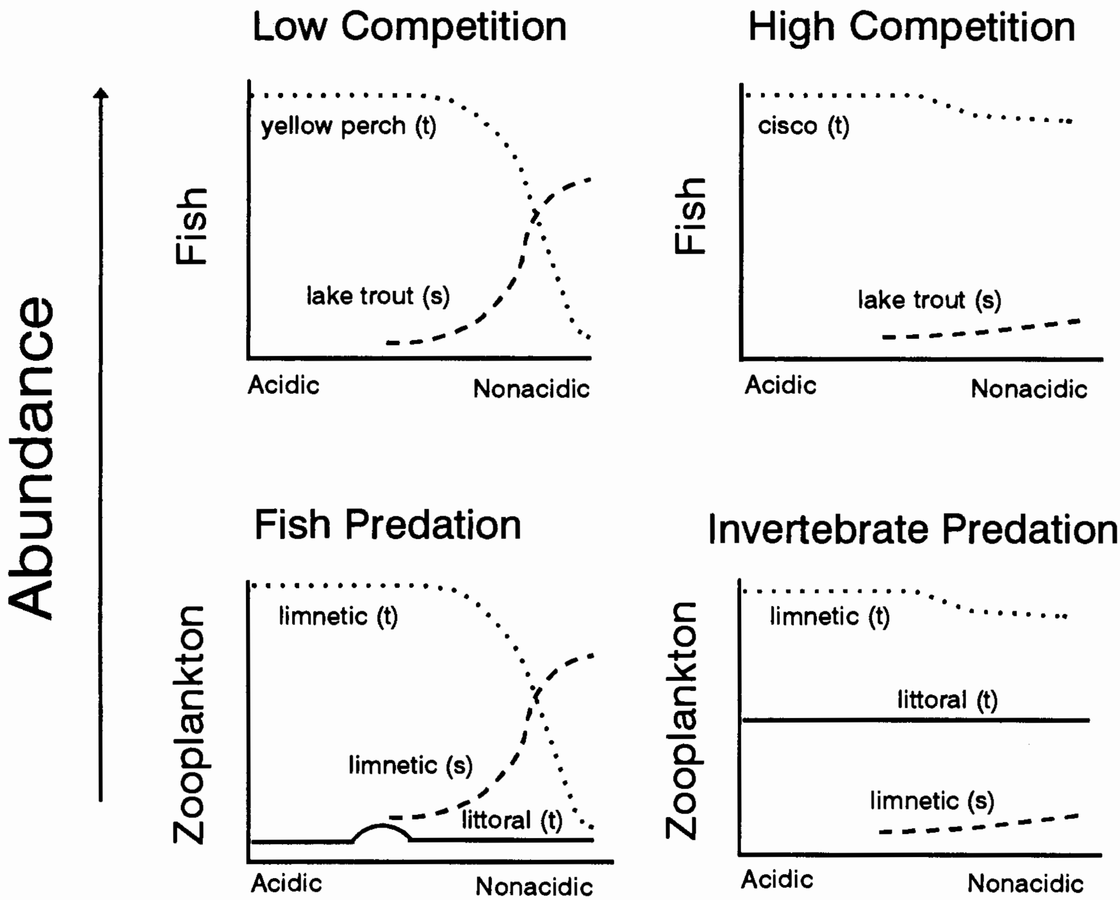



**FIGURE 5.10.** Some of the expected changes and interactions in fish and zooplankton communities that may occur during recovery in lakes with different biological characteristics. Conditions are low competition between acid-tolerant (*t*) forage fish and acid-sensitive (*s*) sportfish (*upper left*); high competition between acid-tolerant forage fish and acid-sensitive sportfish (*upper right*); changing fish predation from small acid-tolerant planktivores to large acid-sensitive piscivores (*lower left*); and, fishless conditions with intense invertebrate predation (*lower right*).

## Summary and Conclusions

Studies in the Sudbury, Ontario, area have shown that water quality changes have occurred in many lakes in response to substantial reductions in sulfur and associated metal emissions in the 1970s. These changes, including decreased acidity, and decreased concentrations of sulfate, calcium, magnesium, aluminum, and manganese, continued into the mid-1980s. By the late 1980s, these trends leveled off or reversed somewhat. During the 1980s, no clear trends in concentrations of copper or nickel, metals directly associated with the smelter emissions, were observed, although decreases in concentrations of these metals did occur between the mid-1970s and early 1980s.

Biological changes have accompanied these chemical improvements. At least partial recovery has been observed for benthic filamentous algae, phytoplankton, zooplankton, benthic invertebrates, and some fish species. The patterns of recovery show movement toward the reestablishment of communities typical of Precambrian Shield lakes in this area. For some nonmobile species, however, natural recolonization is unlikely (Bergquist 1991) and restocking efforts will be necessary.

Based on our current understanding of aquatic systems, a pH of at least 6.0 is needed for the protection of healthy aquatic communities (see Fig. 5.2). To date, only a small number of Sudbury lakes have recovered above this chemical threshold. In those lakes nearest Sudbury, the biological effects of elevated concentrations of metals related to smelter emissions, particularly copper and nickel, must also be considered. Large reductions in metal concentrations as well as decreases in acidity will be required to permit ecosystem restoration in some lakes. Such concurrent elevations in surface water acidity and concentrations of some airborne metals, however, occur in other regions experiencing high deposition of atmospheric contaminants, including areas of Scandinavia and Russia near smelters (Nost et al. 1991). Thus, observations in Sudbury provide very useful comparative data for areas influenced by regional sources of acid and metal deposition as well as areas subjected to the long-range transport and deposition of contaminants.

The widespread chemical and biological improvements seen in lakes of the Sudbury area demonstrate the resiliency of aquatic systems and provide strong support for the use of emission controls to combat aquatic acidification. However, many area lakes are still acidic and metal-contaminated. Further recovery is expected to result from the additional, recently implemented controls (Ontario Ministry of the Environment 1987).

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