A Critical Assessment of Effects of Acidification on Fisheries in North America [and Discussion]

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Phil. Trans. R. Soc. Lond. B 1984 **305**, 501-516
doi: 10.1098/rstb.1984.0073

Phil. Trans. R. Soc. Lond. B **305**, 501–516 (1984)
Printed in Great Britain

A critical assessment of effects of acidification on fisheries in North America

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Recently the U.S. Environmental Protection Agency sponsored through North Carolina State University, a critical assessment of acid rain effects in the United States. Our charge was to evaluate critically the peer-reviewed, published literature on effects of aquatic biota.

Three types of evidence are available: field comparative studies across pH gradients (space or time); laboratory experiments where pH is manipulated; and field experiments in which the pH of lakes or streams is manipulated. Most inferences have been made from comparative studies, the least in field manipulations. Our judgements were that the strength of a statement on effects was increased when two or more types of information supported the conclusion. A weakness in the North American experience is the absence of field manipulative experiments. Also the observed correspondence among results inferred by all three types of evidence, strengthened results available only from comparative studies or only from laboratory studies.

After such an analysis, it is clear that when acidification occurs fisheries have been and will be damaged by loss of fish, reductions in benthic and planktonic invertebrates and possibly by the accumulation of periphyton and detritus. Functional responses of aquatic ecosystems are more poorly known. Expected pH values of sensitive waters in the U.S.A. after long-term acidification are expected to be between pH 4.3 and 4.9.

INTRODUCTION

Fish and the effects of habitat acidification on fish are soon prominent in any discussion of damages caused by acidic deposition. This should not be surprising. The evidence is relatively clear on the influence of acidification on fish. Fish are directly used by humans. And fish are not obscure to our common knowledge. This being the case, it is surprising how difficult it is to document the effects of acidic deposition from anthropogenic sources on the acidification of lakes and streams and the subsequent reduction in fishery resources.

Our purpose is to relate one attempt to estimate the influence of habitat acidification on fisheries, namely the preparation of *The acidic deposition phenomenon and its effects – critical assessment review papers* prepared under the direction of Dr R. A. Linthurst of North Carolina State University for the U.S. Environmental Protection Agency. Actually the critical assessment document is much broader than the effects on fish and includes chapters on emission sources, transport processes, chemical transformation in the atmosphere, atmospheric concentrations, precipitation scavenging processes, dry deposition processes, deposition monitoring, and effects on soils, vegetation, aquatic chemistry, aquatic biota, human health, and materials.

Our objectives are to describe briefly the process by which the critical assessment document was developed for effects on aquatic biota, to provide examples of loss of fish populations, to indicate the types of information available to judge the influence of acidification on fish, to give examples of each type of evidence, to evaluate the amount and quality of evidence, and to provide several suggestions for future research.

Loss of fish populations

A high proportion of lakes with a pH less than 5.0 are fishless both in the LaCloche Mountains of Ontario (Harvey 1975) and in the Adirondack Mountains of New York (Schofield 1976*a*). In the same regions almost no lakes with a pH greater than 5.0 are fishless. The major questions are whether the fish are absent owing to low pH and associated toxic materials, whether the fishless lakes previously had fish and a pH greater than 5.0, and finally if this previous statement were true, did acidic depositions cause the pH to decline and thus cause the loss of fish.

The LaCloche Mountain lakes receive SO_2 from a large smelter at Sudbury. Harvey & Lee (1982) estimated that 388 fish populations have been lost from 50 lakes with a pH less than 6.0. Historic fishery data document the loss of 54 fish populations. The acidic lakes of the region also have concentrations of Cu, Ni, Zn, and Pb (Beamish 1976) that may be higher than in other areas with acidified lakes.

In the Adirondacks, Schofield (1976*a*) has historic data on fish populations and lake pH from 40 lakes above 610 m elevation. Seventeen of the 40 lakes appeared to have lost their fish populations from the 1930s to the 1970s. The acidity of the lakes had increased based on pH measurements. Data on loss of fish populations in a larger number of lakes are in the files of the New York Department of Environmental Conservation, but have not been published yet.

These are the only two groups of lakes for which evidence has been published on damage to fish populations in North America resulting from acidic deposition.

Sources of information

Three types of information are available from which to make judgements about effects of acidification on fish populations. These are: (i) observations which either compare fish occurrence among aquatic habitats that differ in pH (spatial association) or fish occurrence within an aquatic habitat that has or is expected to have acidified over time (temporal associations); (ii) laboratory experiments designed to determine toxic levels of pH or associated metals or to elucidate a particular process related to fish survival or performance; and (iii) field experiments in which natural aquatic ecosystems are manipulated, as, for example, the pH of a lake or enclosure in a lake is intentionally lowered and the responses are observed.

Each of the above types of information has its strengths and its weaknesses. Observations in the real world have all the elements of realism but spatial associations of fish and pH may be biased by other variables associated with pH such as lake area or the absence of spawning substrates. Temporal associations are often less than convincing because methods to measure pH or fish populations may have changed and the question of comparability is often challenged. Laboratory experiments can often elucidate cause and effect mechanisms but the artificiality of experimental conditions can bias a result. More importantly, in the absence of good information on the natural system, a laboratory experiment may answer the wrong question or leave out an important covariant. For example, usefulness of laboratory data on the influence of pH on egg mortality may be relatively limited because calcium and aluminium were not also varied (or measured). A field experiment eliminates many problems with confounding factors associated with field correlations and the lack of realism associated with laboratory experiments, but also has its own difficulties. For example, in a field experiment of lake acidification the time scale must be compressed and the results could be affected by a faster rate of acidification.

Conclusions supported by all three types of information are likely to stand the test of time better than conclusions based on only one type of data. Examples of each type of data are given below.

TABLE 1. LOSS OF FISH FROM TWO LACLOCHE MOUNTAIN LAKES: LUMSDEN LAKE AND GEORGE LAKE

lake	date	species information
Lumsden	1950s	eight species present
	1960	last report of yellow perch
		last report of burbot
	1960–65	sport fishery fails
	1967	last capture of lake trout
		last capture of slimy sculpin
	1968	white sucker suddenly rare
	1969	last capture of trout-perch
		last capture of cisco
	1969	last capture of white sucker
	1970	last capture of lake chub
George	1961	last spawning of walleye
	1965	last capture of smallmouth bass
	1966	last spawning of lake trout
		last capture of trout-perch
	1970	last capture of burbot
		most white suckers fail to spawn
	1971	last capture of walleye
		brown bullhead fail to spawn
	1972	northern pike, pumpkinseed, rock bass, brown bullhead, and white sucker fail to spawn
		last capture of lake whitefish
	1973	lake trout rare
	1974	northern pike and pumpkinseed rare
	1978	few age classes of white suckers remain
	1979	brook trout and muskellunge rare
		white sucker, brown bullhead, rock bass, cisco, and yellow perch present

From Baker in chapter E5 of the critical assessment document based on Beamish & Harvey (1972); Beamish *et al.* (1975); Harvey & Lee (1982).

OBSERVATIONS: SPATIAL ASSOCIATIONS

Lakes in the Northern Highlands Lake District of Wisconsin provide an opportunity to compare the occurrence of fish with lake pH in a region that has not seen temporal declines in pH or the loss of fish populations. Some of the larger drainage lakes have a pH as high as the upper 8s; the clear water, oligotrophic seepage lakes have pH levels in the mid 5s; and the dystrophic, kettle bog lakes have pH levels as low as about 4.2 (Black *et al.* 1963).

The type of fish assemblage (Rahel 1983) and the occurrence of individual species (Rahel & Magnuson 1983) are associated with lake pH. For example, 13 species did not occur at pH less than 6.0, another ten species did not occur at a pH less than 5.0 and only eight occurred in lakes between pH 4.0 and 5.0. Those species that did not occur below pH 6.0 included six minnows (Cyprinidae) and three darters (Percidae). Those that occurred below pH 6.0 but not pH 5.0 included two more minnows, three sunfish (Centrarchidae), and two pike (Esocidae). Those that occurred below 5.0 included three sunfish, and two bullheads (Ictaluridae). The two species that occurred at the lowest pH were the yellow perch (*Perca flavescens*) at pH 4.4 and the central mudminnow (*Umbra limi*) at pH 4.0.

It is tempting to conclude that these distributions are caused by differences in pH tolerance. We know that factors other than pH influence which species of fish occur (Rahel 1983; Rahel & Magnuson 1983; Tonn & Magnuson 1982; Tonn *et al.* 1983). However, the lowest pH at which a species occurred in these naturally acidic waters was correlated ($r_s = 0.85$, $n = 12$) in a sensible way with the lethal pH measured in the laboratory for the same species by sequentially lowering pH of their tank (Rahel & Magnuson 1983). The cyprinids died at higher pH levels, centrarchids at intermediate pH levels and the central mudminnow and yellow perch died last at the lowest laboratory pH levels. Thus, while the relationship is not without bias, field occurrences were related to pH tolerances.

It is also tempting to use the field data to predict the tolerance of these species to acidified waters. Again we know that factors other than pH such as metal concentrations in acidified habitats do alter pH tolerance. However, for 13 fish species in common between our data on naturally acid lakes (Rahel & Magnuson 1983) and data from the LaCloche Mountain Lakes which are anthropogenically acidified (Harvey 1980), the lowest pH at which the species occur are associated ($r = 0.84$).

OBSERVATIONS: TEMPORAL ASSOCIATIONS

The best example of a field study with temporal association between declining lake pH and the loss of fish species is data from the LaCloche Mountain Lakes (Beamish & Harvey 1972; Beamish *et al.* 1975, and Harvey & Lee 1982). Two case histories, Lumsden Lake and George Lake show a clear decline in the fish species (table 1).

In Lumsden Lake (table 1) eight fish species were present in the 1950s. By 1970 all eight species had become extinct. The pH of the lake by Hellige colour comparator was 6.8 in 1961 and 4.4 in 1971–73 as measured by a portable pH meter.

In George Lake (table 1) species losses and declines also occurred. The pH in 1961 was 6.5 measured with a Hellige colour comparator and in 1971–73 was 4.8 to 5.3 with a portable pH meter. In contrast to Lumsden Lake a number of species were still present in George Lake in 1979. This observation correlates with the higher pH in George Lake (4.8–5.3) than in Lumsden Lake (4.4) in the early 1970s.

It is tempting to conclude that declining pH and increasing metal loadings from the smelters at Sudbury caused the loss of fish. In fact, it is difficult to come up with an alternative explanation. With a few exceptions, the fish that were lost at earlier dates are those that are less tolerant to low pH and those lost at later dates are more tolerant species. However, questions can be raised. The method of measuring pH differed between the two dates. Are the results comparable? Why did a species very tolerant to low pH, the yellow perch, disappear at an early date in the Lumsden Lake when the measured pH was still 6.8? Yellow perch are known to live in lakes with a pH down to the mid 4s (Rahel & Magnuson 1978) and were still present in George Lake in 1979 at a pH apparently near 5.0. Hypotheses can be generated in response to these questions but the doubts that the questions raise point out the problem of using field observations of temporal associations alone to make a general conclusion about the influence of cultural acidification on fish populations.

A second temporal comparison from North America should be mentioned – that of Atlantic salmon (*Salmo salar*) in Nova Scotia reported by Watt *et al.* (1983). Catch data are available on 27 rivers from 1936 to 1980. Historic data on stream pH do not exist. Twelve of the rivers with a pH greater than 5.0 in 1980 had catch rates in the 1960s and 1970s similar to those in the 1930s. But ten of the rivers with a pH less than or equal to 5.0 in 1980 had catches about 15% of those observed in the 1930s. Five of the rivers with major watershed modification were excluded from the analysis. Also seven rivers with a pH less than 4.7, which previously had Atlantic salmon runs, no longer did. Based on annual data, declines in catch began in the mid 1950s. It would be useful to know what the pH levels of these two sets of streams were at that time. Perhaps they can be reconstructed from palaeolimnological data on diatom assemblages. Regardless, the losses of Atlantic salmon constitute 30% of the Atlantic salmon resource in Nova Scotia (Watt *et al.* 1983).

Laboratory experiments

Most laboratory experiments have been on the toxic effects of low pH. A moderate number have dealt with physiological responses, a few on growth and even fewer on behavioural responses. Laboratory experiments seem to be the best method to sort out the interacting effects of pH, aluminium, and other metals including calcium on the survival and performance of fish in acidified waters. Because recruitment failure appears to be a primary mode by which fish populations (Baker in chapter E5 of the critical assessment document) are lost from acidified waters, experiments on the influence of pH and associated toxic materials on the production of eggs, success of fertilization, egg survival and fry survival provide useful information. Because many acidification events are episodic rather than long term, the exposure of various life history stages to low pH and associated toxic materials for short periods is also important.

Reduction in egg production at lower pH levels occurred for three out of four North American species tested (Menendez 1976; Mount 1973; Craig & Baksi 1977; Lee & Gerking 1981). In three of the species the numbers of eggs produced at pH 5.0 were 10% or less of the numbers produced at pH levels near 7.0 or higher. The percentage hatching declined at pH 6.0 for fathead minnow (*Pimephales promelas*) and brook trout (*Salvelinus fontinalis*) and at pH 5.5 for flagfish (*Jordinella floridae*). At pH 5.0 egg survival was near 20% and fry survival near 0%.

These experiments can perhaps be faulted for application to cultural acidification. One of the four species, the desert pupfish (*Cyprinodon n. nevadensis*) (Lee & Gerking 1981) normally lives in alkaline desert waters of southwestern United States. Thus low alkalinity and low pH would be a more stressful environment factor for it than for species normally living in waters susceptible to cultural acidification. Information on the sensitivity of this species to low pH is not too useful. Two of the species, fathead minnow and brook trout, were tested in acidified hard water, which would not be susceptible to long term acidification. Results on these two species would be more useful for estimating effects of more episodic events which can occur during egg and fry stages, than for judging the effects of long term acidification on the adults. The fourth species, the flagfish, occurs in areas of Florida susceptible to acidification and was tested in soft water. Interestingly, effects of lowering pH to 6.0 and to 5.0 were similar for the flagfish experiments and the experiments with brook trout and fathead minnow. Lower pH significantly reduced the number of eggs produced, the success of fertilization, egg survival, and fry survival. An exception was that brook trout did not have reduced egg production at lower pH.

TABLE 2. CHANGES IN FISH POPULATIONS IN THE EXPERIMENTAL ACIDIFICATION OF LAKE 223 IN ONTARIO

date	pH	recorded change for fish
1976	6.8	none
1977	6.1	none
1978	5.8	fathead minnow – impaired recruitment lake trout – possible increase in embryonic mortality
1979 1980	5.6 5.4	fathead minnow – population collapse pearl dace – increase in abundance slimy sculpin – decrease in abundance white sucker – increase in abundance lake trout – increase in abundance
1981	5.1	lake trout – recruitment failure white sucker – recruitment failure

Mills 1982; Schindler & Turner 1982.

Another problem with these experiments was that aluminium was not considered as a treatment variable. Thus effects of low pH are likely underestimated. For example aluminium increased egg survival at pH 4.2 to 4.8 but increased mortality of sac fry and older fry to all pH levels for white sucker (*Catostomus commersonii*) and brook trout (Schofield & Trognar 1980; Baker & Schofield 1982; Muniz & Leivestad 1980*a*). These levels of aluminium occur in the Adirondack region (Schofield 1976*a*) and in the Pine Barrens of New Jersey (Budd *et al.* 1982).

Laboratory experiments help determine the mechanisms by which cultural acidification affects fish populations, but they can be unrealistic and can either overestimate or underestimate the expected affects of low pH in a field habitat exposed to episodic or long term cultural acidification.

FIELD EXPERIMENTS

The first experiments in North America relative to acidification of lakes were liming experiments in dystrophic acid lakes (Hasler *et al.* 1951). One by Smith (1957) in the Pine Barrens of New Jersey demonstrated that centrarchids, which had not reproduced successfully, produced a year class after the lake was limed. Another in the Upper Peninsula of Michigan divided a small bog lake which was hour-glass shaped (Peter and Paul) into two parts (Stross *et al.* 1961; Kitchell & Kitchell 1980). One half was limed, the other was used as a reference or a control for the treated half of the lake.

The most useful field experiment to estimate the effects of anthropogenic acidification on fish was conducted in the Experimental Lakes area of western Ontario (Mills 1982; Schindler & Turner 1982). Lake 223 had a pH of 6.5–6.9 and an average alkalinity of 80 μeq l^{-1} in 1976 before acidification. Each spring the pH was lowered by applying sulphuric acid directly to the lake and maintained at a new pH level until pH 5.1 was reached in 1981. The influence on fish, summarized in table 2, began as pH levels decreased below 6.0. The fathead minnow began to have impaired recruitment. By 1981 when a pH of 5.1 was reached major effects on all five species of fish had been observed. This important experiment provides a link between the field observations and laboratory experiments on the influence of acidification. It also points out the importance of biological interactions within species assemblages being influenced by progressive acidification. When recruitment failure occurred in fathead minnows, their competitor, the pearl dace (*Semotilus marginata*), increased in abundance. Before acidification pearl dace were rare.

Results from field experiments such as the acidification of lake 223 can also be criticized. The atmospheric pollutant was applied directly to the lake and watershed interactions that might release aluminium are not included in the experiment. Owing to the length of life of fishes, populations can persist as adults at lower pH levels than would be expected after a recruitment failure at slower rates of acidification. However, a field experiment is the most powerful means of combining the benefits of realism in field observations and the control available in laboratory experiments.

Strength of the information

Information on the response of fish to acidification is extensive and occasionally conflicting. The strength of a conclusion is stronger when the three types of information (field correlations, laboratory experiment, and field experiment) are available and support each other. Since each of the three methods has different strengths and weaknesses, the consistency in a result among them provides the strongest evidence available for a response to acidification. Also, the more studies to reach similar conclusions from similar methods but under different conditions or with different species, the stronger the conclusion. The strongest information on the influence of acidification of surface waters on fishes is tabulated in table 3.

The conclusion for example that the fathead minnow will be lost from North American waters which decline in pH to near 6.0, is well documented. In naturally acid lakes of northern Wisconsin they do not occur at a pH less than 6.7 (Rahel & Magnuson 1983). In laboratory experiments when pH was reduced from 6.5 to 6.0, the number of eggs produced per day decreased to 40% of control animals, the survival of eggs to hatching decreased from 80% to 40%, and the survival of fry declined from 80% to 60% of the number hatched (Mount 1973). Finally, when lake 223 was experimentally acidified with sulphuric acid, recruitment of fathead minnows was impaired at pH 5.8–6.0 and the population collapsed at pH 5.3–5.8 (Mills 1982). Thus, each type of information predicts the loss of fathead minnow populations at pH levels near 6.0. Also, the certainty of a prediction is greater if predictions are not more precise than the methodologies allow. While reasonable hypotheses can be raised to explain the difference in results among the three studies on fathead minnows, it might be safer to predict that fathead populations would be negatively influenced or lost at pH levels between 5.5 and 6.5. Similar discussion could be put forth for other species that disappear near pH 5.0 such as Atlantic salmon (table 3) or near pH 4.2–4.5 such as yellow perch (table 3).

Acidification causes the loss of fish populations from aquatic environments (table 3). Some species are influenced at pH levels as high as 6.0. Many are influenced at levels of 5.0 and below. A few species flourish or persist below pH 5.0.

If we are less critical and include data from only single approaches or single papers, a

Table 3. Effects of increasing acidity on fishes

	sources of information			
taxa	field observation	lab experiment	field experiment	observed effects
fathead minnow (*Pimephales promelas*)	Rahel & Magnuson 1983	Mount 1973	Mills 1982	One of the most acid-sensitive fish species. Reproductive failure occurs near pH 6.0. Generally absent in waters below pH 6.5.
darters (*Etheostoma exile*, *E. nigrum*, *Percina caprodes*) and minnows (several *Noptropis* spp. *Pimephales notatus*)	Harvey 1980; Rahel & Magnuson 1983	Rahel & Magnuson 1983		Very acid sensitive. Generally absent below pH 6.0 in both naturally acidic and anthropogenically acidified waters
smallmouth bass (*Micropterus dolomieui*)	Beamish 1976; Harvey 1980; Rahel & Magnuson 1983			reproduction ceases and populations become extinct below pH 5.2–5.5
lake trout (*Salvelinus namaycush*)	Beamish 1976; Beamish *et al.* 1975	Beamish 1972;	Mills 1982	experiences reproductive failure near 5.0. Generally absent below pH 5.0 in both naturally acidic and anthropogenically acidified waters
white sucker (*Catostomus commersoni*)	Harvey 1980; Rahel & Magnuson 1983	Baker & Schofield 1982	Mills 1982	as lake trout.
rainbow trout (*Salmo gairdneri*)	many	many		adversely affected by pHs below 5.0–5.5
Atlantic salmon (*Salmo salar*)	many	many		adversely affected by pHs below 5.0
brown trout (*Salmo trutta*)	many	many		lower pH limit between 4.5 to 5.0
brook trout (*Salvelinus fontinalis*)	many	many	Hall *et al.* 1980	lower pH limit between 4.2 to 5.0
sunfishes (*Ambloplites rupestris*, *Micropterus salmoides*, *Lepomis* spp.)	Harvey 1980; Rahel & Magnuson 1983		Smith 1957	lower pH limit near 4.5
yellow perch (*Perca flavescens*)	Svardson 1976; Keller *et al.* 1980; Harvey 1980; Rahel & Magnuson 1983	Rahel 1983		lower pH limit 4.2 to 4.5 May become very abundant after other species have become extinct.

For references see footnote to table 4.

Table 4. Preliminary estimates of the relation between pH and the loss of fish populations

species	lowest pH 6.9–6.5	6.4–6.0	5.9–5.5	5.4–5.0	4.9–4.5	4.4–4.0
blacknose shiner	- - -					
mimic shiner	- - -	- - -				
logperch	- - -	- - -				
Johnny darter	- - -	- - -				
Iowa darter	- - -	- - -				
bluntnose minnow	- - -	- - -	- - -			
common shiner	- - -	- - -	- - -			
rainbow trout	- - -	- - -	- - -			
muskellunge	- - -	- - -	- - -			
black crappie	- - -	- - -	- - -			
mottled sculpin	- - -	- - -	- - -			
northern redbelly dace	- - -	- - -	- - -	- - -		
creek chub	- - -	- - -	- - -	- - -		
golden shiner	- - -	- - -	- - -	- - -		
fathead minnow	――	――	――	- - -		
arctic char	――	――	――	――		
burbot	――	――	――	- - -		
troutperch	――	――	――	――		
brook stickleback	- - -	- - -	- - -	- - -		
walleye	――	――	――	- - -		
slimy sculpin	――	――	――	――		
lake chub	――	――	――	――	――	
brook trout	――	――	――	――	――	
brown trout	――	――	――	――	――	
Atlantic salmon	――	――	――	――	- - -	
lake trout	――	――	――	――	- - -	
brown bullhead	――	――	――	――	――	
black bullhead	- - -	- - -	- - -	- - -	- - -	
yellow bullhead	- - -	- - -	- - -	- - -	- - -	
white sucker	――	――	――	――	- - -	
smallmouth bass	――	――	――	――	- - -	
largemouth bass	――	――	――	――	- - -	
cisco	――	――	――	――	――	- - -
lake whitefish	――	――	――	――	- - -	- - -
bluegill	- - -	- - -	- - -	- - -	- - -	- - -
pumpkinseed	――	――	――	――	- - -	- - -
rock bass	――	――	――	――	――	- - -
northern pike	――	――	――	――	――	- - -
yellow perch	――	――	――	――	――	- - -
central mudminnow	――	――	――	――	――	――

――, Range of successful reproduction, if known; - - - -, lowest pH at which the population occurs.†

† Sources: Figure 1 in Rahel & Magnuson (1983) and figures 5–16 developed by Baker in chapter E5 of the critical assessment document. The references used are Almer *et al.* (1978); Baker & Schofield (1982); Beamish (1972); Beamish (1976); Beamish *et al.* (1975); Brown (1981); Carrick (1979); Daye & Garside (1976); Dunson & Martin (1973); Edwards & Hjeldnes (1977); Farmer *et al.* (1981); Grahn *et al.* (1974); Grande *et al.* (1978); Harriman & Morrison (1982); Harvey (1979); Harvey *et al.* (1982); Hoglund (1961); Hulsman & Powles (1981); as reported in M.O.I. (1982); Hulzberg (1977); Jacobsen (1977); Jensen & Snekvik (1972); Johansson & Kihlstrom (1975); Johansson & Milbank (1976); Johansson *et al.* (1977); Johnson (1975); Johnson & Webster (1977); Kwain (1975); Leivestad *et al.* (1976); Lloyd & Jordan (1964); McDonald *et al.* (1980); Menendez (1976); Milbrink & Johansson (1975); Mills (1982); Mount (1973); Muniz & Leivestad (1980*b*); Nelson (1982); Overrein *et al.* (1980); Peterson *et al.* (1908*a*); Peterson *et al.* (1980*b*); Rahel & Magnuson (1983); Robinson *et al.* (1976); Runn *et al.* (1977); Ryan & Harvey (1977); Ryan & Harvey (1980); Schofield (1965); Schofield (1976*b*); Schofield & Trojnar (1980); Swarts *et al.* (1978); Trojnar (1977); and Watt *et al.* (1983).

preliminary table of pH dose and fish response can be generated for 40 species of fishes that occur in North America (table 4).

Of the 40 species, five would be expected to be absent in waters below pH 6.0, 11 absent below pH 5.5, 21 absent below pH 5.0, 32 absent below pH 4.5 and all absent below pH 4.0. Reduced recruitment would be expected to begin at a pH about 0.5 pH units higher. Thus, when pH declined below 5.0, 32 species or 80% would be expected to have population declines from impaired recruitment.

Galloway *et al.* (chapter E4 in the critical assessment document) estimated the expected alkalinities of surface waters susceptible to long term anthropogenic acidification and to episodic acidification. When converted to pH, these estimates are: waters originally in the mid 5s would decline to pH 4.3–4.9 after long term acidification, and waters with a pH as high as 7.0 would experience episodic acidification to pH 4.3–4.9.

If these pH levels are compared with the results of table 4 on fish tolerance to pH, it is apparent that only the most tolerant fish species would persist in affected waters and most of these species would experience reduced recruitment.

These conclusions are probably conservative, because current results (tables 3 and 4) do not fully account for metal toxicities, sublethal effects on fish, or alterations to other aquatic biota that provide food or cover to fish. These conclusions are probably an overestimate because not all waters in North America are susceptible to acidification nor are all susceptible waters likely to receive acidic deposition.

This paper does not cover all the significant results presented in the critical assessment document that relate to fish. To alleviate this problem in part, the conclusions relating to effects on fish and a portion of the general summary on the effects on aquatic biota are quoted below.

Fish populations

'The clearest evidence for impacts of acidification on aquatic biota is adverse effects on fish.

Loss of fish populations associated with acidification of surface waters has been documented in the LaCloche Mountain range of Ontario, Nova Scotia, and southern Norway. Available data for these regions include historical records of declining fish populations coupled with historical records of increasing water acidity. Additional evidence for loss of fish populations is available from the Adirondack region of New York State and southern Sweden.

'In the United States, only in the Adirondack region have adverse effects of acidification on fish populations been observed. The presence of fish in Adirondack lakes and streams is correlated with pH level. Particularly below pH 5.0, the occurrence of fish is reduced. Loss of fish populations has been documented for about 180 Adirondack lakes (out of a total of approximately 2877), although historical records are not available at this time to relate each loss specifically to acidification or acid deposition.

'Fish kills have been observed during episodic acidification of surface waters in Norway and Ontario. In addition, in hatcheries receiving water directly from lakes or rivers, unusually heavy mortalities of adult and young fish have occurred in the Adirondack region, Nova Scotia, and Norway. These mortalities are typically associated with rapid decreases in pH (generally to pH levels below 4.5–5.0) during snowmelt.

'Many fish populations in acidic waters (pH 4.5–5.0) lack young fish, implying that failure to reproduce is a common, although not the only, cause for extinction of fish populations with acidification. In Sweden, neutralization through lake liming resulted in the recurrence of young fish.

'Field observations of growth of adult fish in acidic (pH 4.0–6.0) versus non-acidic waters, or through time with acidification, typically indicate no change or increased growth with increased acidity. In some cases, increased growth may be a result of reduced competition for food as fish populations decline.

'Experiments in the laboratory and the field have established a direct cause-and-effect between acidification and adverse effects on fish. In the field, acid additions to lake 223 in the Experimental Lakes area of Ontario produced pH declines from pH 6.5 to 5.9 in 1976 to pH 5.1 in 1981 and resulted in reproductive failures and, or, extinction of several fish populations. In laboratory bioassays, pH and aluminium levels typical of acidified surface waters were toxic to fish.

Summary of effects on aquatic biota

'Biological effects owing to acidification become apparent as pH values decline to between 6.5 and 6.0. Since the biological response to acidification is a graded one, continuing pH declines below this range will result in escalating biological changes. These pH levels, along with other changes associated with the acidification process (for example increased aluminium, clarity, accumulation of detritus and algal mats), will have significant harmful effects on aquatic organisms. In waters where pH values average 4.9 or lower, most fish species, virtually all molluscs, and many groups of benthic invertebrates will be eliminated. Increased aluminium concentrations may eliminate fish species otherwise tolerant of low pH. The plankton community will be simplified and dominated by a few acid-tolerant taxa. Benthic algal mats will often cover the lake bottom, and water clarity may increase. These represent the best documented effects of acidification. Effects on ecosystem processes remain largely unconfirmed and are an important area for future research efforts.'

Research needs

Many research needs can be identified. I wish to highlight three general research areas.

First, to increase the confidence in conclusions about the influence of acidification and associated toxic substances on fish, manipulative field experiments are needed to test hypotheses apparent from field observations and laboratory experiments. There are few such experiments (table 5) and the existing ones greatly aid in the confirmation of results and the rationalization of contradictions in both field observations and laboratory experiments.

Second, the influence of acidification is apparent in all biotic components of aquatic ecosystems (Kinsman, this symposium). Yet, studies on biota other than fish are almost exclusively field correlations in space or time (table 5). Our knowledge of the ecosystem on which the fish depend is less than our knowledge of the fish themselves. Laboratory experiments and field experiments on both benthos and plankton are rare or uncommon so that conclusions on cause and effect are almost impossible to make. Studies of macrophytes and decomposers are uncommon, rare or absent (table 5) in the acidification literature.

Third, most studies on effects of cultural acidification on fishes and other aquatic biota are on the influence of acidification on the biotic structure of aquatic ecosystems. Studies on processes such as primary production, energy transfer between trophic levels, decomposition, and altered species interactions (predation and competition) are rare. Such studies are needed to reduce contradictions in the present literature and to understand the functioning of a healthy aquatic ecosystem rather than to just understand the direct toxic effects of pH and associated materials on fish populations.

The critical assessment document is presently in a public review draft and has not been formally released by the U.S. E.P.A. nor should it be construed to represent the E.P.A.s policy. Its purpose is to 'address our present status of knowledge relative to the acidic deposition phenomenon and its effects'. The goal was to make the information as unimpeachable as possible. To do this the document is authored, uses literature references of high quality, discusses potential versus known effects, attempts to evaluate the certainty of information, avoids extrapolation, and includes information without regard to policy implications. In addition, drafts have received extensive review from scientists, policy makers, and users. Finally each author remains responsible for what is in his or her portion of the text and has accepted and rejected recommendations of reviewers accordingly. The general outline and the authors of chapter E5 entitled 'Effects on aquatic biota' are:

TABLE 5. NUMBER OF STUDIES ON THE BIOLOGICAL EFFECTS OF CULTURAL ACIDIFICATION ON DIFFERENT BIOLOGICAL COMPONENTS OF AQUATIC ECOSYSTEMS

	number of investigations		
taxa	field observation	laboratory experiment	field experiment
fish	many	many	rare
macrophytes	rare	rare	absent
benthos	many	uncommon	uncommon
plankton	many	rare	uncommon
decomposers	uncommon	uncommon	uncommon

5.1. Introduction – John J. Magnuson (University of Wisconsin–Madison).
5.2. Biota of naturally acidic waters – Frank J. Rahel (University of Wisconsin–Madison).
5.3. Benthic organisms – Robert Singer (Colgate University).
5.4. Macrophytes and wetland plants – John H. Peverly (New York State College of Agriculture and Life Sciences).
5.5. Plankton – Joan P. Baker (North Carolina State University).
5.6. Fishes – Joan P. Baker.
5.7. Other related biota – Robert Singer and Kathleen Fischer (Environment Canada).
5.8. Observed and anticipated ecosystem effects – Joan P. Baker, Frank J. Rahel and John J. Magnuson.
5.9. Mitigative options relative to biological populations at risk – Charles T. Driscoll and Gary C. Schafran (Syracuse University), with the help of Charles A. Guthrie (New York State Department of Environmental Conservation) in the section on improving fish survival in acidified waters.
5.10. Conclusions – Magnuson, Rahel, Baker, Singer, and Peverly.

Most of this paper comes from the material prepared by Joan P. Baker, Frank J. Rahel or myself for the critical assessment document.

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APPENDIX 1. COMMON AND SCIENTIFIC NAMES OF FISH USED IN THE TABLES LISTED HERE ALPHABETICALLY BY COMMON NAME

common name	scientific name
arctic char	*Salvelinus alpinus*
Atlantic salmon	*Salmo salar*
black bullhead	*Ictalurus melas*
black crappie	*Pomoxis nigromaculatus*
blacknose shiner	*Notropis heterolepis*
bluntnose minnow	*Pimephales notatus*
bluegill	*Micropterus samoides*
brook stickleback	*Culaea inconstans*
brook trout	*Salvelinus fontinalis*
brown bullhead	*Inctalurus nebulosus*
brown trout	*Salmo trutta*
burbot	*Lota lota*
central mudminnow	*Umbra limi*
cisco	*Coregonus artedii*
common shiner	*Notropis cornutus*
creek chub	*Semotilus atromaculatus*
darters	*Etheostoma* sp.
fathead minnow	*Pimephales promelas*
golden shiner	*Notemigonus crysoleucas*
Iowa darter	*Etheostoma exile*
Johnny darter	*Etheostoma nigrum*
lake chub	*Couesious plurebeus*
lake trout	*Salvelinus namaycush*
lake whitefish	*Coregonus clupeaformis*
largemouth bass	*Micropterus salmoides*
logperch	*Percina caprodes*
mimic shiner	*Notropis volucellus*
minnows	Cyprinidae
mottled sculpin	*Cottus bairdi*
muskellunge	*Esox masquinongy*

common name	scientific name
northern pike	*Esox lucius*
northern redbelly dace	*Phoxinus eos*
pearl dace	*Semotilus marginata*
pumpkinseed	*Lepomis gibbosus*
rainbow trout	*Salmo gairdneri*
rock bass	*Ambloplites rupestris*
slimy sculpin	*Cottus cognatus*
smallmouth bass	*Micropterus dolomieui*
sunfishes	*Centrarchidae*
trout-perch	*Percopsis omiscomaycus*
walleye	*Stizostedion vitreum vitreum*
white sucker	*Catostomus commersoni*
yellow bullhead	*Ictalurus natalis*
yellow perch	*Perca flavescens*

Discussion

J. R. Kramer (*McMaster University*, *Hamilton*, *Ontario L8S 4M1*, *Canada*). Given an acid stress and associated metal concentrations (Al, Cu, etc.), would you rank in decreasing order of importance other factors that would, in your opinion, lead to fish extinctions.

J. J. Magnuson. Fish extinctions have frequently occurred from the introduction of exotic fishes (Magnuson 1976) and from loss of habitat (Magnuson 1978).

Extinctions caused by introduced or invading species are common in many areas of the world. Good examples are the influence of lamprey (*Petromyzon marinus*), alewife (*Also pseudoharengus*), and smelt (*Osmerus mordax*) in the Laurentian Great Lakes of North America. These three exotics were keystones in the extinction of lake trout, several deep water cisco, and certain cyprinids in Lake Michigan and Lake Huron. Such extinctions alter the species composition of fish communities in lakes. They do not cause the loss of all species of fishes.

Habitat loss or destruction can remove essential features of the environment for particular species and cause an extinction in streams or lakes. Examples are dams, which may prevent migrating fish from reaching their spawning habitat or may convert a stream to an impoundment with different thermal features and with riffle areas being covered by soft sediment. Other examples are the loss of nursery areas in backwaters of rivers caused by channelization, or the loss of habitat owing to water pollution. The River Thames has provided a good example of the loss of salmon and other species owing to the biological oxygen demand (b.o.d.) of wastes deposited in the river. Acidification and associated metal pollution is a habitat modification (chemical modification) which like b.o.d. loading can alter a habitat sufficiently to make it unsuitable for fish life. Thus, the water body is lost as a habitable environment for fish.

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