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Acid rain – perspectives on lake recovery

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Abstract

During the 1970's and 1980's, the acidification of surface waters by atmospherically deposited sulphur became a major international concern. Large sulphur emission control programs were implemented in Europe and North America with the expectation that many affected aquatic ecosystems would recover. Because of a variety of factors, these positive expectations have been slow to be realized. Only limited evidence of the chemical recovery of acid lakes has emerged from areas other than the Sudbury, Canada region, where sulphur emission reductions were particularly large. Lake response models indicate that when current sulphur emission control strategies in Europe and North America are fully implemented, many lakes will still be acid-damaged even though substantial overall improvements in lake chemistry are expected. An increasing body of evidence indicates that substantial biological recovery, among many groups of organisms, can be expected when chemical conditions improve in lakes. Not all species, however, are capable of unassisted recovery and some lakes can pose biological or physical barriers to colonizers. Thus, stocking may be an important element in management strategies for the restoration of some recovering lakes. Communities in recovered lakes may not achieve predisturbance conditions, but establishment of typical communities appears to be a reasonable recovery target.

1. Introduction

In the late 1970's and early 1980's the acidification of lakes and rivers by atmospherically conveyed acids became a major international concern (Cowling, 1982). Surface water acidification problems had been recognized much earlier in Europe, especially in Scandinavia, and in North America (Fisher et al., 1968; Oden, 1968; Hultberg & Stenson, 1970), but it was later that very intensive research on the scope and nature of the acidification problem began. Following on the first international "Acid Rain" Symposium in 1975 (Dochinger & Seliga, 1976), four major international conferences addressed the growing awareness of the extent, severity, and complexity of the global Acid Rain problem between 1980 and 1995 (Drablos & Tollan, 1980; Martin, 1986; Dempster & Manning, 1992; Grennfelt et al., 1995).

Controversy surrounded the acid rain issue from the start. One of the arguments initially proposed against the need for large cuts in sulphur emissions, identified as the main cause of acid rain, was that the damage caused by acidification might not be reversible, and emission control programs might therefore simply waste money or reduce industrial sector jobs without creating substantial environmental benefits. That position was eventually countered by results from lakes around the large metal smelting operations near Sudbury, Ontario, Canada. Studies around Sudbury in the 1980's demonstrated that reduced lake acidity had followed the large reductions of sulphur emissions at Sudbury area smelters that began in the early 1970's (Dillon et al., 1986; Hutchinson & Havas, 1986; Keller & Pitblado, 1986; Keller et al., 1992a; McNicol & Mallory, 1994). Evidence also began to emerge of improvements in biological communities that followed these water quality changes (MacIsaac et al., 1986; Gunn & Keller, 1990; Keller & Yan, 1991; Keller et al., 1992b). The observed benefits of pollution controls in the Sudbury area (Keller et al., 1999 [this issue]) gave reason for guarded optimism about the ultimate fate of lakes in other regions affected by acid deposition.

During the 1980's and 1990's, large sulphur emission control programs were implemented in many areas including Canada (Environment Canada, 1995), the United States (NAPAP, 1993) and Europe (United Nations, 1994) with the expectation that conditions in affected aquatic ecosystems would improve. The focus of some acid rain assessment programs slowly began to change from evaluating damage to investigating ecosystem recovery. Unfortunately, the positive expectations have been slow to be realized. To date, other than in the Sudbury region where emission reductions were particularly large (Keller, 1992), only limited evidence of chemical recovery of lakes has emerged from regions where declines in sulphur emissions have been achieved (NIVA, 1997). It has become apparent that a variety of factors other than just sulphur deposition levels determine the recovery or lack of recovery of acidic lakes.

2. Factors affecting chemical recovery

Precipitation quality responds quickly to changes in atmospheric sulphur emissions (Hedin et al., 1987; Dillon et al., 1988), but precipitation acidity is also affected by other factors, including concentrations of nitrogen species and base cations (Gorham, 1955; Fisher et al., 1968). While expectations of chemical recovery in lakes resulting from sulphur emission reductions must allow for some lag in lake response, simply due to the time required for lake water replenishment (Figure 1), even when hydrological lag time is considered, lakes in most acid-affected regions have shown limited responses to reduced sulphur deposition (e.g. Clair et al., 1995; Driscoll et al., 1995; Rapp & Bishop, 1995; Webster & Brezonik, 1995; Dillon et al., 1997). A number of factors can be involved in delaying or possibly even preventing the chemical recovery of lakes (Figure 2).

Reductions in sulphur deposition and corresponding declines in lakewater sulphate levels are not necessarily accompanied by decreased lake acidity. Declines in sulphate can also be balanced through other chemical reactions, notably declines in concentrations of base cations (Skeffington & Brown, 1992). The availability of base cations in lake watersheds is of major importance in the recovery process. If watershed supplies of easily available base cations have been depleted through chronic acidification, renewal of watershed buffering capacity through soil mineral weathering will be a very slow process (Likens et al., 1996). Recent evidence indicates that along with

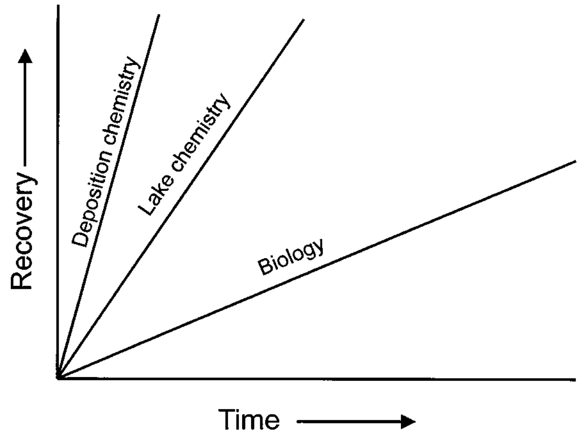

Figure 1. The general sequence of recovery from acidification. While deposition chemistry responds very quickly to changes in atmospheric emissions of contaminants, there is a lag in the response of lake chemistry because of hydrology and watershed storage of contaminants. Biological improvements will lag behind lake chemistry improvements, since suitable chemistry is a prerequisite for biological recovery.

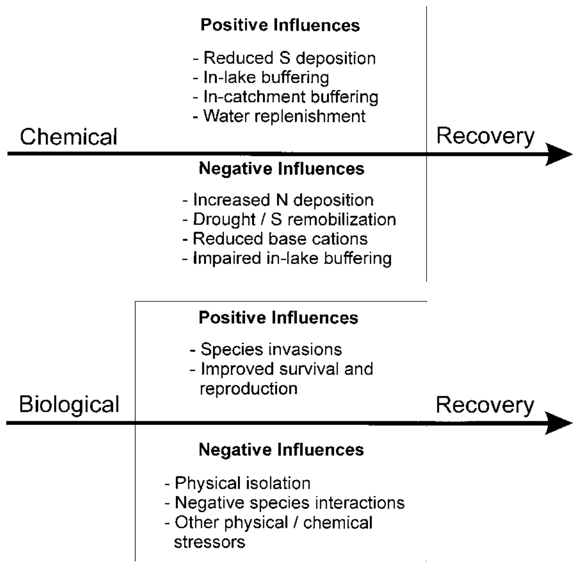

Figure 2. General factors potentially affecting the recovery process. Lake recovery involves a complex combination of chemical, physical, and biological factors.

reduced sulphur deposition, the deposition of base cations from the atmosphere has also widely declined (Hedin et al., 1994; Likens et al., 1996). Factors contributing to reduced base cation deposition may include decreases in emissions from industries and vehicles and reduced particulate emissions from land uses such as agriculture. With simultaneous declines in sulphate concentrations and base cation concentrations the net effect in lakes may be little or no change in water acidity.

Acid rain controls have focussed on reducing emissions of sulphur, generally identified as the acid precursor of main concern. In some regions, however, deposition of nitrogen can also be an important contributor to acidification. While emissions and deposition of sulphur have generally declined in many affected areas, nitrogen emissions have not shown comparable reductions, and have in fact increased in some areas (NIVA, 1997). Increasing nitrogen deposition may negate some of the beneficial effects of reduced sulphur deposition if catchments become nitrogen saturated (Henriksen et al., 1997; Jeffries, 1997). Future acid rain control programs must therefore seriously consider the issue of nitrogen emissions.

Elevated atmospheric sulphur deposition has been occuring for many decades, leaving a legacy of sulphur stored in water-saturated lake catchments. Wetlands and saturated organic soils in particular are important sites of sulphur storage (Bayley et al., 1986; Dillon & LaZerte, 1992). During droughts, reduced sulphur stored in lake catchments and sediments can be oxidized and create acidity when wet conditions resume. The export of this regenerated acidity can delay or even reverse the recovery of lakes from acidification (Keller et al., 1992a; McNicol & Mallory, 1994; Yan et al., 1996a; Dillon et al., 1997). And, interactions between lake acidity and other important global stressors like climate change and UV-B irradiance can greatly affect lake ecosystems (Schindler et al., 1996; Yan et al., 1996a), and may influence future lake recovery.

Internal, biologically-mediated lake processes may also have a large effect on lake recovery. Recent lake-scale experimental work suggests that at least in the short-term the impairment of important internal alkalinity-generating mechanisms in severely acidified lakes may be a factor inhibiting subsequent lake recovery when acid inputs are reduced (Turner et al., 1998).

The chemical recovery process is greatly complicated by the factors outlined above and others, and requires much further study. However, it is widely accepted that the emission controls achieved so far are not sufficient to protect all acid-sensitive aquatic resources in North America or Europe (Likens et al., 1996; Jeffries, 1997; NIVA, 1997; Hindar et al., 1998). Further reductions in emissions of sulphur are needed and the influence of nitrogen deposition on aquatic systems must be monitored. Additional assessment is required to more accurately define the acid loadings that lakes can tolerate against a background of other global stressors like climate change and ozone depletion.

3. Critical sulphur loads and water quality targets

A frequently used approach for assessing the acid-tolerance limits of terrestrial and aquatic ecosystems is the “Critical Load” concept (Hettelingh et al., 1995). This modelling approach involves calculating the deposition level of a contaminant below which significant damage to sensitive components of ecosystems is not expected. When applied to lakes, the critical load is usually estimated as the load that is expected to protect a defined proportion of the lakes within a region. In essence the critical load represents both a chemical and a biological threshold.

In the context of sulphur deposition and lake acidification, pH or acid neutralizing capacity (ANC) are commonly used as water quality variables and estimates for threshold levels of these may be based on the acid sensitivity of single target species e.g., brown trout (*Salmo trutta*; Hindar et al., 1998) or on levels necessary for general protection of aquatic communities (Jeffries, 1997). The acid-sensitivity of the particular species or groups of species selected to form the basis for the water quality thresholds applied is obviously very important in making critical load estimates. Critical loads i.e. sulphur deposition levels that do not cause exceedence of threshold levels for key aquatic variables, may also vary from region to region and lake to lake because the distribution of acid-sensitive species varies, the acid-sensitivity of fauna can vary with background conditions (Raddum & Skjelkvale, 1995), and aquatic systems vary in their inherent ability to buffer acid inputs.

Recovery is not an all or none phenomenon. Small water quality improvements may lead to some biological improvements even in lakes that are still chemically stressed (Keller & Yan, 1991; Yan et al., 1996b), and early in the recovery process modest recovery targets may be realistic (Steinberg et al., 1998). In the long term, however, targets reflecting a high level of ecosystem protection are more appropriate goals.

In Canada, for example, a pH of 6.0 is generally accepted as a level affording protection to most of the acid-sensitive components of aquatic systems (Neary et al., 1990; Doka et al., 1997) and is commonly used as a basis for critical sulphate load estimates (Jeffries, 1997). It must be recognized, however, that some lakes may be naturally acidic with pH under 6.0 before industrialization (Dixit et al., 1992; Smol et al., 1998), and the proportion of naturally acidic lakes may vary widely between different geographical areas (Jeffries, 1997). Appropriate water quality targets for lake recovery must therefore consider historic chemical conditions which sometimes can only be revealed from inferences derived by paleolimnological methods (Dixit et al., 1995; Smol et al., 1998).

Unfortunately, at present it may not be possible to protect all aquatic ecosystems from damage, given currently established technology. If we accept this less than perfect scenario, then decisions must be made on acceptable levels of damage. Critical load estimates can be used to predict regional percentages of affected lakes under different sulphur deposition scenarios. Decisions about the percentage of damaged lakes that is allowable in an area, and the corresponding acceptable acid deposition level, can then be made. The concept of acceptable damage raises a difficult philosophical question that needs to be considered along with the scientific and economic aspects of the acid rain issue. This will, however, be a very difficult question to answer as a society, given the often divergent viewpoints of the various interest groups involved in the acidification issue. Environmental protection efforts felt to be great political achievements are sometimes labelled as modest and inadequate by the scientific community or environmental organizations (e.g. Schindler, 1992). Lake managers are caught in the middle of such opposing views when making their decisions.

4. Biological recovery

4.1. *General considerations*

A major ultimate objective of emission control strategies is the protection or restoration of aquatic communities. This fact is reflected in the general use of the critical load approach which has a biological basis.

With our present state of knowledge, emission control programs must still be regarded as large-scale experiments in habitat restoration. As indicated above, many poorly understood factors can influence the chemical response of lakes to reduced acid deposition, and the responses of complex biological systems to these chemical changes are difficult to predict.

Where protection is the emphasis, the situation is comparatively straightforward. If we can maintain a certain chemical status we can expect to maintain a more-or-less known assemblage of species since the enviromental tolerances of many of our key aquatic species are fairly well established. For example, the threshold pH of 6.0 widely used in Canada is based on survey and experimental results for many acid sensitive species from different groups (e.g. Schindler, 1988; Keller et al., 1990a; Matuszek et al., 1990; Havens et al., 1993; Gunn & Belzile, 1994).

When the objective is restoration the situation is more complicated. The initial degree of damage, the physical nature of aquatic systems, and the characteristics and interactions of the many organisms making up aquatic communities are some of the elements that greatly complicate development of appropriate restoration targets and strategies (Keller & Yan, 1998).

The lake recovery process has two main elements – improvement in habitat quality and biological response. If restoration of habitat quality is successful, will the natural recovery of aquatic communities simply follow? It depends upon the potential of a particular system for biological recovery. This potential depends on many factors, both physical and biological, including degree of isolation of a water body (ease of access for invading species), degree and duration of damage (the starting point in the recovery process), characteristics of the species involved (mobility, fecundity) and existing biological communities (biological barriers to species colonization or expansion). Our understanding of such processes and how they interact, is still very limited (Cairns, 1990; Detenbeck et al., 1992).

4.2. *Trajectories*

Empirical and experimental evidence is mounting that indicates that decreased acidity (improved habitat quality) should result in substantial improvements in biological communities. There is concern about hysteresis (e.g. O'Neill, 1999 [this issue]) and divergent recovery trajectories (Findlay & Kasian, 1991; Malley & Chang, 1994; Sampson et al., 1995; Frost

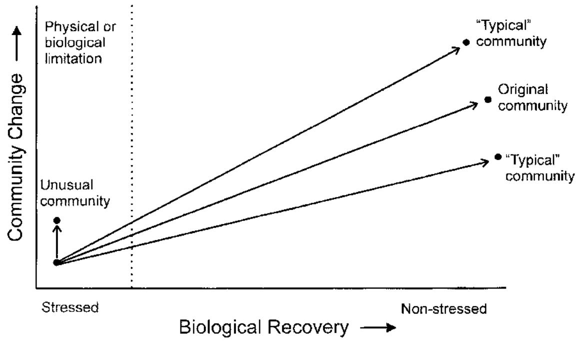

Figure 3. Possible trajectories of biological recovery. If there are no severe physical or biological barriers to recovery, once water quality becomes suitable, aquatic communities are expected to progress towards communities considered typical of a region, not necessarily back to the original community.

et al., 1998; Turner et al., 1998). Some of this concern, however, may reflect the limited time scale of the experimental studies involved. While such results provide important cautions, patterns in biological change observed over a few years may not necessarily reflect what will happen in the longer term.

While recovery of some communities may not follow the path expected from acidification responses (Figure 3), with sufficient time communities of many groups of organisms including phytoplankton (Molot et al., 1990; Nicholls et al., 1992; Findlay & Kasian, 1996), rotifers (MacIsaac et al., 1986; Keller et al., 1992c), crustacean zooplankton (Keller & Yan, 1991; Locke et al., 1994; Yan et al., 1996b) and benthic invertebrates (Griffiths & Keller, 1992; Carbone et al., 1998) tend to move toward those considered natural when acid stress is removed. Residual populations of acid-sensitive species have often responded rapidly to the removal of acid stress and invading species, presumably ones present historically, have often appeared within a few years.

4.3. *Targets*

Recovered communities may not duplicate the original pre-acidification community in a given system. But, if they can be considered "normal" or "typical" (Figure 3) then resource managers should probably be content with the result. For a variety of reasons including invasion sequence and rate (Patrick, 1967; Robinson & Dickerson, 1987; Robinson & Edgmon, 1988) and changes to other parts of the ecosystem (Cairns, 1989) it may not be reasonable to expect a return to the predisturbance community. In fact, we are rarely in a position to even know exactly what the original community was in a given lake. In the absence of historical information, adequate temporal and spatial reference data are essential to establish realistic biological recovery targets (Yan & Keller, 1991; Yan et al., 1996b; Chapman, 1999 [this issue]).

With reference data, statistical approaches to recovery assessment can be employed, and examples of such applications are beginning to emerge. For univariate measures of community structure such as species richness, comparisons of values for recovering lakes with the confidence limits reflecting the variability within groups of physically and zoogeographically similar non-acidified lakes have proven useful (Keller & Yan, 1991; Yan et al., 1996b). For multivariate measures, the plotting of recovery trajectories in ordination space with appropriate non-affected reference lakes has proved to be a sensitive method of community recovery detection (Keller et al., 1992c; Locke et al., 1994; Yan et al., 1996b; Chapman, 1999 this issue). Such approaches (Figure 4), and recent refinements of them (Kilgour et al., 1998), offer much promise as tools for the evaluation of the recovery of biological communities.

4.4. *Timeframes*

It is logical to expect that biological improvements will lag behind chemical changes (Figure 1). But, overall, the prognosis for biological recovery from acidification, given the necessary chemical recovery, is promising. The evidence suggests that if we are willing to a wait a reasonable length of time after habitat quality is adequately improved, we can expect substantial natural recovery among many of the common aquatic organisms. What length of time is "reasonable" is open to argument, but since the damage we face occurred over many decades it does not seem unreasonable to allow a decade or more for significant improvements.

There are numerous case histories of substantial biological improvements occurring within about a decade of water quality improvements resulting from either emission controls (MacIssac et al., 1986; Gunn et al., 1988; Gunn & Keller, 1990; Keller & Yan, 1991; Griffiths & Keller, 1992; Nicholls et al., 1992) or lake liming (Keller et al., 1990b; Molot et al., 1990; Howell et al., 1991; Keller et al., 1992c; Hornstrom et al., 1993; Degerman et al., 1995; Yan et al., 1995; Carbone et al., 1998). These studies included a variety of biota, including residual and colonizing

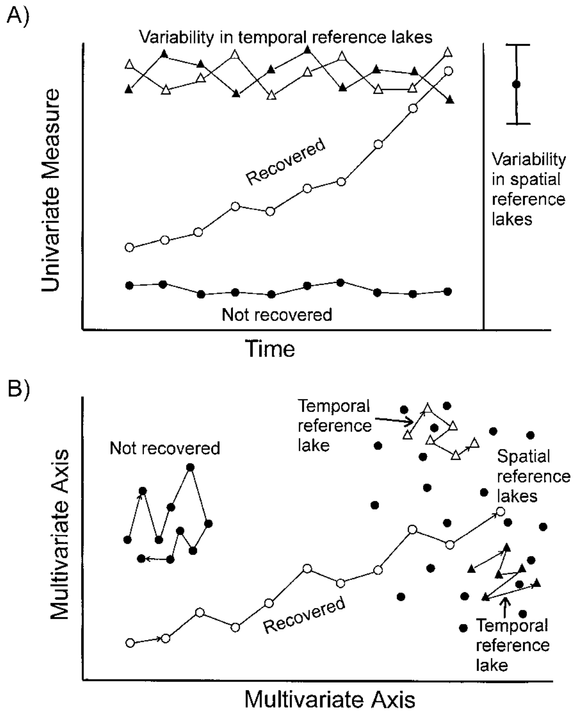

Figure 4. Generalized examples of some statistical approaches to assessing biological recovery using non-affected reference lakes. Reference data are essential to establish realistic recovery targets in the absence of historical data.

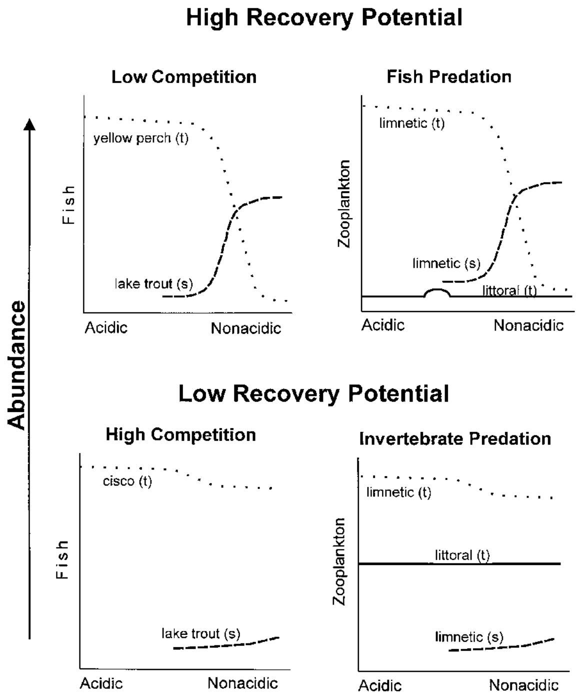

Figure 5. Examples of biological interactions that may favour or inhibit recovery of fish and zooplankton communities (modified from Keller & Gunn, 1995). The conditions considered for fish are low competition between acid-tolerant (t) forage fish and acid-sensitive (s) sport fish (upper left), and high competition between acid-tolerant forage fish and acid-sensitive sportfish (lower left). For zooplankton the conditions are changing fish predation from small acid-tolerant planktivores to large acid-sensitive piscivores (upper right) and fishless conditions with intense invertebrate predation (lower right).

species. However, virtually all the work on biological recovery from acidification deals with species or assemblage recovery. The genetic aspect of recovery from acidification is essentially unknown (Yan et al., 1996c).

4.5. *Complications*

While many positive responses to reduced acidity have been documented, and lakes and lake communities appear to be remarkably resilient, not all organisms are capable of responding to improved habitat quality within a "reasonable" time frame. Dispersal ability is very limited for some organisms. Examples include the so-called "glacial relicts" in North America (Schindler, 1987), such as the acid-sensitive *Mysis relicta* and a number of acid-sensitive zooplankton species, which have modern distributions that have changed little since the end of the last glaciation (Dadswell, 1974; Carter et al., 1980).

Natural recolonization by fish is also difficult. Residual sportfish populations may recover rapidly (Gunn et al., 1988; Gunn & Keller, 1990; Rask et al., 1995; Gunn & Mills, 1998) although in some cases competition from established acid-tolerant species may offer substantial resistance to recovery (Figure 5). However, the potential for natural reinvasion of fish species in situations where they have been completely eliminated is very limited. Colonization by fish will probably depend on the presence of connections to source populations in unaffected waterbodies (Bergquist, 1991; Kelso et al., 1992; Appelberg, 1998) unless circumstances are extremely unusual (Bajkov, 1949). Restocking of sport fish in formerly acidified lakes has been very successful (Snucins et al., 1995; Gunn & Mills, 1998).

When fish have been completely eliminated from a lake, intensive predation by large populations of invertebrate predators, normally preferred fish prey (Eriksson et al., 1980; von Ende & Dempsey, 1981; Vanni, 1988; Yan et al., 1991) can prevent re-establishment of typical invertebrate communities (Figure 5). Without fish re-establishment to control these predatory invertebrates, substantial invertebrate community recovery is unlikely in fishless situations (Nyberg, 1984; Carbone et al., 1998). Fish introductions can lead to rapid changes in invertebrate communities (Keller et al., 1990b; Carbone et al., 1998).

5. Managing recovery

Within management schemes for recovering lakes, key organisms may sometimes need assistance through stocking (Schindler, 1988; Keller & Gunn, 1995). It is important that we determine which organisms need help and which do not, to better direct management efforts. Reintroductions need to be done in an ecosystem context, thus restoration plans should consider key elements of the food web that may be missing as well as the sportfish that usually draw the attention of management agencies. It is also important that management strategies be developed for recovering lakes that include limiting exploitation during the time needed for community restructuring (Gunn & Mills, 1998).

Clearly the jury is still out on the ultimate effects that emission control programs will have on the chemical and biological recovery of aquatic ecosystems. Much research is needed to more fully understand the recovery process. Monitoring programs must be continued since in the end it is only from ongoing monitoring that we will be able to know what we have actually accomplished and what else needs to be done. The evidence to date indicates that the acid rain problem is far from over. Many scientific and economic questions will need to be resolved as we make decisions about the future of lakes affected by acidification. But, to set realistic goals we also need to consider some fundamental, societal questions like what do we ultimately want from our acidic lakes and how long are we willing to wait?

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