EVIDENCE OF FISH POPULATION RESPONSES TO ACIDIFICATION IN THE EASTERN UNITED STATES

Terry A. Haines
U.S. Fish and Wildlife Service
Columbia National Fisheries Research Laboratory
Field Research Station
Department of Zoology, University of Maine
Orono, ME 04469 USA

Joan P. Baker
Kilkelly Environmental Associates
P.O. Box 31265
Raleigh, NC 27622 USA

ABSTRACT. The hypothesis that acidification has reduced or eliminated fish populations in certain areas of the eastern United States was investigated by examining present and historical fishery survey records. The causes of acidification (e.g., atmospheric deposition) were not specifically considered, although instances of obvious alternative explanations (e.g., acid mine drainage, organic acids) were avoided. The number of usable data sets located was small. Trend analyses are severely limited by the lack of high quality historical data. The strongest evidence for fisheries declines associated with acidification is provided by data for the Adirondack Mountain region of New York. In some lakes, fish populations have declined or disappeared; lakes experiencing fishery declines are now acidic. Alternative explanations for changes in fish communities over time were examined. In 49 lakes, some or all fish populations have apparently been lost with no available explanation other than acidification. Extrapolation of these data to the entire Adirondack Mountain region suggests that perhaps 200 to 400 lakes may have lost fish populations as a result of acidification. Streams in Pennsylvania and Massachusetts also had documented declines in fish populations that were associated with acidity; however, the data are fewer and less complete than those for New York. Acidification effects on fishery resources in other regions of the eastern United States are apparently minimal. The extent of the damage to date appears small relative to the total resource.

Water, Air, and Soil Pollution **31** (1986) 605–629.
© 1986 *by D. Reidel Publishing Company.*

1. INTRODUCTION

The most widely reported consequence of acidic deposition is the reduction or elimination of fish populations in acidified waters (Overrein et al., 1980; Haines, 1981; Altshuller and Linthurst, 1984; Dillon et al., 1984). That acidification (below pH 5 to 6, depending on fish species) adversely affects fish and fish populations has been clearly demonstrated in laboratory and field experiments. In the laboratory, chemical conditions characteristic of acidified waters (low pH, elevated Al concentration, and low Ca concentration) decrease fish survival, growth, and reproductive potential (Baker and Schofield, 1982; Brown, 1983). Fish transferred into acidic lakes and streams, or held in cages during episodic acidification typically experience osmoregulatory stress and high mortality, occasionally 100% (Leivestad and Muniz, 1976; Johnson et al., 1986). The experimental acidification of Lake 223 in western Ontario (Schindler, et al., 1985) confirmed that acidification results in significant population effects - most notably recruitment failure and population extinction.

The issue, therefore, is not cause-and-effect. If acidification occurs, fish populations will be lost. However, difficult questions remain:

What levels of acidity (low pH, elevated Al, or both) result in fish population decline and loss?

How many fish populations have been lost or adversely affected as a result of acidic deposition?

What fraction of the resource has been lost or is likely to be lost in the near future?

To demonstrate conclusively that fish population trends in a water body are related to acidic deposition, certain criteria concerning temporal changes in surface water chemistry and fish populations are required. It must be shown that (1) the water body formerly supported a viable fish population, either self-sustaining or hatchery-maintained, (2) one or more fish species formerly present have been reduced or eliminated, (3) the water body is more acidic now than when fish were present or more abundant, (4) the increased acidity did not result from local factors, and (5) other factors have not adversely affected the fish population. Few available data sets meet these criteria, and most have not been published in the peer-reviewed literature.

Presumably, each region in the U.S. with surface waters potentially acidified by atmospheric deposition may have experienced loss of fisheries resources. Geographic areas of concern are (1) the Adirondack region of New York, (2) northern New England (Vermont, New Hampshire, Maine), (3) parts of Massachusetts and Rhode Island, (4) the Catskills/Pocono/Kittatinny Ridge regions of New York, New Jersey, and Pennsylvania, (5) the central Appalachian mountain region (Southern Blue Ridge Province) of western North Carolina, eastern Tennessee, and northern Georgia, and (6) northern Florida.

The following discussions briefly summarize our current understanding of the status of fish populations in these areas. The potential effects of acidic deposition and acidification on fisheries resources in each of these regions have not been thoroughly evaluated. The causes of acidification (e.g., acidic deposition) are not specifically considered, although instances of obvious alternative explanations (e.g., acidic mine drainage, organic acids) are avoided.

Some of the best documentation for loss of fish populations as a result of acidification involves historic records on water quality and fisheries status in the La Cloche Mountain region of Ontario (Harvey and Lee, 1982), in Nova Scotian salmon rivers (Watt et al., 1983), and in southern Norway (Muniz, 1984). These data are well known, have been widely published, and consequently are not repeated here.

2. CASE STUDIES

2.1. New York

The first reports of acidic deposition-induced acidification of lakes and concomitant declines in North American fish populations concerned the Adirondack Mountain region (Schofield, 1965, 1973, 1976a,b). Several reports (Pfeiffer and Festa, 1980; Colquhoun et al., 1984) summarized recent survey data concerning water chemistry and fish populations in lakes within this region. Schofield (1976b) surveyed 40 lakes that had been surveyed in the 1930s. In the 1930s, three lakes had pH <5.0 and no fish; one lake with pH between 6.0 and 6.5 was also fishless. In 1975, 19 of the 40 lakes had pH <5.0 and were fishless. Two additional lakes with pH between 5.0 and 5.5 also lacked fish. Thus 17 lakes apparently lost fish populations between the 1930s and 1975. Pfeiffer and Festa (1980) estimated that at least 180 lakes in the region had lost fish populations as a result of acidification; however the data supporting their conclusion were not published.

We recently reviewed all available fish population and water chemistry data for the Adirondack Mountain region (Baker and Harvey, 1984). The objectives of the study were to evaluate fish population status, scrutinize explanations for decline or loss of fish populations, and analyze statistical associations between fish population decline or loss and chemical variables indicative of acidity. Because fish sampling procedures have been highly variable over time, quantitative indicators of fish population status, such as catch per unit effort or population presence/absence, could not be used. To evaluate temporal changes in fish population status, discrete indicators of population status were developed. These indicators, known as ordered classifications, are used in cases where different levels of some factor can be recognized but not quantified with a standard unit of measurement on a continuous scale (Kleinbaum and Kupper, 1978). Population status was evaluated for 14 fish species common to the area and considered vulnerable to capture with the gear used. Evaluations were based on results from field surveys, including number, size, age, and sex of fish caught; sampling technique, e.g., gear used, gear size, effort, and depth fished; stocking records; and physical data on lake area, depth, and elevation. Ratings were based on a series of objective criteria to ensure consistency. All evaluations were conducted by the same person

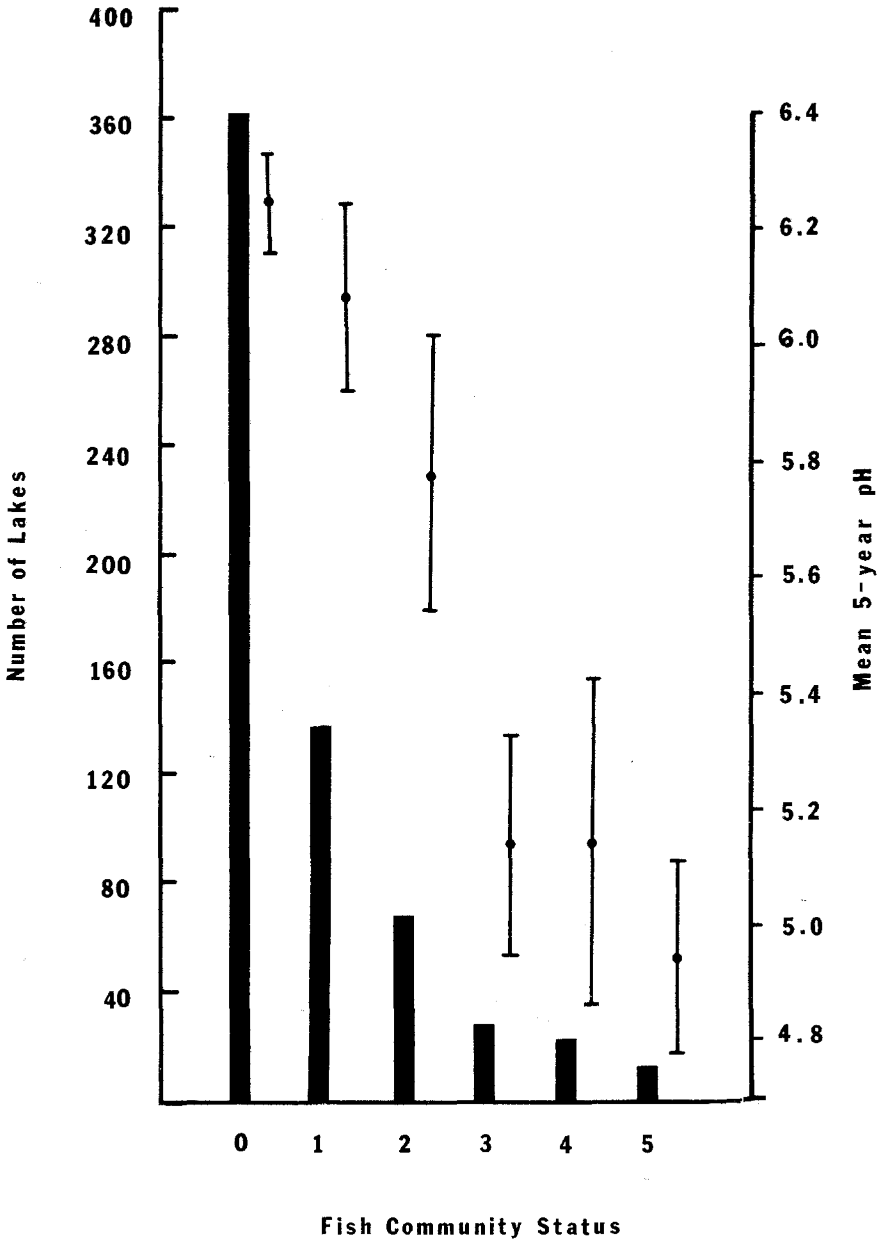

Figure 1. Number (solid bar) and fish community status rating for Adirondack lakes with mean 5-yr pH for the period centered on the year of the last fishery survey (dot). Vertical bar represents 95% confidence interval.

and based solely on fish population information, without knowledge of lake identity or acidity status.

Three ratings were assigned to each species population on a scale of probability from 0 (low) to 9 (high). Ratings were assigned for each of three probabilities: (1) that the fish population was constant or increased over time, (2) that the population declined over time, and (3) that the population was lost. For each population assigned a probability rating above 0 for decline or loss over time, the likelihood that the decline or loss resulted from factors other than acidification was evaluated. These evaluations were based on survey results, stocking records, and comments by field biologists regarding angler pressure, yield, presence of beavers, or other factors that could affect fish populations. Again, the evaluations were made without reference to lake identity or chemical status. The objective was to evaluate alternative explanations for fish population declines, such as reclamation, change in stocking practices, and introduction of new species. The rating scale ranged from 0 to 9, such that ratings 0 to 3 indicated that factors other than acidification were responsible for the change, ratings 4 to 5 were marginal, and ratings 6 to 9 represented increasing probabilities that the change resulted from acidification (i.e., no apparent alternative explanation). In addition, a single overall fish community status rating was assigned to each lake (Table I). After ratings were assigned, the statistical association between the ratings and lake chemical status was examined.

Table I. Fish community status ratings applied to New York lakes.

Rating	Community Status
0	Normally diverse, apparently healthy fish community, only random changes.
1	1 or 2 species declined or disappeared, but not acid-sensitive species. Population decline or loss apparently due to factors other than acidification.
2	1 or 2 species declined or disappeared, may be acid-sensitive species. Cause of population decline or loss uncertain.
3	1 or 2 acid-sensitive species declined or disappeared; no apparent explanation other than perhaps acidification.
4	Most or all species disappeared; no apparent explanation other than perhaps acidification. Any remaining species are acid-tolerant.
5	All species disappeared; no apparent explanation other than perhaps acidification. Confirmed fishless.

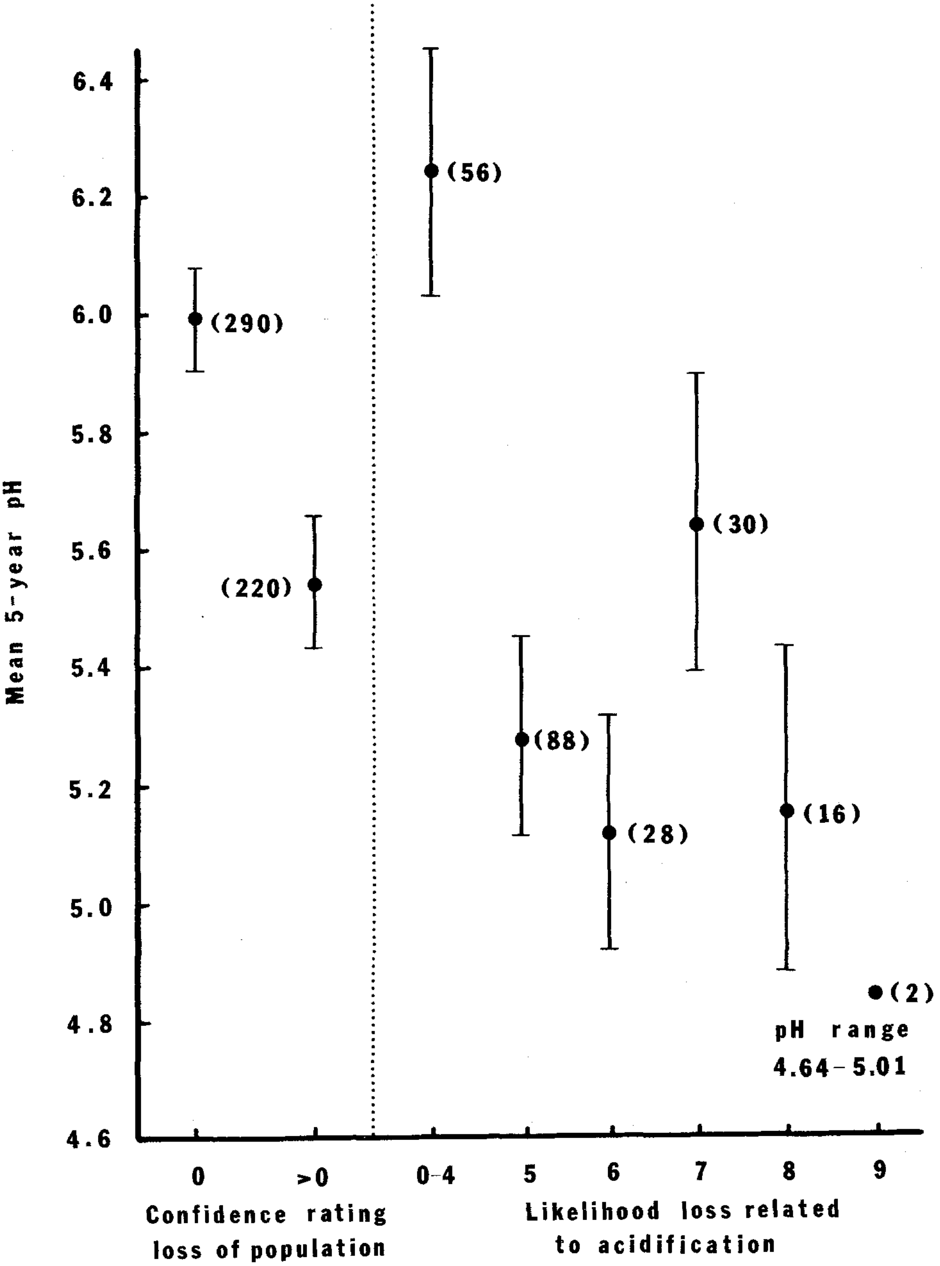

Figure 2. Adirondack brook trout population confidence ratings for the likelihood that the population was lost, and the likelihood that the loss was related to acidification, as compared to mean 5-yr pH. The number of lakes in each rating class is given in parentheses. (0 = low probability; 9 = high probability). Vertical bar represents 95% confidence interval.

Of the 2759 lakes (total area 99,666 ha) in the Adirondack Mountain region, chemical data were located for 1543 (95,304 ha) and fish survey data for 1461 (90,897 ha). Recent (1974-1983, excluding 1979) chemical data including electrometric pH measurements were available for 693 lakes (47,982 ha), and recent fish survey data for 427 (57,495 ha). Large lakes were overrepresented in the data set for lakes having both chemical and fish population data. Of the 693 lakes with recent chemical data, 171 (24.7%) had pH <5. Fish population data were sufficient for 604 lakes to assign fish community summary ratings; 49 (8.1%) were rated 3 to 5 and thus had a high probability that fish populations had actually declined or disappeared with no available explanation other than acidification (Figure 1). Both fish population and recent pH data were available for 396 lakes; 38 (9.6%) of these received summary fish community status ratings of 3 to 5. A series of _t_-tests indicated that lakes rated 3 to 5 had significantly (p <0.05) lower pH than lakes rated 0 to 2 (Figure 1). Many lakes in the Adirondack Mountain region are classified as brook trout lakes (Pfeiffer, 1979), including 220 of the 396 lakes discussed above. Of these, 30 (13.6%) received fish community summary ratings of 3 to 5.

Temporal change in pH was evaluated for lakes with both fish and water chemistry data. Lakes with summary fish community status ratings of 0 to 2, which were not likely to have populations that declined or disappeared, had a mean pH increase of 0.035 unit/decade. Lakes with summary ratings of 3 to 5 had a mean pH decrease of 0.117 unit/decade, which differed significantly from the 0 to 2 group (_t_-test, p <0.01); this suggests that pH had declined in lakes that probably had lost fish populations. However, the rate of change in pH over time was highly correlated with present pH.

Similar analyses were conducted for each of the 14 fish species considered. All species had populations that were rated as likely to have been lost (Table II). The proportion of populations lost was substantial for all species, ranging from 18% for white sucker to 67% for lake chub. Two species, lake chub and chain pickerel, had no populations for which population loss was rated as likely to have resulted from acidification (rating >5). The remaining 12 species received at least some probability ratings above 5, indicating that population losses had occurred with no apparent explanation other than acidification. The proportion of the populations for these 12 species that had disappeared probably because of acidification ranged from <1% for yellow perch to 12 to 14% for brook trout and lake trout. For all species, the proportion of populations lost for reasons other than acidity exceeded that lost apparently because of acidity. For these 12 species, analysis of variance indicated that lake pH was not significantly different among those rated 0 to 4, but was significantly (p <0.05) lower for those rated 6 to 9. Examples for three common species are presented in Figures 2 to 4.

Eight lakes having chemical and fishery data have also been sampled for evaluation of sediment diatoms and trace metals, allowing examination of multiple sources of information on chemical and biological trends (Table III). Sagamore and Panther lakes exhibit little or no evidence of acidification. Fish populations reflect only

Table II. Number and percent of fish species populations (with adequate data for evaluation of trends) rated as likely to have been lost (rating >0), and number and percent with no apparent explanation for population loss other than acidification (rating >5).

Species	Number of Populations	Likely to Have Been Lost		Likely Caused by Acidification	
		Number	Percent	Number	Percent
Brook trout (*Salvelinus fontinalis*)	707	298	42.1	98	13.9
Lake trout (*Salvelinus namaycush*)	111	43	38.7	8	11.8
Rainbow trout (*Salmo gairdneri*)	90	36	40.0	2	2.2
White sucker (*Catostomus commersoni*)	412	76	18.4	10	2.4
Brown bullhead (*Ictalurus nebulosus*)	520	100	19.2	13	2.5
Pumpkinseed (*Lepomis gibbosus*)	351	111	31.6	7	2.0
Golden shiner (*Notemigonus crysoleucas*)	326	113	34.7	12	3.7
Creek chub (*Semotilus atromaculatus*)	254	107	42.1	7	2.8
Lake whitefish (*Coregonus clupeaformis*)	53	25	47.2	1	1.9
Smallmouth bass (*Micropterus dolomieui*)	136	44	32.4	2	1.5
Largemouth bass (*Micropterus salmoides*)	62	13	21.0	1	1.6
Chain pickerel (*Esox niger*)	41	12	29.3	0	-
Yellow perch (*Perca flavescens*)	267	82	30.7	2	0.7
Lake chub (*Couesius plumbeus*)	18	12	66.7	0	-

local management activities and are otherwise unchanged. The chemistry of Woodhull Lake is ambiguous. The pH has fluctuated between 5.0 to 6.5 since 1954. Diatom stratigraphy indicates no acidification, and sediment chemistry demonstrates possible slight acidification. The fish population in Woodhull Lake may be experiencing acid stress as demonstrated by the disappearance of smallmouth bass and brook trout, and a recent decline in lake trout abundance. However, eight fish species are still present, including lake trout, cisco, lake whitefish, and white sucker, and declines in

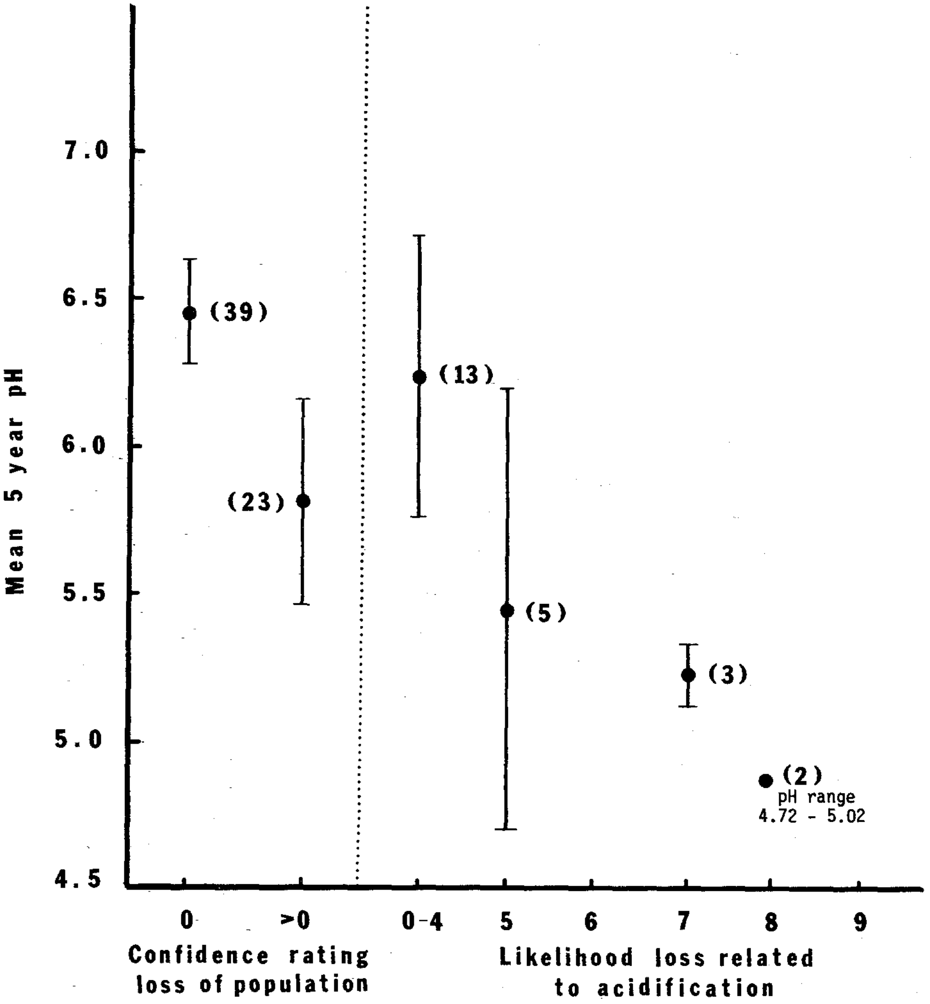

Figure 3. Adirondack lake trout population confidence ratings for the likelihood that the population was lost, and the likelihood that the loss was related to acidification, as compared to mean 5-yr pH. The number of lakes in each rating class is given in parentheses. (0 = low probability; 9 = high probability). Vertical bar represents 95% confidence interval.

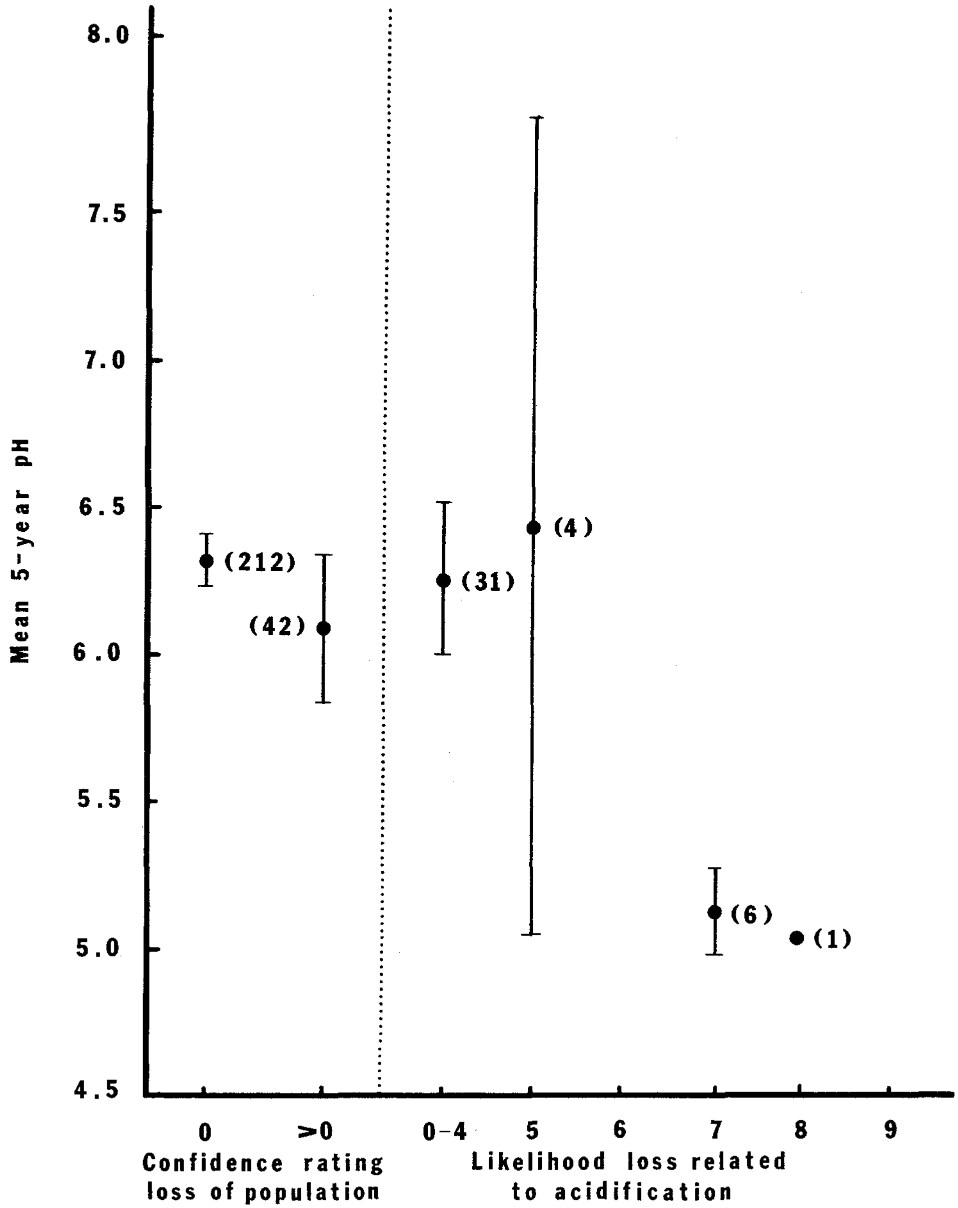

Figure 4. Adirondack white sucker population confidence ratings for the likelihood that the population was lost, and the likelihood that the loss was related to acidification, as compared to mean 5-yr pH. The number of lakes in each rating class is given in parentheses. (0 = low probability; 9 = high probability). Vertical bar represents 95% confidence interval.

Table III. Water chemistry, sediment diatom, sediment chemistry, and fish population changes over time in eight New York Lakes. Diatom data were provided by Donald Charles, Indiana University, and sediment chemistry data were provided by Stephen Norton, University of Maine.

Measured pH			Diatom Inferred pH	Sediment Chemistry	Fish Survey Data
Lake	Year	pH	Present/pre-1980		
Panther	1975 1978-80	6.88 6.2	6.1/6.4 Steady decrease toward surface from 5-10 cm in core.	No acidification indicated.	Fish population eradicated in 1951 and then restocked; no changes in any species other than that caused by direct action.
Sagamore	1933 1961 1976 1978-80	7.0 5.6 6.0 5.6	6.3/6.1 No overall significant trend.	No acidification indicated.	Nine species in 1933, 8 species remaining in 1976; no changes in any major species.
Woodhull	1954 1969 1974 1975 1976 1978 1981 1982	5.0 6.5 6.0 5.8 5.1-5.3 5.7 5.4 5.6	6.0/6.1 No obvious trend.	Dating poor. Possible slight acidification indicated by decline in Zn in surface sediment.	6 species in 1931; 8 species collected plus 3 reported in 1954; 8 species in 1974-81; brook trout last collected 1954 and smallmouth bass last collected 1974, but lake trout and lake whitefish still present.
Big Moose	1948 1960 1965 1971 1974 1978-79 1981 1982	6.0 5.2 5.2 5.5 4.9 4.6-5.0 5.3 4.9	4.9/5.8 Marked diatom-inferred pH decrease and floristic change beginning about 1950.	Acidification indicated by declining relative concentration of Zn, Ca, and Mn as well as declining deposition rates relative to TiO2.	Ten species in 1948, 5-6 species since 1962; smallmouth bass and lake whitefish last collected in 1948; lake trout recruitment failure in late 1940s, last collected in 1966.

Table III continued - page 2.

Honnedaga	1959-60 1975 1976 1981 1982	3.9-6.0 4.91 4.7-4.8 4.92 4.84	5.2/6.1 Insufficient data to determine pattern of change; major floristic change from bottom to top of core.	Not sampled.	Lake trout became rare and emaciated in early 1950s, last collected in 1954; brook trout declined in mid-1960s and were very rare by the mid-1970s.
Upper Wallface	1963 1968 1975 1978 1979	5.6 4.9 4.9 5.0 5.0	4.7/5.1 Most rapid pH and floristic change starting in 1945-55.	Slight acidification indicated by relative decline of deposition rates for Ca and Zn.	Brook trout moderately abundant in 1963-68, absent in 1975.
Woods	1968 1973 1975 1976 1978-80 1982	5.0 6.0 5.2 5.8 4.7	4.8/5.2 Dating information not available. More low pH indicators at top of core.	Dating poor. Only trace metal data available. Acidification not indicated by Zn. Ca and Mn data not available.	Lake trout reported present previously, but were never collected; formerly known for large brook trout, brook trout abundant in 1961, but scarce and all of hatchery origin since 1966; golden shiner last collected in 1966.
Deep	1954 1968 1978 1979	4.70 4.70 4.62-4.76 4.62-4.72	4.8/5.0 Decrease in diatom-inferred pH and major floristic changes beginning 1940-50.	Slight acidification indicated by relative decline in Ca, Mn, and Zn concentrations and deposition rates.	Brook trout present, moderately abundant in 1954, absent in 1964; no survival of stocked fish since 1964.

Table IV. Recent and historical pH and fish species composition of 20 New Hampshire lakes. Historical data on fish species composition includes reports and surveys. (Source: Singer and Boylen, 1984).

Lake	pH		Fish Species		Reclaimed
	Recent	Historical (year)	Recent	Historical	
Cone	4.5	5.2 (51)	-[a]	CP, BB, YP	yes
Rocky	4.9	- (52)	-[a]	BT[b], BB	no
Caldwell	5.1	6.2 (48)	BT	BT[b]	yes
Loon	5.3	6.1 (51)	-	BT[b]	no
Upper Hall	5.8	5.6 (60)	BT	BT[b], LT, LD	no
Hemingway	5.8	- (50)	BB	BB	no
Crane	5.8	6.4 (62)	BB, CP, YP, LB, GS,	BT[b], CP, YP, BB, S	no
Kiah	5.9	5.7 (51)	BT, BB	BT[b], BB	no
Beaver	5.9	6.2 (53)	BB	BT[b]	no
Bean	6.2	6.0 (52)	BT, WS, GS, LC	BT[b]	no
East	6.3	6.5 (51)	BT	BT[b]	no
Russell	6.3	6.6 (38)	BT	BT[b], GS, BD, BB	yes
Moody	6.5	6.4 (37)	WS, GS, LC	BR[b]	no
Blue	6.6	6.4 (54)	BT, BB, RS	BT[b]	yes
Munn	6.7	6.7 (48)	BT	BT[b]	yes
Long	6.8	5.7 (52)	BT, WS	BT[b], RT[b], BB	no
Sessions	6.8	6.6 (50)	BT, FF, CC	BT[b]	yes
Phillips	6.9	6.5 (52)	BT, LS	BT[b]	yes
Echo	6.9	6.9 (39)	BT	BT[b], RT[b], RS[b]	yes
Round	7.3	7.2 (39)	BT, WS, RD	BT[b], S	yes

[a] Stocked with brook trout; stocking discontinued.
[b] Stocked.

Fish Species Codes:
BB = brown bullhead, BD = blacknose dace, BR = brown trout,
BT = brook trout, CC = creek chub, CP = chain pickerel, FF = fallfish,
GS = golden shiner, LB = largemouth bass, LC = lake chub,
LD = longnose dace, LS = longnose sucker, LT = lake trout,
RD = northern redbelly dace, RS = rainbow smelt, RT = rainbow trout,
S = "shiners", WS = white sucker, YP = yellow perch

Table V. Present pH and historical evidence of fish survival in four south-central Pennsylvania streams. Source: Sharpe et al. (1984).

Stream	Present Ph	Date	Event
Wildcat	5.6-7.0	1900s	Brook trout routinely caught
		1980-81	Brook trout and rainbow trout present and reproducing
McGinnis	4.4-5.7	1910	Fisherman caught 60 brook trout
		1977	Brook trout stocking fails
		1981	No fish present in stream
Card Machine	4.6-6.0	1920s	Brook trout routinely caught
		1960s	Brook trout nursery established
		1966	Brook trout mortality at nursery
		1972	Brook trout mortality at nursery
		1978	Brook trout mortality at nursery
		1981	No fish present in stream
Linn	4.6-5.6	1932	Brook trout stocked, no mortality
		1951	Brook trout nursery established
		1960	Brook trout mortality at nursery
		1970	Brook trout mortality in stream 2 days after stocking
		1976	Brook trout mortality after stocking
		1977	Brook trout mortality after stocking
		1981	No fish present in stream

lake trout abundance may reflect the cessation of hatchery introductions. Big Moose and Honnedaga lakes exhibit pronounced acidification, and all sources of information are consistent. Trends for Upper Wallface, Woods, and Deep lakes are less apparent. All show declines in pH and fish populations, although disappearance of fish generally lags behind pH decline by a few years. However, the change in pH in these lakes is apparently quite small. The consistency of the multiple and independent sources of information leads us to conclude that acidification has occurred. A possible explanation for the loss of fish populations over such a small pH change may be provided by the recent finding that total organic carbon declined in two Norwegian acidic lakes coincident with a decline in pH from ca 4.9 to 5.1 to ca 4.4 to 4.7 (Davis et al., 1985). Thus these lakes may have changed from organic weak acid systems to mineral strong acid systems with a concomitant increase in concentrations of toxic Al species.

2.2. Vermont

The Vermont Agency of Environmental Conservation has completed a fairly systematic assessment of the current status of fish populations in Vermont lakes relative to acidity (Langdon, 1983, 1984). Initially, potential susceptible areas were identified based on maps of bedrock geology, and 205 lakes in these areas were surveyed for chemistry in 1979-1984. Six of these (representing 0.2% of the total lake surface area in the state, excluding large border waters) had alkalinity <0 μeqL^{-1}; 60 (10.8% of the total lake surface area) had alkalinity <100 μeqL^{-1}.

The 36 Vermont lakes with the lowest alkalinity were selected for long-term chemical monitoring. Twenty-nine of these were surveyed to determine fisheries status. Two lakes (0.1% of the total lake surface area) were fishless, presumably due to low pH or high Al. The remaining 27 (about 9% of the total lake surface area) contained 1 to 10 fish species (Langdon, 1983, 1984).

Historical information, occasionally dating back to the 1880s, has been located for 19 of these lakes in Vermont Agency of Environmental Conservation files. Eighteen lakes now have annual mean pH 5.5 or above, with 2 to 10 species per lake. Thirteen of these had historical fisheries data. Although some shifts in species composition have occurred, major fisheries declines or loss of acid-sensitive species, which would be suggestive of acidification, have not.

Eleven lakes now have annual mean pH below 5.5, with 0 to 3 species per lake. Six of these had some historical information. Results from trend analysis are somewhat equivocal. For example, Little and Haystack ponds contained no fish in 1982-83. Little Pond once supported a naturally reproducing population of brook trout, reported as early as 1889 and as late as 1958 to be in good condition (Langdon, 1983). The surface pH was 5.2 in both 1958 and 1982. Haystack Pond (pH 4.6) may never have sustained a naturally-reproducing fish population. The earliest reports (1881), stated that no fish inhabited the lake and that none could live there. Two other lakes (pH 4.7 and 5.0) have been stocked with brook trout with no angler success. Both lakes now support only brown bullhead. Finally, historical data for two additional waters (pH 4.7 and 5.2) suggest that "shiner" populations may have been lost. Brook trout populations in these lakes are currently maintained by stocking.

Given that these 29 lakes are those most likely to have been affected, the overall impact of acidification on Vermont's lakes to date has apparently been minimal (Langdon, 1984). The 29 lakes together represent <10% of the total surface area of lakes in Vermont.

2.3. New Hampshire

Singer and Boylen (1984) surveyed 20 low alkalinity lakes in New Hampshire, ranging in pH from 4.5 to 7.3. Historical fisheries data were located for all lakes, and historical pH data for all but two (Table IV). Three lakes were fishless, and all three formerly supported fish. However, the fish population of Loon Pond (pH 5.3) was maintained by stocking, which was discontinued in the 1950s. No historical pH data were located for Rocky Pond (pH 4.9). Cone Pond (pH 4.5) has apparently been acidic for at least 30 yr; however, pH may have declined slightly. The lake was chemically reclaimed and stocked with brook trout for a number of years, but the stocking was discontinued following reports of poor fishing. Rocky Pond (pH 4.9) contained brown bullhead in 1952 and was stocked with brook trout for a number of years. It was surveyed in 1972, and only one brook trout was caught. The only other lake where fish populations may have declined is Upper Hall Pond (pH 5.8), where lake trout and longnose dace (Rhinichthys cataractae) may have disappeared. Russell Pond (pH 6.3), where golden shiner, blacknose dace, and brown bullhead may have disappeared, has been reclaimed. The interpretation of fish population changes in relation to water chemistry in New Hampshire is complicated by extensive fishery management, including chemical reclamation and hatchery introductions.

2.4. Maine

We have surveyed 88 Maine lakes for chemical and fishery status. Of these, 9 (10.2%) had pH <5.0 and were fishless or contained only hatchery-maintained populations of brook trout. There were no historical fishery data available.

Maine has 5770 lakes of 0.5 ha surface area or larger. Water chemistry and fisheries survey data were obtained for 1459 lakes from the Maine Department of Inland Fisheries and Wildlife. Fisheries survey records were screened to identify lakes that had been surveyed two or more times. About half the records were reviewed and 312 lakes were identified that had suitable survey data. The data for species and number of individuals collected were reviewed without reference to lake chemistry. Lakes for which species disappeared were investigated for evidence of reclamation, stocking, level of collecting effort, type of sampling gear used, or other factors that might explain the absence of species in the catch. We identified 12 lakes (3.9%) that had lost one or more species of fish with no obvious cause. Chemical data were unavailable for two of the lakes. The remaining 10 lakes had colorimetric pH and occasional methyl orange alkalinity data available. Two lakes (Pleasant Lake, MIDAS #1100, and Scraggly Lake, MIDAS #4264) had lost lake trout populations and were acidic (pH 4.4 to 4.8). The remaining lakes had lost brook trout, white sucker, or yellow perch populations, but generally had pH $\geq$5.5. However, much of the pH data were old and predated the most recent fish sample. Therefore, although temporal shifts in species composition occurred in some Maine lakes, there was no clear association between decline or disappearance of fish populations and lake chemistry.

2.5. Massachusetts

A state-wide survey of the chemical status of lakes in Massachusetts showed that 46 of 900 (5.1%) had pH <5.0 and 159 of 829 (19.2%) had alkalinity $\leq$40 μeqL^{-1} (Godfrey et al., 1985). The acidic lakes were located in southeastern (Cape Cod and Buzzards Bay watersheds) and central Massachusetts (Millers, Chicopee, Quinebaug, and Farmington watersheds). Comprehensive surveys of fisheries status in Massachusetts have not been completed. There have been reports of declining fish populations in the Cape Cod region, and in Quabbin Reservoir in central Massachusetts (Halliwell, 1985a), but definitive evidence linking these declines to acidification is lacking.

A temporal association study of water chemistry and fish species distribution was conducted in tributaries to the Millers River, Massachusetts (Halliwell, 1985a,b). Sixteen streams that had been surveyed in 1953 and 1967 were surveyed again in 1983. Fish surveys were conducted with fish toxicant (rotenone) in 1953 and by electrofishing in 1967 and 1983. Species were identified but individuals were not enumerated in 1967. Stream pH was measured colorimetrically in 1953 and 1967, and electrometrically in 1983. Streams that had pH $\geq$6.0 in 1983 generally had relatively stable fish communities and pH over time. Most of the streams with pH <6.0 in 1983 had apparently lost three or more species. Two streams had pH <5.0 in 1983 and had lost all fish species. These streams were of different character than the others surveyed, being of lower gradient, higher color (organic acids), and containing primarily warmwater fish species.

2.6. Rhode Island

Fish kills involving stocked rainbow trout and attributed to low pH were reported for Wallum Lake, a large clear-water oligotrophic lake on the Rhode Island-Massachusetts border. The lake was subsequently neutralized by addition of ground limestone (Guthrie and Stolgitis, 1977). A recent survey noted an apparent loss of the native brook trout population in Cedar Swamp Brook. The stream had pH 6.8 in 1962 and contained trout. In 1983 pH was 4.2 to 5.0 and trout were absent (DeMaine, 1983). No other studies of fishery status in relation to acidity have been conducted in the state.

2.7. Catskill/Pocono/Kittatinny Ridge regions of New York, Pennsylvania and New Jersey

Although some surveys of water quality and aquatic biota have been completed for these regions (e.g., Colquhoun et al., 1981, 1984; Faust and McIntosh, 1983; Berg and Bradt, 1984; Bradt et al., 1984), assessments of current fisheries status or trends relative to potential effects of acidification are unavailable. Colquhoun et al. (1984) noted that most of 50 Catskill streams surveyed had acceptable pH for fish. Well known trout streams (e.g., Willowemoc and Beaverkill) have apparently not been affected. Several small lakes on Kittatinny Ridge in New Jersey are clear-water and moderately to highly acidic (Faust and McIntosh, 1983). Two, with measured pH ranging 3.6 to 4.7 and 3.8 to 4.9, reportedly support only yellow perch, a relatively acid-tolerant species (Brennan et al., 1985). Historical trends have not been evaluated.

2.8. Pennsylvania

A spatial survey of fish populations and water chemistry was conducted in 51 streams in south-central Pennsylvania (Sharpe, 1985). Reproducing fish populations were present in 37 streams, three streams contained only hatchery fish, and 11 streams were fishless. Fish population status was correlated with water chemistry; many of the fishless streams had pH below 5.0 to 5.5 with high levels of Al. Anecdotal information concerning historical trends in fish populations was located for four streams, three of which were included in the above survey (Table V). All three streams that are presently acidic (minimum pH 4.4) and fishless formerly supported fish. Periodic fish mortalities were first reported in the 1960s, and stocking failures were reported in the 1970s. No such mortalities have been reported for the stream that is not acidic and presently supports fish. An _in situ_ fish toxicity bioassay was conducted on one acidic (McGinnis Run) and the non-acidic stream (Wildcat Run)(Sharpe _et al._, 1983). Trout fry survived only 4 to 9 days in the acidic stream, but survived for the duration of the experiment (36 days) in the non-acidic stream. Inasmuch as these streams formerly did support viable populations (either self-sustained or long-term survival of hatchery fish), it is likely that acidification caused the demise of fish in these streams.

Kimmel (1985) reviewed the stream fisheries data files of the Pennsylvania Fish Commission for evidence of fisheries declines or fish kills possibly associated with acidification. Only streams meeting the following criteria were considered: (1) current alkalinity <200 μeqL^{-1}, (2) presence of native or hatchery-reared salmonids or historical record of same, (3) no past or present mining or drilling in watershed, (4) stream order 1 to 3, and (5) undeveloped forested watershed. Of the 344 streams that met the above criteria, 124 (36% totalling 550 km) had records indicating one or more of the following: (1) an absence of fish, (2) a loss of wild salmonid populations, (3) fish kills, particularly following stocking, or (4) a change in fish stocking policy (e.g., elimination of pre-season stocking, replacement of brown or rainbow trout with brook trout, termination of all stocking), presumably due to high acidity and poor survival. This information should be interpreted cautiously. It is based solely on written comments filed by fisheries biologists and presumed effects of acidification. Although these records are inconclusive, they do provide a preliminary indication of a problem. The 124 streams represent 6.6% of the managed trout resource and 2% of the total managed and unmanaged trout resource in Pennsylvania.

2.9. West Virginia

In 1983, the state of West Virginia initiated a survey of 82 streams to obtain baseline data and evaluate potential effects from acidic deposition (Menendez, 1985). About 10% of the streams surveyed (focusing on those areas most likely to be sensitive) in fall 1984 had pH <5.0, and 24% had alkalinity <40 μeqL^{-1}. Unfortunately, associated fisheries surveys have not been completed.

In West Virginia, as in Pennsylvania and other states of the central and southern Appalachians, acidic streams are common, due to acidic mine drainage or naturally acidic bedrock. Thus, effects of acidic deposition are often difficult to distinguish. In addition, prior stream surveys focused on the more fertile streams. Little historical data are available for streams with low alkalinity. However, changes in fisheries and water chemistry that cannot be attributed to logging, mining, or other on-site activity have apparently occurred in some watersheds. For example, in 1935 the Cranberry River was an excellent trout stream (McGavock and Davis, 1935). In the 1960s, surveys in the North Fork of the Cranberry River found only sparse trout populations confined to a few tributaries. In the 1980s, trout populations have consisted principally of stocked fish and springtime pH frequently falls below 5.0 (Menendez, 1985).

Evidence for effects of acidic deposition and acidification on West Virginia fishery resources is thus not definitive. Moreover, the extent of effects or sensitive aquatic systems is not known.

2.10. Southern Blue Ridge Province

Headwater streams in the Southern Blue Ridge Province (SBRP), which encompasses parts of northern Georgia, eastern Tennessee, and western North Carolina, typically have low alkalinity (<100 μeqL^{-1}) with baseflow pH above 6.0 (Winger et al., 1985). There is no documentation of losses or declines of fish populations in streams, rivers, or reservoirs in the region due to acidic deposition. Fowler et al. (1984) surveyed 12 high elevation (>500 m) first and third order streams and found no relationship between fish assemblage characteristics and baseflow pH, alkalinity, or other chemical measurements. Jones et al. (1983) investigated fish kills in fish-rearing facilities near Cherokee, North Carolina, coincident with storm events and pH depressions (pH <5.0) in the tributary stream, Raven Fork. They concluded that the pH depressions resulted from organic acids draining from the forest-soils complex rather than acidic deposition. Monitoring of other streams in the SBRP during storms and high stream flow suggests that Raven Fork is atypical for the region. In five streams sampled during 20 storm events, pH levels never dropped below 5.3, and most (75%) remained above pH 6.0 (Olem, 1985).

Virtually all of these streams have low alkalinity and therefore may be susceptible to future effects of acidic deposition. These streams provide valuable salmonid habitat in this region, but fish communities have historically been affected by logging, overfishing, stocking, and other factors (Larson and Moore, 1985), complicating detection of acidification effects. In addition, fishery survey data are sparse. The available evidence, however, suggests no substantial effects to date. Further, soils in the region generally retain sulfate strongly, which may delay or mitigate aquatic effects of atmospheric inputs (Altshuller and Linthurst, 1984).

2.11. Florida

Results from the U.S. National Lake Survey indicate that Florida had more acidic (pH <5.0) lakes than any other region in the eastern United States, including the Adirondack Mountain region of New York (Linthurst et al., 1986). Yet no effects on fishery resources have been reported. Surveys of fish populations in a small number of Florida lakes having pH ranging 3.7 to 8.9 reveal no loss of major fish populations (Keller, 1984; Canfield et al., 1985). Canfield et al. (1985) surveyed five acidic (pH 3.7 to 4.9) clear-water and three acidic (pH 4.1 to 4.6) colored lakes. All contained populations of largemouth bass. Intensive mark-recapture studies in Cue Lake (clear-water, oligotrophic lake; pH ca. 4.0) demonstrated that all fish species present were reproducing and growing normally (Canfield, 1985). The number and biomass of largemouth bass in Cue Lake are within the range reported for oligotrophic lakes in Florida.

Predictions of effects of acidification on fisheries resources in Florida lakes are uncertain. The reasons for the large number of acidic lakes are not clear. Hypotheses proposed to explain the apparent tolerance of Florida fishes to acidic conditions include low concentrations of Al (Hendry and Brezonik, 1984; Canfield et al., 1985), and long-term adaptation to natural acidity (Canfield, 1985).

3. DISCUSSION

Considering the interest in the effects of acidification on fishery resources, the number of available data sets showing a relation between surface water acidification and fish population status is remarkably small. This may reflect, in part, a lack of historical data for the generally small, remote lakes that are vulnerable to acidification, and of variability in fish census methods and record keeping. The strongest evidence of adverse effects of acidification on fish populations is provided by the Adirondack Mountain data. Rigorous evaluation of the fishery and chemical data for the Adirondacks clearly indicates both that fish populations have declined in some lakes and that lakes where fish populations have declined are now acidic. Alternative reasons for the decline in fish populations in these lakes are not evident. There was a high probability that fish communities had declined as a result of acidification in 49 lakes, and there was marginal evidence for such a decline in 64 additional lakes. Extrapolating this estimate to the entire Adirondack Mountain region indicates that fish communities in 200 to 400 lakes may have been adversely affected by acidification. This is nonetheless a crude estimate, and the error associated with it cannot be quantified.

Pennsylvania and Massachusetts streams also have documented fish population declines associated with acidity; however the data are fewer and less complete than those for New York and the analyses less rigorous. That is not to say that effects have been less severe; rather, the data are not sufficient to document this. Lake surveys in New Hampshire and Vermont identified very few lakes where fish populations may have declined because of acidification, and analysis of fish survey records in Maine failed to identify any such lakes. More so than the other states surveyed, New Hampshire relies on an extensive fish stocking program to manage coldwater fisheries. Such hatchery-maintained fisheries may be less susceptible to decline from acidification. Although acidic, fishless lakes exist in Maine, it is unknown whether these lakes ever supported fish. The lakes having historical fishery data have apparently not been greatly affected by acid deposition. Minimal historical fisheries data were obtained for Rhode Island, the Catskill/Pocono/Kittatinny Ridge region, West Virginia, the Southern Blue Ridge Province, and Florida. Available evidence suggests that effects of acidic deposition on fishery resources in these regions are minimal.

Alternative factors that could reduce or eliminate fish populations have been raised (Retzsch et al., 1982). These factors include use of chemical pesticides, changes in fish hatchery production, changing angler pressure, and increased beaver activity. Direct effects of human activities (e.g., obstruction of fish migrations by dams, degradation of water quality by agricultural and urban run-off, municipal sewage, and industrial wastes) greatly reduced fish populations in accessible waters in the colonial and post-civil war periods (Thompson, 1970). However, such factors primarily affected lakes near population centers; remote lakes were not directly affected. Lumbering and subsequent burning of the watersheds undoubtedly affected fish populations in less accessible lakes, but these factors generally were most important in the late 1800s and early 1900s, and thus predated the acidity-related population declines documented here. For example, Coolidge (1963) tabulated the area of Maine forests burned from about 1900 to 1960. The area was greatest before 1912 and declined substantially to 1960. Smith (1972) stated that wood harvest in Maine was greatest in 1890-1910. Thereafter, harvest gradually declined, reaching a minimum just before World War II. The harvest then increased and in 1969 was about double the previous maximum. In the Adirondack Mountain region, Charles (1984) failed to find a correlation between lake pH inferred from sediment diatom species assemblage and logging or fire in the Big Moose Lake watershed. Similarly, Bradbury (1986) failed to detect any influence of fire in the watershed on sediment diatom species composition in a Minnesota lake.

Early fishery scientists were unaware of the inherently low productivity of high elevation, oligotrophic lakes and believed that supplementing the sparse fish populations with hatchery fish would enhance species diversities and standing crops to levels comparable to those in more productive, low elevation lakes. However, these attempts generally failed and consequently fell into disfavor. For example, Smallwood (1918) documented the failure of stocking to supplement the fish population in Lake Clear, New York. Lake Clear presently has a pH >7.0 and contains at least five species of fish (Colquhoun et al., 1984).

Beaver activity can either enhance or degrade fish populations, depending on the particular circumstances. Beaver were reintroduced into the Adirondack Mountains of New York in 1905. By the 1920s population densities had increased enough to raise concern about beaver damage to various resources (Johnson, 1927). Therefore, beaver activity also apparently predates the acidity-related fish population declines. Aerial photographs from 1968 and 1978 were used to identify Adirondack Mountain region headwater lakes with beaver activity. Fish community status ratings were unrelated to beaver activity (Hunsaker, 1985).

Chemical pesticides have been used in remote areas of northeastern North America to control spruce budworm and blackfly, with detrimental effects on fish (Burdick et al., 1964; Anderson and Everhart, 1966; Elson, 1967; Kerswill and Edwards, 1967; Locke and Havey, 1972). Organochlorine compounds are generally no longer used for these purposes, and most formerly affected fish populations have recovered (Dean et al., 1979). Analyses of brook trout from remote lakes of varying pH in northern New England revealed low organochlorine residues (Haines, 1983); concentrations were comparable to those in Antarctic fish and apparently represent world-wide background levels.

It is impossible to rule out factors other than acidification as important in the decline or loss of fish populations except by intensive, case-by-case studies. Such studies have seldom been made, and the quantity of data for estimating trends in fish populations is exceedingly sparse. However, a few such data sets do exist; in the cases cited herein factors other than acidification apparently were not involved with the decline of fish populations. The extent of the resource that has been damaged is apparently small, however, and the extent is geographically limited. We believe the major focus for future research efforts should be the determination of possible trends in fish communities subjected to present or future acidic deposition scenarios.

ACKNOWLEDGMENTS

The following persons graciously provided us with unpublished data and assessments, without which we could not have prepared this report: Daniel E. Canfield, Jr., University of Florida; David Halliwell, Massachusetts Division of Fisheries and Wildlife; William Kimmel, California University of Pennsylvania; Richard Langdon, Vermont Agency of Environmental Conservation; Raymond Menendez, West Virginia Department of Natural Resources; Harvey Olem, Tennessee Valley Authority; William Sharpe, Pennsylvania State University; Michael Van Den Avyle, U. S. Fish and Wildlife Service, University of Georgia. Financial support for this work was provided by the U. S. Environmental Protection Agency, U. S. Fish and Wildlife Service, and the National Research Council.

REFERENCES

Altshuller, A. and Linthurst, R. (editors): 1984, The acidic deposition phenomenon and its effects: critical assessment review papers. Vol. II. Effects sciences. U. S. Environmental Protection Agency EPA-600/8-83-016BF.

Anderson, R. and Everhart, W.: 1966, *Trans. Am. Fish. Soc.* 95, 160.

Baker, J. and Havey, H.: 1984, Critique of acid lakes and fish population studies in the Adirondack region of New York state. Report to Environmental Research Laboratory, U.S. Environmental Protection Agency, Corvallis, OR.

Baker, J. and Schofield C.: 1982, *Water Air Soil Pollut.* 18, 289.

Berg, M. and Bradt, P.: 1984, Macrozoobenthos of three lakes with varying sensitivities to acidification. Page 7 *in* Abstracts for the 47th Annual Meeting, American Society of Limnology and Oceanography, Vancouver, BC.

Bradbury, J.: 1986, *Arch. Hydrobiol.* 106, 203.

Bradt, P. Barasso, D. and Dudley, J.: 1984, Phytoplankton communities in three lakes with different sensitivities to acidification. Page 11 *in* Abstracts for the 47th Annual Meeting, American Society of Limnology and Oceanography, Vancouver, BC.

Brennan, E., Ehrenfeld, J., Faust, S., Fritz, R., Graedel, T., Kish, G., Lord, D., McIntosh, A., Morgan, M., Nelson, D., Reiss, N., Riley, D., Spatola, J. and Tedrow J.: 1985, Acidic deposition in New Jersey: a report to the Governor and Legislature of New Jersey. Trenton, NJ.

Brown, D.: 1983, *Bull. Environ. Contam. Toxicol.* 30, 582.

Burdick, G., Harris, E., Dean, H., Walker, T., Skea, J. and Colby D.: 1964, *Trans. Am. Fish. Soc.* 93, 127.

Canfield, D.: 1985, personal communication.

Canfield, D., Maceina, M., Nordlie, F. and Shireman J.: 1985, *Trans. Amer. Fish. Soc.* 114, 423.

Charles, D.: 1984, *Verh. Internat. Verein. Limnol.* 22, 559.

Colquhoun, J., Symula, J. Pfeiffer, M. and Feuer J.: 1981, Preliminary report of stream sampling for acidification studies 1980. New York State Dept. Environmental Conservation, Albany, NY, Tech. Rep. 81-2.

Colquhoun, J., Kretzer, W. and Pfeiffer M.: 1984, Acidity status of lakes and streams in New York State. New York State Dept. Environmental Conservation, Report WM P-83(6/84).

Coolidge, P.: 1963, History of the Maine woods. Furbush-Roberts Printing Co., Bangor, ME.

Davis, R., Anderson, D. and Berge F.: 1985, Nature 316, 436.

Dean, H., Skea, J., Colquhoun, J. and Simonin, H: 1979, *N.Y. Fish Game J.* 26, 188.

DeMaine, A.: 1983, Pond and stream surveys: acidification susceptibility. Performance Report for Project F-20-4-24. Rhode Island Division of Fish and Wildlife, West Kingston, RI.

Dillon, P., Yan, N. and Harvey, H.: 1984, *CRC Critical Reviews in Environmental Control* 13, 167.

Elson, P.: 1967, *J. Fish. Res. Bd. Can.* 24, 731.

Faust, S. and McIntosh, A.: 1983, J. Environ. Sci. Health A18, 155.
Fowler, D., Van Den Avyle, M. and Hudy, M.: 1984, Fish assemblage characteristics of acid sensitive streams in the Southern Blue Ridge Province. Page 31 in Abstracts of the 114th Annual Meeting of the Am. Fish. Soc., Ithaca, NY.
Godfrey, P., Ruby, A. and Zojicek, O.: 1985, The Massachusetts Acid Rain Monitoring Project A.R.M.: Phase I. Publication No. 147, Water Resources Research Center, University of Massachusetts, Amherst, MA.
Guthrie, R. and Stolgitis, J.: 1977, Fisheries investigations and fish management in Rhode Island lakes and ponds. Fisheries Report No. 3, Rhode Island Division of Fish and Wildlife, Providence, RI.
Haines, T.: 1981, Trans. Am. Fish. Soc. 110, 669.
Haines, T.: 1983, Water Air Soil Pollut. 20, 47.
Halliwell, D.: 1985, Massachusetts Wildlife 36, 10.
Halliwell, D.: 1985b, personal communication.
Harvey, H. and Lee, C.: 1982, Historical fisheries changes related to surface water pH changes in Canada. Pages 45-55 in R. Johnson, editor, Acid Rain/Fisheries. American Fisheries Society, Bethesda, MD.
Hendry, C. and Brezonik, P.: 1984, Water Resour. Bull. 20, 75.
Hunsaler, C.: 1985, personal communication.
Johnson, C.: 1927, Roosevelt Wild Life Bull. 4, 501.
Johnson, D., Simonin, H., Colquhoun, J. and Flack, S.: 1986, Biogeochemistry, in press.
Jones, H., Naggle, J., Young, R., Kelly, J., Olem, H., Ruane, R., Pasch, R., Hyfantis, G. and Parkhurst W.: 1983, Investigations of the cause of fishkills in fish-rearing facilities in Raven Fork watershed. TVA/ONR/WR-83/9.
Keller, A.: 1984, Fish communities in Florida lakes: relationship to physico-chemical parameters. M.S. Thesis, University of Florida, Gainesville, FL.
Kerswill, C. and Edwards, H.: 1967, J. Fish. Res. Bd. Can. 24, 709.
Kimmel, W.: 1985, personal communication.
Kleinbaum, D. and Kupper, L.: 1978, Applied regression analysis and other multivariable methods. Duxbury Press, Boston, MA.
Langdon, R.: 1983, Fisheries status in relation to acidity in selected Vermont lakes. Vermont Agency of Environmental Conservation Report, Montpelier, VT.
Langdon, R.: 1984, Fishery status in relation to acidity in selected Vermont lakes, 1983. Report of the Dept. of Water Resources and Environmental Engineering, Agency of Environmental Conservation, Montpelier, VT.
Larson, G. and Moore, S.: 1985, Trans. Am. Fish. Soc. 114, 195.
Leivestad, H. and Muniz, I.: 1976, Nature 259, 391.
Linthurst, R., Landers, D., Eilers, J., Keller, T., Brakke, D. and Jeffries, D.: 1986, Water Air Soil Pollut. this volume.
Locke, D. and Havey, K.: 1972, Trans. Am. Fish. Soc. 101, 638.
McGavock, A. and Davis, H.: 1935, A stream survey of the waters of the Monongahela National Forest. Dept. of Commerce, Bureau of

Fisheries, Washington, DC.
Menendez, R.: 1985, personal communication.
Muniz, I.: 1984, Phil. Trans. R. Soc. Lond. B305, 517.
Olem, H.: 1985, personal communication.
Overrein, L., Seip, H. and Tollan, A.: 1980, Acid precipitation - effects on forest and fish. Research Report 19, Acid Precipitation - Effects on Forest and Fish Project, Aas, Norway.
Pfeiffer, M.: 1979, A comprehensive plan for fish resource management within the Adirondack Zone. FW-P142 (12/9), New York State Department of Environmental Conservation, Albany, NY.
Pfeiffer, M. and Festa, P.: 1980, Acidity status of lakes in the Adirondack region of New York in relation to fish resources. New York State Department of Environmental Conservation Report FW-P168 (10/80), Albany, NY.
Retzsch, W., Everett, A., Duhaime, P. and Northwanger, R.: 1982, Alternative explanations for aquatic ecosystem effects attributed to acidic deposition. Report prepared for Utility Air Regulatory Group by Everett and Associates, Rockwell, MD.
Schindler, D., Mills, K., Malley, D., Findlay, D., Shearer, J., Davies, I., Turner, M., Linsey, G. and Cruikshank, D.: 1985, Science 228, 1395.
Schofield, C.: 1965, Trans. Am. Fish. Soc. 94, 227.
Schofield, C.: 1973, The ecological significance of air-pollution-induced changes in water quality of dilute-lake districts in the northeast. Trans. N.E. Fish Wildl. Conf. 98-111
Schofield, C.: 1976a, Lake acidification in the Adirondack Mountains of New York: causes and consequences (abstract). Page 477 in L. Dochinger and T. Seliga, editors. Proceedings of the First International Conference on Acid Precipitation and the Forest Ecosystem. USDA Forest Service, Gen. Tech. Rep. NE-23.
Schofield, C.: 1976b, Ambio 5, 228.
Sharpe, W.: 1985, personal communication.
Sharpe, W., Kimmel, W., Young, E. and DeWalle, D.: 1983, Northeast Environ. Sci. 2, 171.
Sharpe, W., DeWalle, D., Leibfried, R., Dinicola, R., Kimmel, W. and Sherwin L.: 1984, J. Environ. Qual. 13, 619.
Singer, R. and Boylen, J.: 1984, Biological field surveys of northeastern acidified lakes. Final Report to EPA/NCSU Acid Deposition Program, North Carolina State University, Raleigh, NC.
Smallwood, W.: 1918, Amer. Naturalist 52, 322.
Smith, D.: 1972, A history of lumbering in Maine 1861-1960. University of Maine Press, Orono, ME.
Thompson, P.: 1970, The first fifty years - the exciting ones. Pages 1-12 in N. Benson, editor. A Century of Fisheries in North America. Special Publication 7, American Fisheries Society, Bethesda, MD.
Watt, W., Scott, C. and White. W.: 1983, Can. J. Fish. Aquat. Sci. 40, 462.
Winger, P., Lasier, P., Hudy, M., Fowler, D. and Van Den Avyle M.: 1985, J. Environmental Qual., Submitted.