BIOLOGICAL INDICATORS OF LAKE ACIDIFICATION

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ABSTRACT. Indicator taxa are identified, based on both synoptic surveys and whole lake acidification experiments, for lake acidification in the pH 6.0 to 5.0 range. Acidobiontic diatoms (e.g *Asterionella ralfsii*, *Fragillaria acidobiontica*, etc.), periphyton (*Mougeotia* and related species), macroinvertebrates (e.g. *Hyalella azteca*, *Orconectes* sp., etc.), leeches, and cyprinid fishes (e.g. *Pimephales promelas*, *Notropis cornutus*, etc.) are identified as target organisms during early phases of lake acidification.

1. INTRODUCTION

Our knowledge of fish population losses, and losses of other aquatic organisms, due to acidification has increased rapidly during the past 10 yrs. In many surveys the occurrences of taxa are correlated with lake pHs to infer pH tolerance of each species. These surveys generally show that many species are absent when lake pH is below 5.0, but changes in the pH 6.0 to 5.0 range are not as well understood (Hendrey, 1984). The purposes of this paper are to briefly summarize changes in selected species of aquatic groups (algae, zooplankton, benthos, and fishes) as lakes are acidified to pH 5.0, and to identify losses or appearances of indicator species which may be useful for future monitoring programs.

In this paper we will rely heavily on previous literature reviews of the susceptibility of aquatic organisms to acidification (Magnuson *et al.*, 1984; Haines, 1981), on surveys of presence or absence of species in lakes with different pH (Eilers *et al.*, 1984; Økland and Økland, 1980), and on results from the experimental acidification of a small lake trout lake in northwestern Ontario (Schindler *et al.*, 1985). An assumption in this approach is that species occurrences in lakes of different pH do reflect species tolerances. The potential problems of this assumption are listed in Eilers *et al.* (1984) and Magnuson *et al.* (1984), but results from both the experimental acidification of the small lake trout lake and laboratory studies support survey inferences.

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2. SURVEYS: PHYTOPLANKTON, PERIPHYTON, AND INVERTEBRATES

Altered species composition and reduced species number have been correlated with low pH levels in many lakes (Hendrey, 1982; Magnuson et al., 1984). Species losses occur in many taxonomic groups (Figure 1); diversity of most taxonomic groups decreases as lakes acidify. While changes occur in all taxonomic groups, specific changes of algae, crustacean zooplankton, benthic macroinvertebrates, and leeches are potential indicators of change in the early phases of lake acidification.

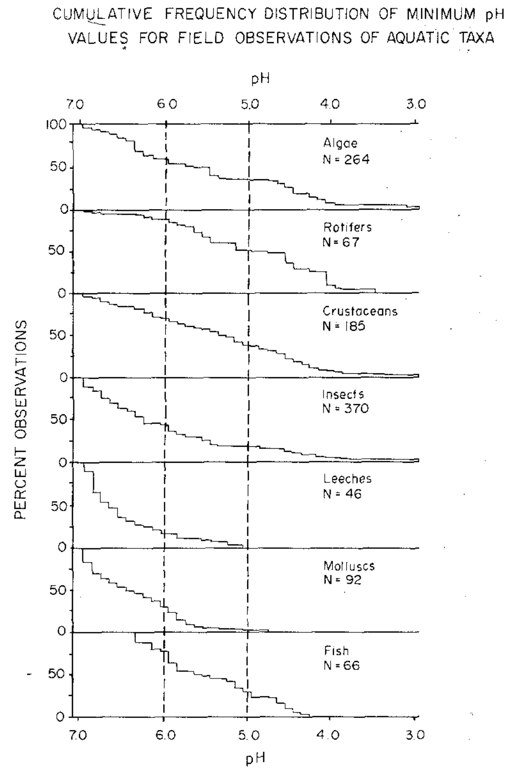

Figure 1. Minimum pH values reported for field observations of aquatic taxa, showing the percent reducton from pH 7.0 to pH 3.0. The range of pH from 6.0 to 5.0 is shown within the dotted lines. N is the number of species included in each panel. Redrawn from Eilers et al. (1984).

For algae, species losses occur in all taxonomic phyla, but in the pH 6.0 to 5.0 range the losses may be more dependent on nutrient status of a lake than pH (Almer et al., 1978; Dillon et al., 1979; NRCC, 1981). Acidobiontic diatoms, such as Asterionella ralfsii, Fragillaria acidobiontica, Tabellaria quadriseptata, and Tabellaria binalis first occur when lake pH is lowered to approximately 5.5 (Davidson, 1984; Charles, 1985; Batterbee et al., 1985). The change from alkaliphilous to acidobiontic species is probably a good indicator of changing pH in a lake and is being used for the paleoreconstruction of pH status of some lakes (Renberg and Hellberg, 1982; Charles, 1984; Davidson, 1986).

Another characteristic change in the algal community of many acid lakes is the development of dense mats of periphyton (Almer et al., 1974; Stokes, 1981; Hendrey, 1982). Stokes (1981) characterized the types of mats which occur in acid lakes, but most of the observations and experimental research on periphytic algal growth have been conducted at very low pH (<5.0). While the type and extent of mats may vary among acid lakes, rapid development of Mougeotia-dominated Chlorophycean mats occurred in the experimentally acidified Lake 223 and the south basin of Lake 302 when pH was lowered below 6.0 (Schindler et al., 1985; Turner et al., 1986). These mats were very extensive and may be a widespread, obvious change that is characteristic of the early stages of lake acidification.

Acidic lakes have fewer crustacean zooplankton species than neutral lakes (Figure 1), but generally the species that are dominant in acidic lakes are important components of zooplankton communities in nearby non-acidified lakes (Sprules, 1975; Magnuson et al., 1984). Some Daphnia species are absent below pH 5.5 (Yan and Strus, 1980; Malley et al., 1982; Nilssen, 1984), but losses of species such as Mysis relicta (Nero and Schindler, 1983) may be more useful as indicators of lake acidification. A potentially confounding factor is that changes in upper trophic levels due to acidification could influence community composition of zooplankton (Erickson et al., 1980; Nilssen et al., 1984).

There is a general decline in species diversity of benthos as lakes are acidified (Magnuson et al., 1984). Potential indicators of lake acidification in the pH 6.0 to 5.0 range are losses of macroinvertebrates. Gammarus lacustris is widely distributed in North America (Holsinger, 1972) and is not found in Norwegian lakes with pH below 6.0 (Økland and Økland, 1985). Hyalella azteca is not present in Ontario lakes with pH less than 5.5 (Stephenson and Mackie, 1986). Gastropods and sphaeriids (e.g. Pisidium sp., Sphaerium sp., etc.) are usually not found in lakes with pH less than 6.0 (Økland and Økland, 1980). In addition, some species of mayflies (e.g. Baetos sp., Caenis sp., etc.) are very sensitive to pH change in the 6.0 to 5.0 range (Raddum and Fjellheim, 1984; Engblom and Lingdell, 1984). The ability of crayfish to tolerate acidic conditions varies between genera. Cambarus sp. are relatively acid tolerant (Warner, 1971), while Orconectes sp. apparently are not found in lakes that have pHs less than 5.5 (Berrill et al., 1985).

Based on a limited number of observations, leeches are a potentially valuable indicator group for acidification in the pH 6.0 to 5.0 range (Figure 1). Raddum (1980) and Raddum and Fjellheim

(1984) report that leeches are particularly sensitive in Norway, although there is little supporting data for North America (Magnuson et al., 1984). Leeches are not always common in oligotrophic lakes (Magnuson et al., 1984), but this is an obvious group for future research.

3. SURVEYS: FISHES

Because the losses of fish populations were often documented in initial acid rain research, there are many synoptic surveys of the presence or absence of fish species related to pH (Haines, 1981; Magnuson et al., 1984; Eilers et al., 1984). Many species are lost in the pH 6.0 to 5.0 range (Figure 1). In general, the occurrence of salmonid and centrarchid species does not change appreciably in the pH 6.0 to 5.0 range, but rapid changes occur for cyprinids and percids (Figure 2). The rapid decrease in presence of percids in the 6.0 to 5.0 range is due primarily to the loss of darters below pH 5.8 (Eilers et al., 1984). The greatest relative change in the 6.0 to 5.0 range occurs for cyprinids. Ironically, this family of important prey species is one of the least studied groups of fishes (Scott and Crossman, 1973). Although few centrarchid, salmonid, and percid species other than darters are lost in the 6.0 to 5.0 range, some important sport and commercial species such as lake trout (Salvelinus namaycush), walleye (Stizostedion vitreum), and smallmouth bass (Micropterus dolomieui) are lost (Magnuson et al., 1984).

As a taxonomic group, cyprinids are almost ideal indicators of the initial phases of lake acidification. Reproductive failures are the prime cause of fish population losses in acidic lakes (Haines, 1981; Magnuson et al., 1984). Minnow species have very short life spans (Tallman et al., 1984; Scott and Crossman, 1973); reproductive failures would be rapidly reflected in abundance declines. For longer-lived species, such as lake trout, walleye, and lake whitefish (Coregonus clupeaformis), the onset of reproductive failures might not be evident in catches for three or more years after the first occurrence. In addition, over-exploitation is usually not a confounding problem for cyprinids, and many species spawn in lake inflows during spring snow melt, a time of pH depression in many lakes. There are many small, shallow lakes which contain only cyprinids. These lakes often have extremely low alkalinities (<50 $\mu eq \cdot L^{-1}$) and rapid flushing rates (<1 yr). Such lakes probably would be affected by acidification prior to larger lakes, which often contain commerically important species.

The occurrence of some cyprinid species is restricted in the pH 6.0 to 5.0 range (Figure 3). Results of surveys by McNicol et al. (1986), Beamish et al. (1976), and our own survey data (Experimental Lakes Area staff, unpublished data) support this generalization. Common shiner (Notropis cornutus), blacknose dace (Rhinichthys atratulus), fathead minnow (Pimephales promelas), and creek chub (Semotilus atromaculatus) are usually not found in lakes with pH

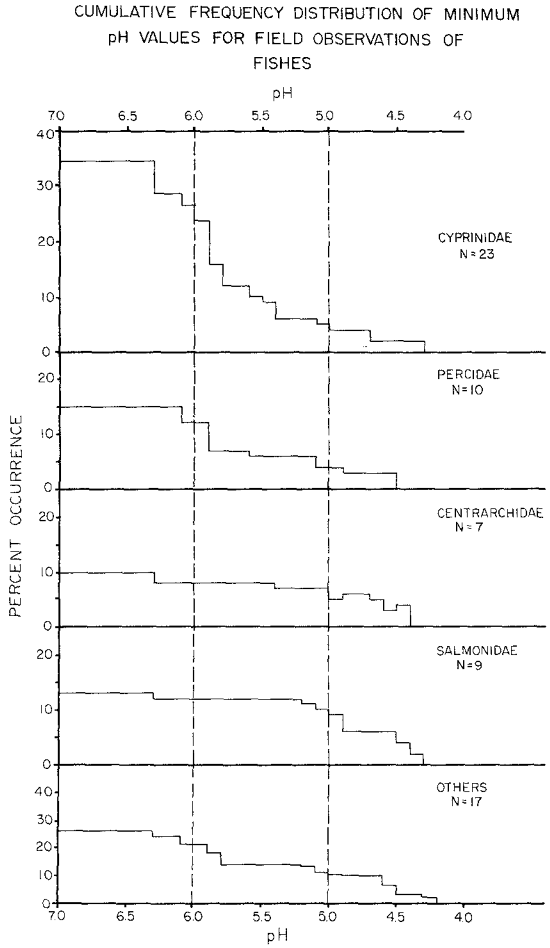

Figure 2. Minimum pH values reported for field observations of fishes, showing the percent reduction from pH 7.0 to pH 3.0. The range of pH from 6.0 to 5.0 is shown within the dotted lines. N is the number of species included in each panel. Redrawn from Eilers et al. (1984).

≤5.8. Pearl dace (Semotilus margarita), finescale dace (Phoxinus neogaeus), and redbelly dace (Phoxinus eos) are found in lakes of lower pH, but usually are not present in lakes with pH ≤5.3 (Mills et al., 1986; Beamish et al. 1976; McNicol et al., 1986, Figure 3).

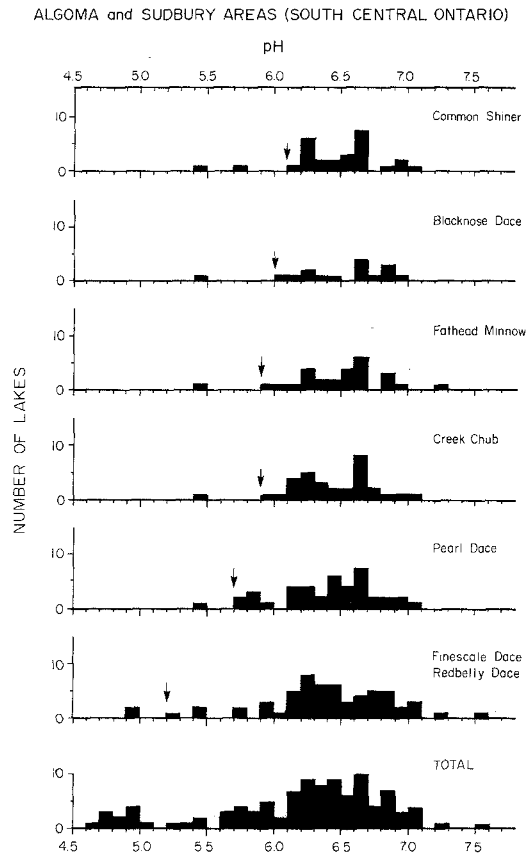

Figure 3. Presence of selected species of Cyprinidae in small lakes in the Sudbury and Algoma areas of Ontario. The bottom panel is the pH frequency distribution for all lakes that were sampled. Arrows represent approximate lower pH limit for each species. The single observations for each species at pH 5.4 are from one lake. Data were provided by D.K. McNicol, B.E. Bendell, and R.K. Ross, Canadian Wildlife Service, Hull.

4. THE LAKE 223 ACIDIFICATION

An important test of the relationship of field survey data to actual species pH tolerances is the detailed monitoring of those species during gradual lake acidification. With the exceptions of fish populations in a few lakes of the La Cloche Mountains, Ontario (Beamish and Harvey, 1972; Beamish 1974; Harvey and Lee, 1982), extensive temporal data for sequential losses of species from lakes undergoing gradual acidification are rare. One of the purposes of the experimental acidification of Lake 223, a small oligotrophic lake in northwestern Ontario, was to test predictions of species losses based on survey results. Changes in water chemistry and biota of Lake 223 are discussed extensively elsewhere (see Schindler et al., 1985 for a synopsis). As the lake epilimetic pH was lowered from 6.8 (1979) to 5.1 (1983), species losses and appearances occurred. In general, diversity of most algae, zooplankton, benthos, and fishes declined. Important lake trout prey (such as Mysis relicta, Pimephales promelas, etc.) were lost.

Table I
pH thresholds of biotic changes for selected Lake 223 organisms and thresholds for these changes inferred from synoptic surveys.

Biota	Lake 223 pH (year)	Survey pH
Mysis relicta abundance decline	5.93 (1978)	
Fathead minnow abundance decline	5.93 (1978)	5.8[a], 5.9[b], 6.7[c]
Mougeotia mats appear	5.64 (1979)	5.5[d], 5.8[e]
Asterionella ralfsii appears	5.64 (1979)	5.5[f]
Orconectes virilis abundance declines	5.59 (1980)	
Lake trout recruitment ceases	5.59 (1980)	5.5[g]
White sucker recruitment ceases	5.02 (1981)	4.9[c], 5.0[h]
Pearl dace abundance declines	5.09 (1982)	5.2[b], 5.4[a]
Leeches become rare	5.09 (1982)	
Mayfly Hexagenia disappears	5.13 (1983)	

[a] Beamish et al. 1976
[b] McNicol et al., 1986 (Fig. 3)
[c] Rahel and Magnuson, 1983
[d] Stokes, 1981
[e] Eloranta and Kumas, 1976
[f] Lowe, 1974
[g] Beggs et al., 1985
[h] Harvey, 1982
[i] Raddum and Fjellheim, 1984

Toxic thresholds for Lake 223 taxa confirmed many thresholds inferred from survey data (Table I). Survey data for other species which disappeared from Lake 223 are not available or are sparse. Mysis relicta is a widespread glacial relict in Canada, but no survey data are presently available to compare to the toxic threshold observed in Lake 223 by Nero and Schindler (1983). Despite frequent observations of Mougeotia mats in acid lakes, systematic surveys of its occurrence in lakes related to pH, similar to those for fishes, are not available. The data that are available support the threshold observed in Lake 223, although Mougeotia appeared during the acidification of Lake 302 at a somewhat higher pH (Turner et al., 1986). Survey data are not available for Orconectes virilis, but the toxic threshold observed for this species in Lake 223 is similar to pH thresholds inferred for other Orconectes species (Berrill et al., 1985). Comprehensive survey data are presently not available for leeches and Hexagenia mayflies. Toxic effects on lake trout and white sucker, two species that are often monitored in lake acidification surveys, occurred relatively late in the Lake 223 acidification. In addition, we could not confirm the recruitment failure for lake trout (which first occurred 1979) until 1981; age 0 and 1 lake trout are difficult to catch in lakes regardless of pH. Based on our Lake 223 experiment and survey data, a strong case can be made for use of (a) acidobiontic diatoms, (b) macroinvertebrates, and (c) non-sport or non-commercial fish species as indicators of the early phases of lake acidification.

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