FISH, ACIDS & AQUATIC ECOLOGY

8

THE BIOLOGICAL EFFECTS OF ACIDIFICATION ARE REVISITED AND DECISIVELY PROVEN

In the 1970s, very little was known about the biology of acidification except that it killed fish and probably other organisms as well. By 1990, as a result of much research here and in Europe, a fairly coherent picture of the effects of acidification had emerged. The picture drew its general outline from a relatively few large, synoptic, multilake studies and its details from a larger number of studies of individual lakes and species. The basic results were that:

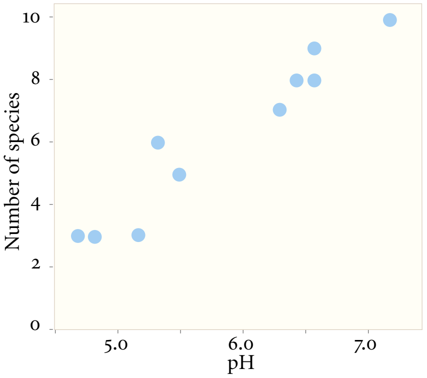
> Acidification is biologically harmful both because it increases toxics like aluminum and hydrogen ion and because it decreases the base cations and DOC that can mitigate aluminum and hydrogen ion toxicity.
>
> Mild acidification acts primarily by reducing or eliminating individual species and thus decreasing diversity.
>
> Severe acidification acts by eliminating whole taxonomic groups and ecological guilds and thus causing changes in ecological function.

Nothing learned in the 1990s changed this picture, but important details were added. Field experiments proved that acids could kill adult as well as young fish and that transient acid episodes could reduce fish diversity. A reanalysis of records of fish population losses, using data on recent acidification from the PIRLA study, showed that relatively small changes in average pH had, as long conjectured, been associated with losses in fish diversity. A new generation of large-scale lake surveys quantified several major ecological stresses. And, as described in Chapter 7, the first synoptic surveys of mercury showed that mercury was an acid-related pollutant, and that it was now found in biologically significant quantities in wilderness lakes.

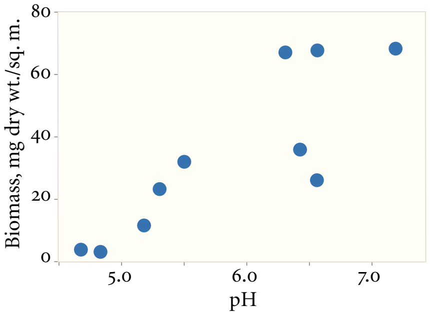
The Biology of Acidification

By 1990, studies in the Adirondacks and elsewhere had established connections between acidification and lake and stream biology. Most aquatic plants and animals, it turned out, could tolerate a fairly broad range of high pHs but were sensitive to low pHs. Below a certain critical pH that was characteristic of the species, organisms experienced stress and often had difficulty growing or reproducing. A few tenths of a pH unit below that, their mortality increased, and a few tenths of a pH unit below that, they couldn't live at all.

DIVERSITY OF MACRO-ZOOPLANKTON IN TEN ADIRONDACK LAKES



DENSITY OF MACRO-ZOOPLANKTON IN TEN ADIRONDACK LAKES



Redrawn with permission from Confer, Kaaret, and Likens, "Zooplankton diversity and biomass in recently acidified lakes." Copyright 1983 National Research Council of Canada. These results are typical of many studies that show that the diversity of many animal and plant groups decreases as pH decreases. For a general review, see Baker and Christensen, "Effects of acidification on biological communities in aquatic ecosystems," 1991.

The critical pHs for a wide variety of organisms lay between 6.0 and 4.0. Above pH 6.0, only the most sensitive species showed pH effects. Below 4.0, only the most acid tolerant could live.

Low pHs affect organisms by creating both physiological and ecological stresses. Physiologically, pH affects organisms by altering respiration, excretion, ionic balance, water retention, and the functioning of ion channels. It also controls the solubility of many other elements and so has important indirect effects. Toxics like aluminum and zinc are typically more abundant in low-pH environments, and necessary nutrients like calcium and magnesium less abundant.

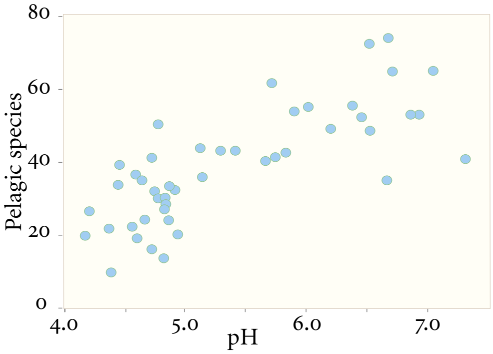
Ecologically, pH affects organisms by changing their own reproductive success and the diversity of the communities in which they live. Through changes in reproductive success it affects population growth and the ability of populations to recover from disturbance; through community changes it affects foraging, competition, and predation. A species whose adults are not strongly acid sensitive in the laboratory may still be reduced or eliminated if its food species are acid sensitive or if its larvae can't survive in low-pH waters.

Some groups of animals and plants are uniformly pH sensitive or insensitive. Many blackflies, midges, dragonflies, and aquatic beetles and bugs are pH tolerant and present even in very low-pH waters. Mayflies, caddis flies, snails, clams, and many crustaceans, on the other hand, are quite pH sensitive. In many waters, amphipods are absent below pH 5.7, mayflies and most crayfish absent below pH 5,5, snails absent below pH 5.2, and most caddis flies absent below pH 5.0. Likewise chrysophytes, the yellow planktonic algae characteristic of circumneutral softwater lakes, tend to drop out below pH 5.6 and are typically replaced by the more acid-tolerant diatoms and blue-green algae.

Other groups like fish, diatoms, and aquatic vascular plants contain both acid-sensitive and acid-tolerant species. In these groups the overall diversity of the group declines with pH but the group doesn't vanish. Fish are a classic example. A review of 25 common species of fish by Baker and Christensen found that only 3 species were sensitive to pHs above 6.0. Another 6 became stressed at pHs between 5.5 and 6.0, and another 11 at pHs between 5.0 and 5.5. All the remaining 5 became stressed somewhere between pH 4.5 and 5.0 As a consequence, Adirondack fish diversity declines strongly with pH (p. 77). Lakes with pHs over 6.0 average 5–6 species of fish. Lakes with pHs under 5.0 average less than 2.

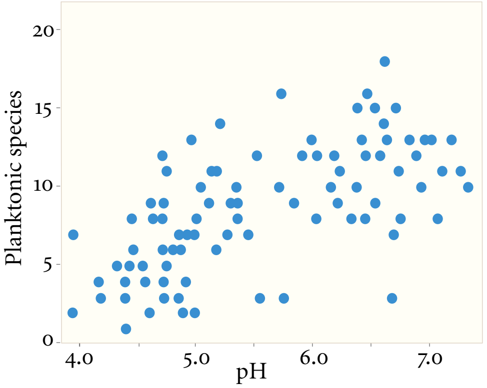
A 1988 study of the vascular plants of Adirondack lakes by Jackson and Charles found a similar relation between diversity and pH. The number of aquatic plants decreased sharply as pH, ANC, and calcium decreased, and only 15 of the 45 species encountered in their study were found in lakes whose pH was less than 6.0.

DIVERSITY OF PELAGIC FISH, ZOOPLANKTON, AND PHYTPLANKTON IN TEN ADIRONDACK LAKES



Redrawn with permission from Havens, "Pelagic food web structure in Adirondack Mountains, USA, lakes of varying acidity." Copyright 1993 National Research Council of Canada. The average number of pelagic species at pH 4.0 is less than a third of what it is at pH 7.0. At lower pHs, food chains become shorter and simpler; individual species have fewer food choices, and the effects of losing a species are correspondingly greater.

DIVERSITY OF ROTIFERS IN 50 ADIRONDACK LAKES



From Siegfried, Bloomfield and Sutherland, "Planktonic rotifer community structure in Adirondack lakes: Effects of acidity, trophic status, and related water quality characteristics," 1990. This was part of the Adirondack Biota Project, which examined water chemistry, plankton, fish, and vegetation in 50 Adirondack lakes. The diversity of phytoplankton and planktonic crustaceans decreased with pH in much the same way as the diversity of rotifers. For the complete report of the Biota Project, see Sutherland, ed., *Field Studies of the Biota and Selected Water Chemistry Parameters in 50 Adirondack Mountain Lakes,* 1990.

Ecosystem-Level Effects of Acidification

While no long-term biological studies have followed the progressive acidification of a lake from acid deposition, many field studies have compared lakes of different acidities, and several experimental studies have followed the changes when an lake or stream was experimentally acidified. These studies suggest that there is very a predictable relation between acidification and biodiversity and that major changes in diversity occur between pH 6 and pH 5:

> At about pH 6.0 there are decreases in the most sensitive mayflies and sensitive fish.
>
> Between pH 6.0 and pH 5.5 there are significant decreases in species diversity in all the main ecological groups: phytoplankton, zooplankton, aquatic plants, benthic invertebrates, and fish. Some acid-sensitive or calcium-dependent groups like chrysophytes, mayflies, snails, and amphipods are largely gone. Fish diversity decreases and approximately a third of the common northern fish species experience stress and reduced reproduction.
>
> Also between pH 6.0 and pH 5.5, acid-tolerant species of algae, cyanobacteria, and midges usually increase. Often the transparency of the water increases, possibly because of changes in the amount of dissolved organic carbon, and surface-living algae proliferate and cause algal blooms.
>
> Between pH 5.5 and 5.0 diversity decreases further in all groups; the total number of planktonic species drops by 30% to 70% between pH 6.0 and 5.0; many benthic invertebrate groups are now gone; and about 80% of the common fish species experience pH stress or reproductive failure.

At pHs between 5 and 6, the effects of acidification on overall ecosystem processes vary considerably. In some experimental lakes there were no trends in primary productivity, nutrients, or decomposition rates. In others there were declines in primary productivity, nitrogen mineralization, and phosphorus levels.

The effects of pHs below 5.0 are much less studied. None of the experimental lakes had pHs below 5. In one stream experiment in which the pH was reduced to 4.0, the number of invertebrates was reduced by 75%; simultaneously, the biomass of attached algae increased, likely because the grazing pressure from mayflies and other invertebrate herbivores was reduced.

CRITICAL PH RANGES OF FISH

Figure not available for the web. Please see the printed version.

Redrawn with permission from Baker and Christensen, "Effects of acidification on biological communities in aquatic ecosystems." Copyright 1991 Springer Science and Business Media and used with their kind permission. The critical ranges shown are based on 88 papers from the 1970s and 1980s. Twenty of 25 species suffer at least some acid-related mortality above pH 5.0. All the species except the arctic char and blacknose shiner are found in the Adirondacks.

In summary, both experimental and field studies suggest that pH 6.0 is a critical biological threshold. Above it little happens. Below it, species composition and overall diversity begin to change rapidly. Between pH 6.0 and 5.5 the changes mostly involve individual species. Species that increase replace the ones that decline and except for the frequent presence of blooms of attached algae, there is little indication of ecosystem-level changes. Below pH 5.5 the diversity changes are severe, often on the order of 50% or more. Whole functional guilds are missing, food chains are altered, and there are indications, though not consistent ones, of ecosystem-level changes. Below pH 5.0 waters enter a little-studied but ecologically demanding zone where only a few species from a few groups seem to prosper. The changes in ecosystem-level functions in this range are still largely uninvestigated.

Do fish die in acid episodes?

By the middle 1980s it was becoming increasingly clear that there were important chemical differences between chronic and episodic acidity (p. 54). Chronic mineral acidity was sulfate controlled, present year-round, and only rarely produced pHs below 5.0. Episodic acidity was nitrate and dilution controlled, relatively short lasting, and often produced pHs below 5.0.

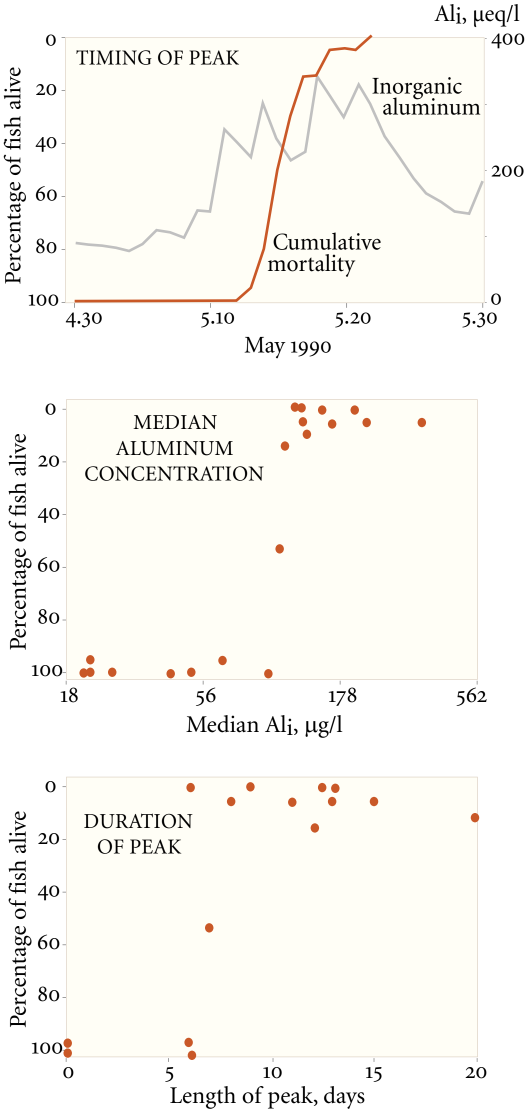
The obvious question was whether there were also biological differences between chronic and episodic acidification. In particular, could the short but intense peaks of acidity and inorganic aluminum that occurred during snowmelt have as much, or even more, effect on fish as the baseline acidity that was present all year?

Several early studies suggested that this might indeed be the case. In 1979, Colquhoun and his collaborators surveyed 42 Adirondack headwaters streams. They found that brook trout, one of the most acid-tolerant fish, were absent from over half of the streams and that 12 streams had no fish at all. Eight years later Sharpe and his collaborators did a similar study on the Appalachian Plateau in western Pennsylvania and found that 12 of the 61 streams they studied had no trout and 10 had no fish at all.

In 1984 and 1985, as part of the RILWAS, Driscoll, Yatsko, and Unangst (p. 51) gave the first detailed description of spring acidity peaks in Adirondack lakes and showed that inorganic aluminum and pH were both at levels believed toxic to fish.

Also in 1984 and 1985 and also as part of the RILWAS, Johnson and his collaborators did the first in-stream bioassays on an Adirondack stream by placing brook trout, lake trout, creek chub, and blacknose dace in cages in the North Branch of the Moose River. They found that acid episodes could kill both young and adult fish of all four species. Blacknose dace were the most sensi-

MORTALITY OF BLACKNOSE DACE IN BIOASSAYS DURING ACID EPISODES



Redrawn from Van Sikle et al., "Episodic acidification of small streams in the northeastern United States: Fish mortality in field bioassays." Copyright 1996 Ecological Society of America via the Copyright Clearance Center.Dace are acid sensitive, and their mortality rose abruptly when a peak lasted for more than 6 days or when the aluminum concentration exceeded 100 µg/l. Brook trout (opposite page, top) are less sensitive but still show a sharp increase in mortality when their critical aluminum concentration of about 200 µg/l is exceeded.

tive and brook trout the least; pH, aluminum concentration and duration of exposure were the most important variables.

Thus by the time the Episodic Response Project (ERP, p. 109) began in 1988, there was considerable knowledge of spring acidity peaks and considerable suspicion that these peaks were affecting fish distribution. But there were also doubts. The RILWAS studies had seen mortality in adult fish but only with caged fish and after fairly long exposures. It was possible that free-swimming fish might evade acid peaks by moving to less acid refugia in lakes or to stream pools where neutral groundwater was entering the stream. Furthermore, the RILWAS investigators had sampled chemistry intermittently and so were not really sure how intense the acid peaks had been or how long they had lasted.

The ERP sought to resolve these doubts. The investigators selected 12 streams in New York and Pennsylvania with low baseline ANCs and naturally reproducing brook trout populations, placed both caged and radio-tagged fish in the streams, and then monitored the fish during acid episodes. The mortality studies used brook trout and blacknose dace. The tracking studies and censuses concentrated on brook trout.

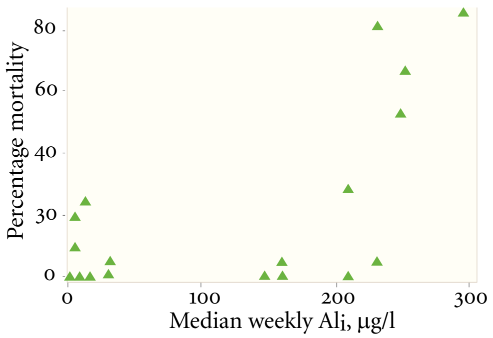
The results of the bioassays were decisive. As expected, the dace were highly sensitive to low pHs in general and to inorganic aluminum in particular. They could tolerate inorganic aluminum concentrations below 100 µg/l for long periods, but after 6 days at higher concentrations their mortality increased rapidly and quickly reached 90% to 100%.

Brook trout were less sensitive but still showed significant amounts of mortality in many acid episodes. As with dace, the average aluminum concentration was critical for survival, and above 200 µg/l of inorganic aluminum mortality rose sharply. The lowest pH reached was also important, especially in conjunction with the calcium and aluminum concentrations. Together the median aluminum and calcium concentrations and the minimum pH explained 72% of the variance in brook trout mortality.

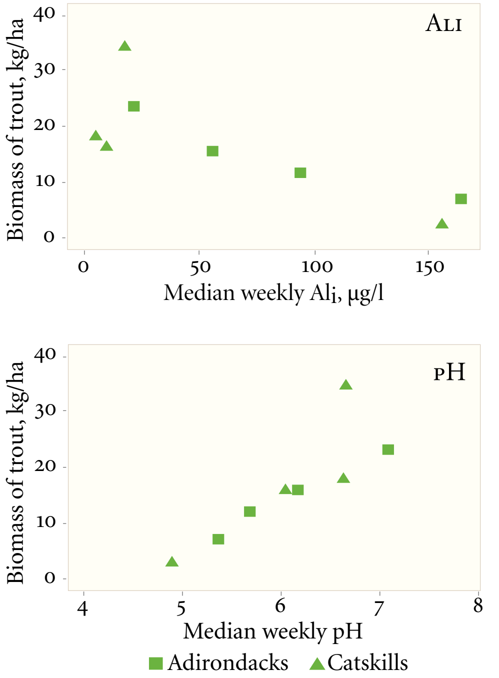
As many biologists had suspected, calcium and DOC (which binds inorganic aluminum) seemed to mitigate the effects of elevated aluminum and low pH. Dissolved organic carbon had the largest effect: at high aluminum levels, 8 mg/l of dissolved carbon could reduce mortality from 100% to 50%.

The ERP's observations of radio-tagged fish were also interesting. Fish were clearly able to detect acid episodes and often moved downstream or into lakes and tributaries when the pH decreased. In Buck Creek, which is an inlet stream of the well-buffered Seventh Lake, the majority of the radio-tagged trout in the study area moved into the lake at the start of acid episodes. But refugia and acid-avoiding behavior apparently did not offer complete protec-

BROOK-TROUT MORTALITY & ALUMINUM CONCENTRATION



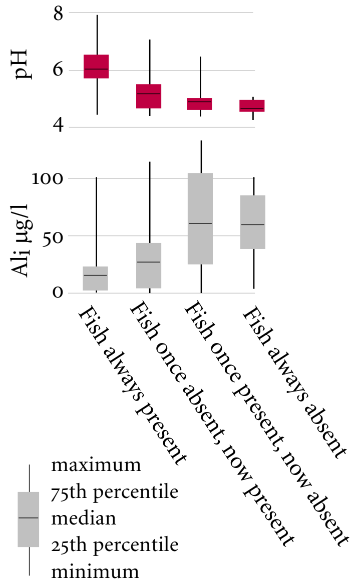
BROOK-TROUT BIOMASS & STREAM ACIDITY



Top graph, showing that mortality increases rapidly with the inorganic aluminum concentration, redrawn from Van Sikle et al., "Episodic acidification of small streams in the northeastern United States: Fish mortality in field bioassays." Two lower graphs, showing fish biomass in acid streams, from Baker et al., "Episodic acidification of small streams in the northeastern United States: Effects on fish populations," 1996. All graphs copyright 1996 Ecological Society of America via the Copyright Clearance Center. By using refugia, trout can survive moderate acidity peaks but only in fairly low numbers. Their biomass in the most acidic streams in which they can survive is less than a quarter of that in near-neutral streams.

tion: censuses showed that streams whose median pHs during high flows were less than 5 or whose median aluminum concentrations during high flows were more than 100 µeq/l had half or less the biomass of trout of less acidic streams.

PH AND ALUMINUM RANGES OF ALS LAKES WITH & WITHOUT FISH



Redrawn with permission from Baker et al., "Fish population losses from Adirondack lakes: The role of surface water acidity and acidification." Copyright 1993, Americal Geophysical Union. Lakes that are fishless or have lost fish populations have consistently lower pHs and higher aluminum concentrations than other lakes.

Apparently, acid-avoiding behavior allows the trout to survive in some acidic streams where conditions might otherwise be lethal but does not let them maintain the populations that they have in nonacidic streams. And not all streams have refuges: recall that the ERP studies were limited to streams where brook trout still survived and that half of the streams studied by Colquhoun et al. had no trout and thus very likely no refuges for trout, at all.

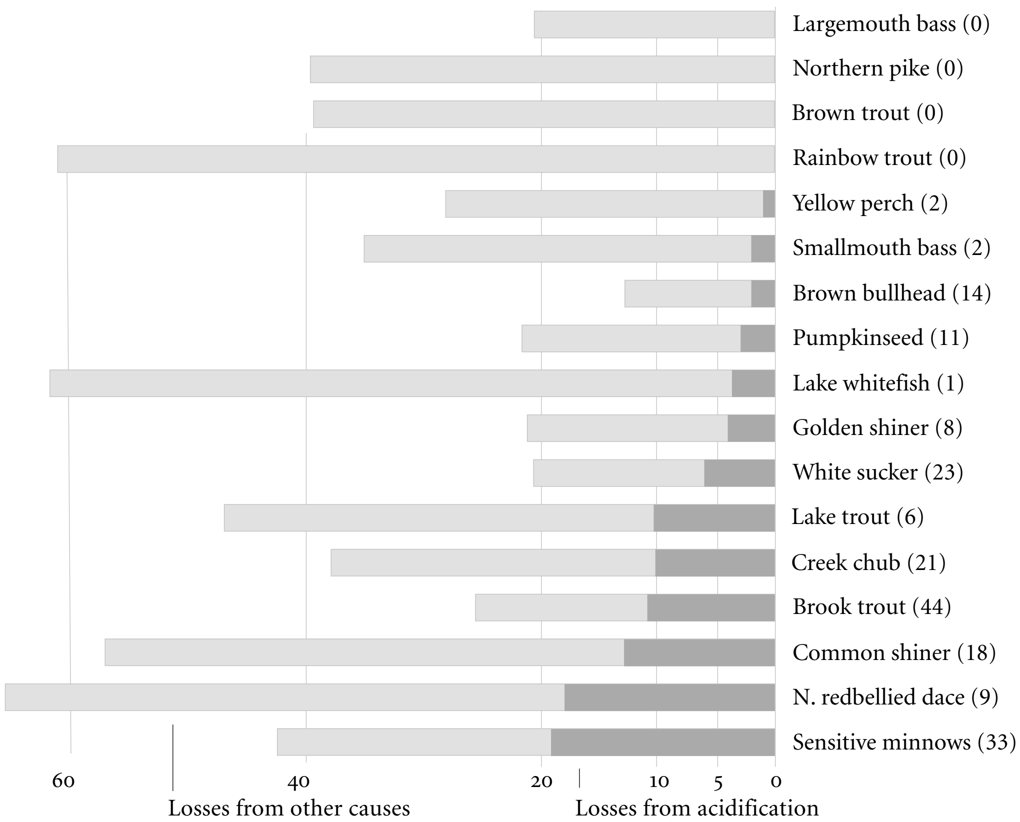
Historical Losses of Fish Populations

Assessing the historical changes in fish populations is notoriously difficult. Historical information on fish is usually incomplete and mixed in quality; historical information on chemistry is very sparse and hard to compare with modern results. Further, because fish populations are intensively managed and exploited, the historical record itself is complex and messy. The acid-related extinctions that are of interest to researchers can be masked by reintroductions, simulated by incomplete surveys, and also simulated by genuine but not acid-related extinctions caused by fishing pressure, reclamation, introduced predators, and other causes.

Nonetheless, the Adirondack historical record is better than most. But still there are problems with data quality and sampling bias. Many of the older DEC surveys focused on sport fish and on the larger lakes with good potential for sport fishing. They did not use a uniform sampling protocol and probably overlooked some minnows and smaller forage fish. The Adirondack Lakes Survey was more systematic and sampled far more small ponds and high-elevation lakes than the earlier surveys. But no survey catches all fish with equal success, and the ALS may well have missed some species that were found in earlier surveys.

The first comparison of the ALS data with data from earlier surveys was reported by Baker and her colleagues in 1990 (p. 79). The results were mixed. When they examined the set of 295 lakes for which there both contemporary and historical data they were not able to show a significant change in the percentage of fishless lakes and found only a weak relation between the change in the number of species and the current pH of the lake. But they noted that since the early data were biased toward large, deep, high-ANC lakes where extinctions were less likely, there may have been many acid-related extinctions in lakes that for which there were no historical records.

When they focused on losses of individual species and examined the set of 988 lakes for which they had 1980s and pre-1970



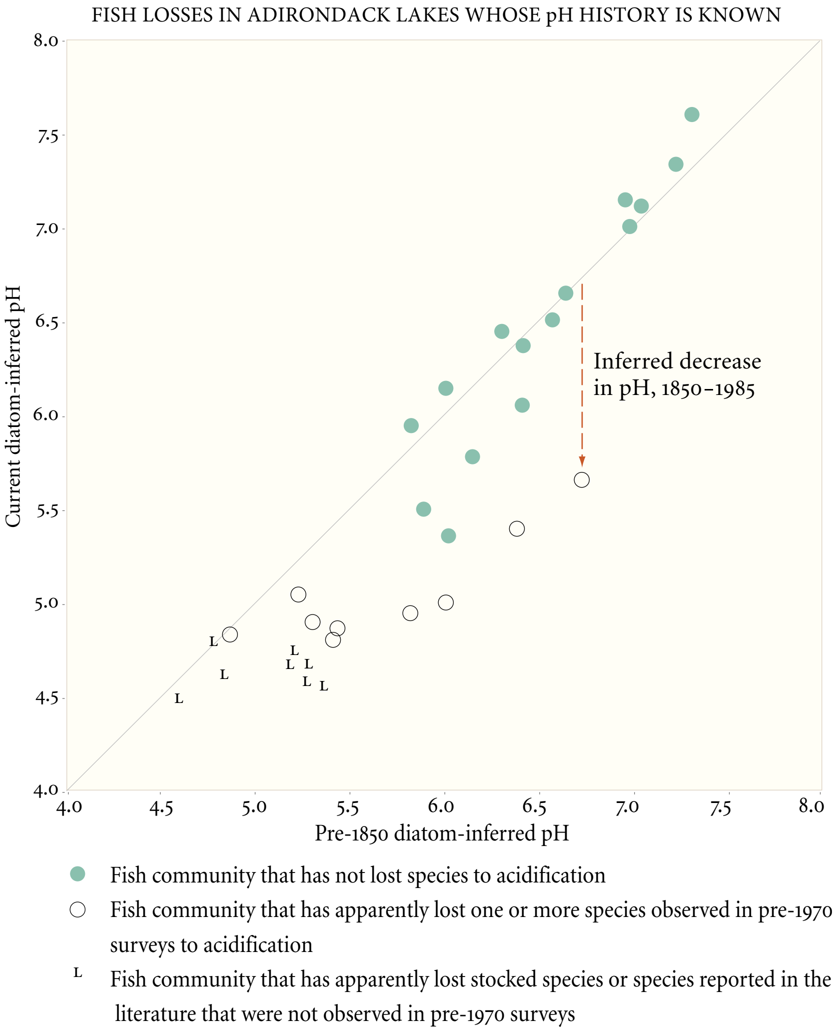
ESTIMATED ADIRONDACK FISH POPULATION LOSSES

From Baker et al., "Fish population losses from Adirondack lakes: The role of surface water acidity and acidification," 1993. The bars represent the number of Adirondack lakes with is a confirmed historical record at which the species was not found during the Adirondack Lakes Survey. The light gray segment of each bar gives the number of lakes at which the population loss may have resulted from stocking, fishing pressure, reclamation, beaver activity, anoxic episodes, etc. The dark gray segment of each bar is the number of unaccounted for population losses in acidic lakes. These are assumed to be caused by acidification.

data, the results were quite different. They found 2,824 records of fish populations that had been confirmed by pre-1970 surveys in lakes sampled by the ALS. Of these, 851 (30%) populations had apparently been lost between the original survey and the ALS. They identified possible nonacid-related causes for 659 of these losses and were left with 192 losses that they regarded as probably acid related. This analysis suggested that at least – and their estimates were surely minimums – 6.8% of the populations for which they had historical records had been lost to acidification, and 23% of all fish population losses were acid related.

The losses that they believed to be acid related showed clear ecological patterns. The species that were most often lost were brook trout and several minnows that had previously been identified as acid sensitive. The lakes that had lost any particular species tended to be higher in elevation and to have more acid and more inorganic aluminum than the lakes in which the species still survived. All this suggested that even though they could not quantify the extent of acid-related population losses exactly, they had made a convincing case that these losses had occurred.

The case was made even more convincing a few years later when the results of the PIRLA study of historical acidification became available. Historical fish data were available for 32 of the PIRLA lakes. When Baker and her colleagues analyzed these lakes, they found a clear connection between historical pH changes and the loss of fish species. On the graph at right, the lakes that have lost fish species lie below and to the left of the lakes that haven't, showing elegantly that the historical fish and chemical data are in fact consistent: the lakes that have acidified the most or that were the most acid originally are also the ones that have lost fish.



From Baker et al.: "Fish population losses from Adirondack lakes: The role of surface water acidity and acidification." Copyright 1993 American Geophysical Union. These are the lakes for which there are both fisheries data and records of historical acidification from sediment cores (p. 85). The graph plots current and historical diatom-estimated pHs; the farther a point is below the line, the more the lake is believed to have acidified. All the lakes that have lost fish species either have current pHs below 5.51 or are estimated to have acidified by 0.5 pH unit or more, or both.

Ecological Monitoring in the 1990s

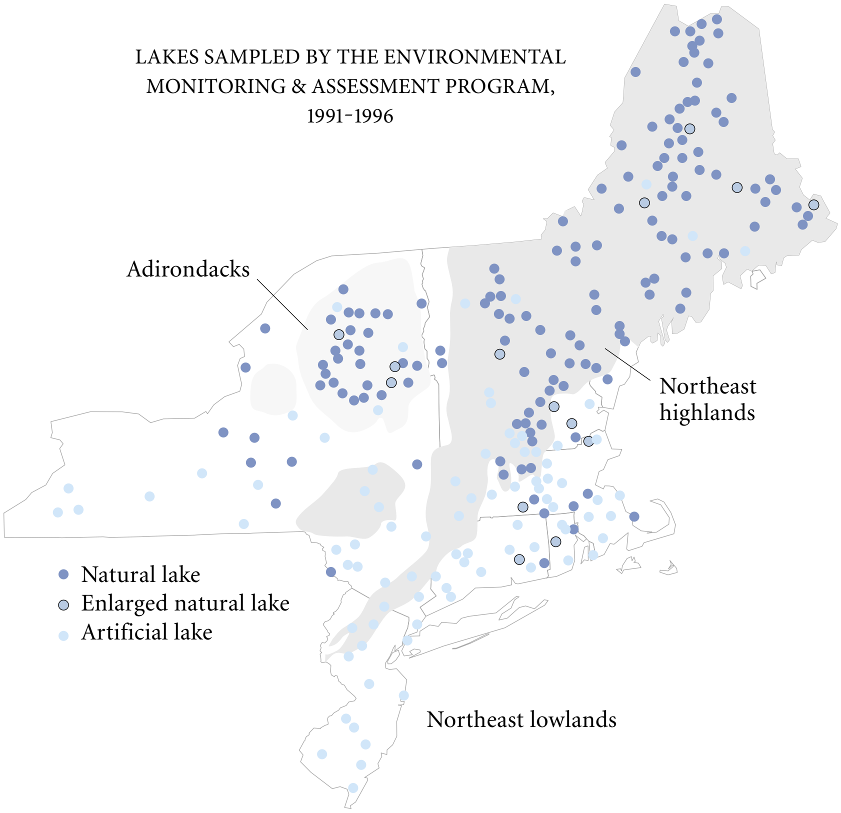
The heroic period of Adirondack acid rain biology that had begun with Schofield's work in the early 1970s ended with the publication of the results of the Adirondack Biota Project in 1989, the Adirondack Lakes Survey's *Interpretive Analysis* in 1990, and the biological data from the Episodic Response Project in the early 1990s. Nationally, this coincided with the publication of the NAPAP *State of Science* reports in 1990 and then with a post-1990 reduction in federal funding for new biological and chemical research and a redirection of the remaining funding toward long-term monitoring.

Unfortunately, relatively little of the Adirondack long-term monitoring since 1990 has had a biological component. Despite the importance of the biological surveys of the 1980s, neither the Adirondack Long-Term Monitoring Program nor the Temporally Integrated Monitoring of Ecosystems project (p. 194) had an integrated biological component.* Several one-time studies, including the Episodic Response Project and the Adirondack mercury studies described Chapter 6, gathered biological information, but relatively few of them did quantitative or statistically based sampling, and none of them were designed to detect long-term trends.

The lack of new biological data was partially remedied in the early 1990s when the U.S. Environmental Protection Agency created two biological monitoring programs, the Adirondack Effects Assessment Program (AEAP) and the Environmental Monitoring and Assessment Program (EMAP).

---

* The Adirondack Effects Assessment Program now does annual biological monitoring, mostly of plankton, on 28 of the Adirondack Long-Term Monitoring Program lakes, but has not yet published any results.


LAKES SAMPLED BY THE ENVIRONMENTAL MONITORING & ASSESSMENT PROGRAM, 1991–1996

From Whittier et al., “Indicators of ecological stress and their extent in the population of northeastern lakes: A regional-scale assessment,” 2002. Approximately 245 waterbodies were sampled in the first 6 years of the program. The large number of artificial lakes in the lowland region occurs because the lakes are selected randomly, and in many lowland areas there are far more artificial lakes than natural ones.

The Adirondack Effects Assessment Program is run by Rensselaer Polytechnic Institute. It is a regional program that collects annual samples from 30 lakes in the southwestern Adirondacks and focuses on the relations between water chemistry, microbiology, and plankton populations. It began in 1994 and continues at present.

The *Environmental Monitoring and Assessment Program* is a national program, run by the EPA with many collaborators, that was intended to monitor trends in ecological resources and appraise ecological health on a community basis. It contains both terrestrial and aquatic programs. Its Aquatic Resources Program began a northeastern lakes survey in 1992, with a complex sampling design using a triangular grid and random sampling around grid points. The program was designed as a long-term, statistically based monitoring program but gathered only three years of data before being terminated in 1994.

Neither the EMAP nor the AEAP has published any results addressing the biological effects of acidification. But before the EMAP was terminated it did produce several regional analyses of lake biology, two of which we describe here. They are interesting both because of the information they provide about Adirondack lakes, and because they illustrate the potential, and currently unrealized, value of regional biological monitoring.

Indicators of Ecological Stress

The first analysis of the northeastern EMAP data, by Whittier and his collaborators, compared the levels of ecological stress generated by various human activities. The researchers measured five kinds of biological stress – acidification, nonnative fish, mercury pollution, eutrophication, and shoreline development – and binned the measurements into three categories they called moderate, high, and severe stress. They then estimated the number of lakes in each region in each category. Thus lakes with summer ANCs between 0 and 50 µeq/l were called moderately stressed, and about 32% of Adirondack lakes fell in this category.

Because the different levels of stress are arbitrary, the comparisons between regions mean more than the comparisons between stresses. Thus different definitions of the stress categories could easily change the relative ranking of mercury and acidification in the Adirondacks, they would not change the conclusion that both mercury and acidification are more important in the Adirondacks than in the Northeast lowlands.

Despite the arbitrariness, the results are fascinating. Acidification, as we would expect, is more important in the Adirondacks than elsewhere in the region. Eutrophication, a major problem in the Northeast lowlands, is less important in the Northeast highlands and rare in the Adirondacks. Severe shoreline development occurs only in the lowlands, but high stress from development occurs on 20% or Adirondack and Northeast highlands lakes as well. And mercury in fish is not only a widespread Adirondack problem but, unlike acidification, an important regional problem as well.

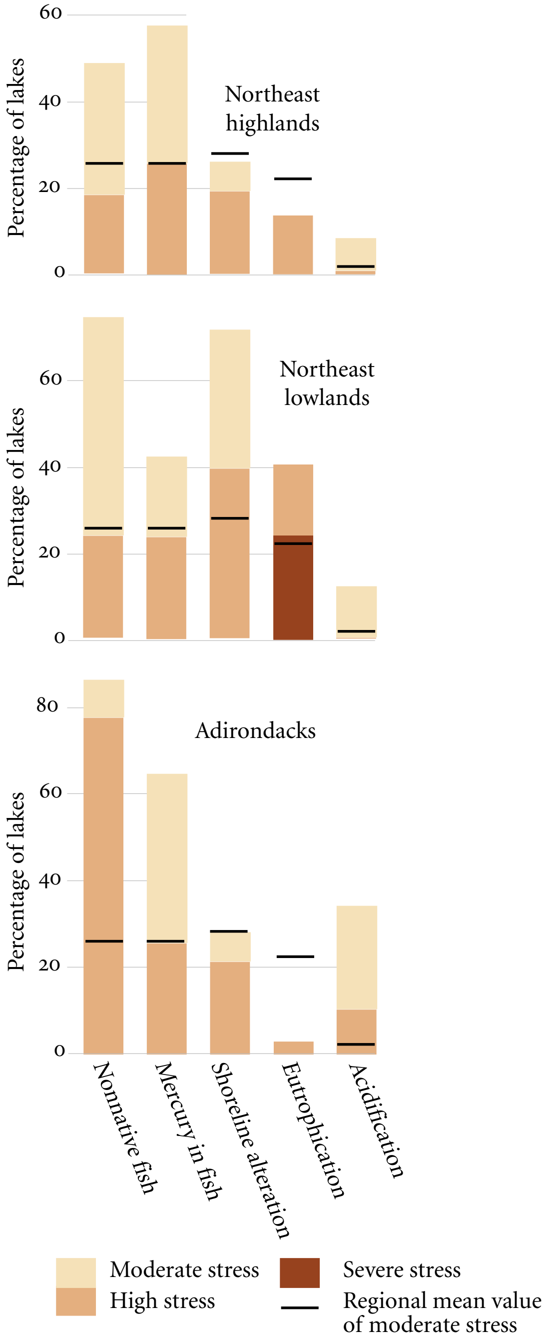
Regional Fish Diversity

As the historical analysis of fish population losses (p. 183) by Baker and her collaborators showed, many human activities cause fish population losses. An interesting question is whether the effects of these losses are mostly local, or whether they have combined to produce overall changes in the regional diversity of native fish.

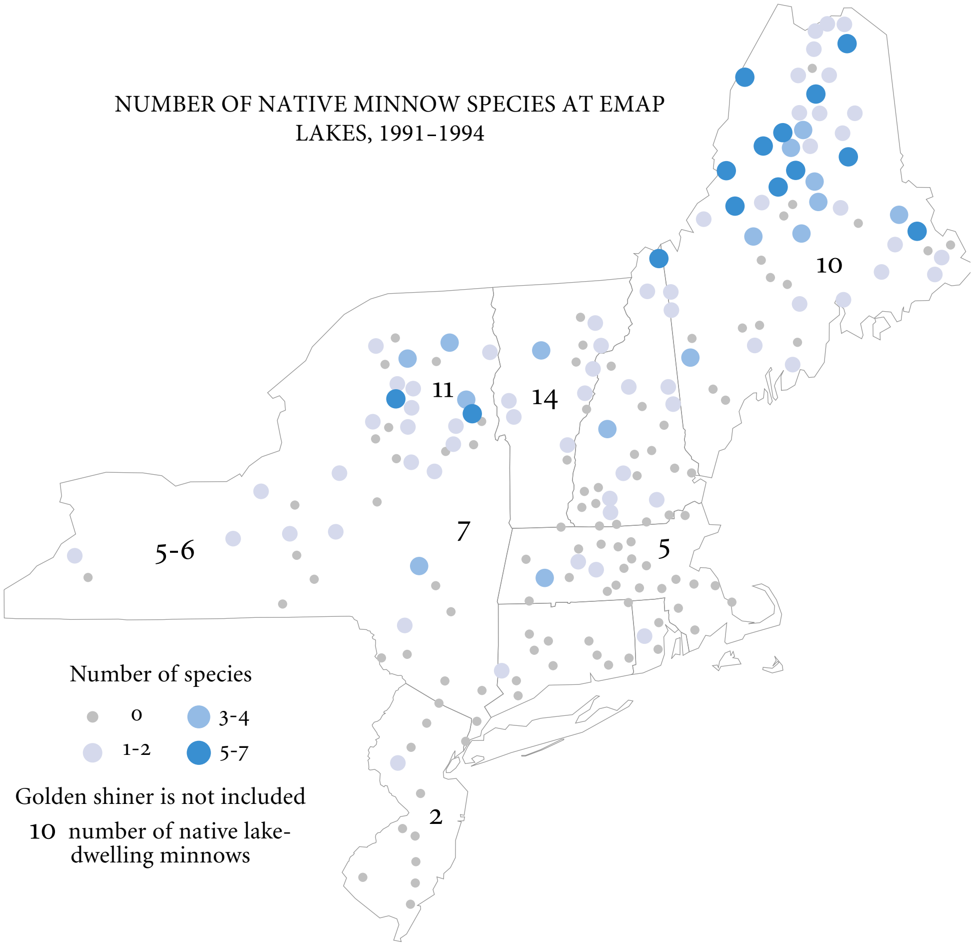
Two recent papers based on the 1992–1994 EMAP data by Whittier and his collaborators give an interesting and complex answer. Apparently human activities are both reducing diversity and converting native-dominated faunas to nonnative faunas, but the two are not well correlated and introduced fish do not always reduce native diversity.

Whittier, Halliwell, and Paulsen used the EMAP survey data to map cyprinid minnow diversity. The cyprinids are our most diverse family of freshwater fishes. They are also small, sensitive to

ESTIMATED PERCENTAGES OF EASTERN LAKES WITH ECOLOGICAL STRESSES



From Whittier et al., "Indicators of ecological stress and their extent in the population of northeastern lakes: A regional-scale assessment," 2002. The bars give the estimated percentage of the 11,000 northeastern lakes in which each stress is at or above a given level.



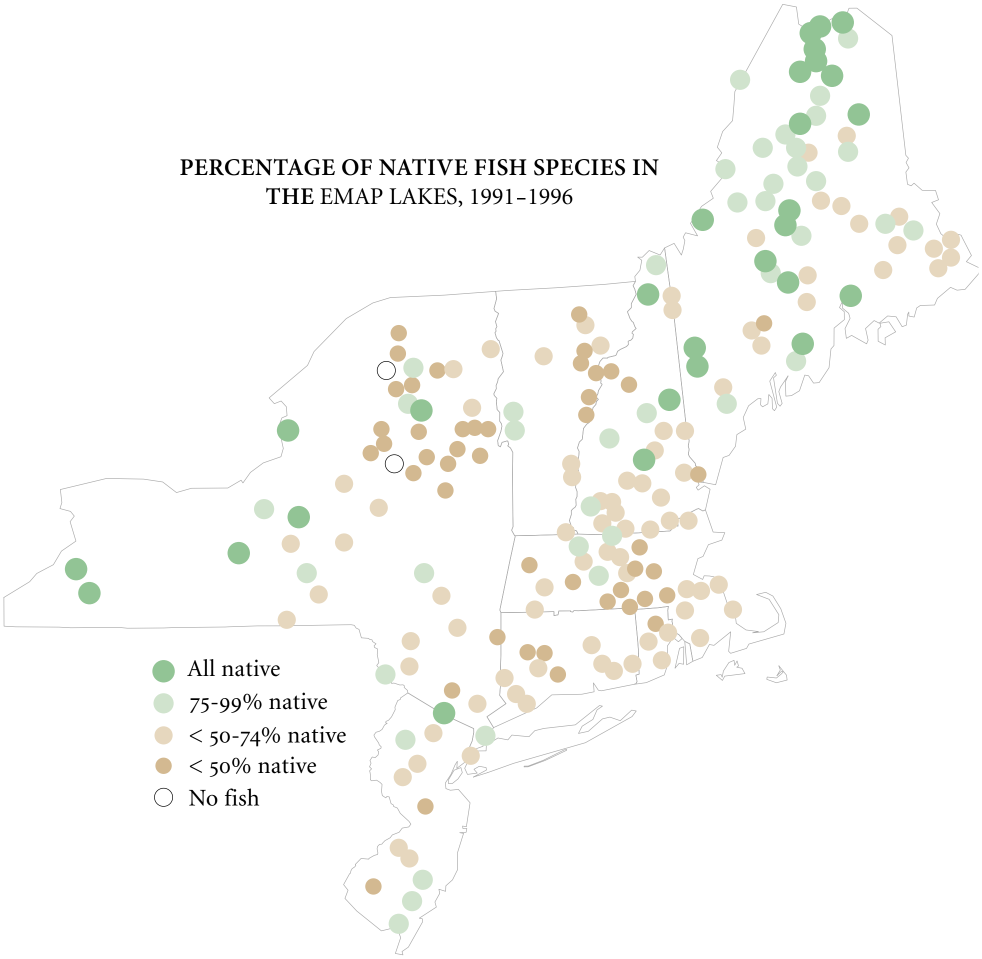
NUMBER OF NATIVE MINNOW SPECIES AT EMAP LAKES, 1991–1994

From Whittier, Halliwell, and Paulsen: "Cyprinid distributions in Northeast U.S.A. lakes: Evidence of regional-scale minnow biodiversity losses," 1997. The native minnows are sensitive to acidification, shoreline development, and introduced predators like pike and bass. Currently, they are most diverse in remote lakes where both acid rain and shoreline development are low and where there are few introduced species of fish (p. 188). They are absent from most of the lakes in developed areas.

acidification and other chemical changes, and vulnerable to predatory fish and especially to introduced game fish. With the exception of the golden shiner they are rarely introduced. They are thus potential indicators of lake integrity and disturbance and should be most diverse where the lakes have had the least human impact and least diverse where the impacts have been the greatest.

The map shows that this is in fact the case. Cyprinid diversities are highest in northern Maine, next highest in the Adirondacks, still moderately high in northern Vermont and New Hampshire, and low or absent everywhere else. While ten lakes in northern Maine had five or more species, only six lakes in all southern New England had any species at all.

Further analysis by Whittier and his colleagues confirmed that minnow diversity is closely related to human impact. The number of minnow species decreased, very predictably, as either the amount of shoreline development or the number of shallow-water predators like pike, white perch, largemouth bass, and smallmouth bass increased. Both are measures of human influence. Further, because many of the shallow-water predators are nonnative sport fish, development tends to be correlated with exotic fish: almost every lake where there is shoreline development has at least one introduced predator. The Adirondacks, for example, have large



PERCENTAGE OF NATIVE FISH SPECIES IN THE EMAP LAKES, 1991–1996

From Whittier and Kincaid, "Introduced fish in northeastern USA lakes: Regional extent, dominance, and effect on native species richness," 1999. Extrapolating from their survey to the full population of northeastern lakes they estimate that 74% of the lakes over 1 ha contain introduced species and that in 32% of the lakes nonnative fish are more common than native. The number of nonnative fish is generally highest in the areas with the most shoreline development, but it is also high in the Adirondacks, where there has been much recreational use and management of undeveloped lakes. Interestingly, however, and contrary to what has been found for stream fish, the number of native species does not necessarily decrease as the number of introduced species increases.

numbers of nonnative fish, which may be one of the reasons that their minnow diversity is not as high as in Maine.

This being the case for minnows, it might be expected that overall native fish diversity might decrease as the diversity of introduced species increased. An analysis of the EMAP data from the same lakes by Whittier and Kincaid found, rather surprisingly, that this was not generally true. What was clearly stressful for native minnows was not necessarily stressful for other native groups. The percentage of introduced species was, as expected, high in both the developed areas and areas like the Adirondacks where there has been a history of sport fishing and fisheries management. But except along the New England coast, the total number of native species did not decrease as the number of nonnatives increased. Possibly, the authors speculated, "the ecoregional template as characterized by lake size, elevation, and depth defined a species carrying capacity that was not fully used in presettlement times." In other words, the presettlement Northeast may have had more fish niches than fish. Some introduced fish may have moved into unoccupied nitches, and some native fish may have been able to cope with introductions by sharing or changing their niches.

SUMMARY

1 Acidification causes both *species-level and community-level changes* in the biology of lakes and streams. Many common aquatic species have ecological thresholds somewhere between pH 6 and pH 5. When these thresholds are exceeded, even fairly briefly, mortality rises rapidly and species may be reduced or vanish altogether. Adirondack biological surveys show this very clearly: in the more acid waters, the diversity of almost all biological groups is reduced.

2 *Fish mortality* from acidification has been demonstrated in both lakes and streams. Acid episodes of the sort that are common on many Adirondack streams kill sensitive minnow species outright, make brook trout move downstream or seek refuges, and cause year-round reductions in the numbers and biomass of the trout that survive. The chronically low pHs and high aluminum concentrations found in many low-ANC Adirondack lakes are associated with increased losses of fish populations, of both relatively sensitive species like the cyprinid minnows and relatively insensitive species like brook trout.

3 Relatively little *new biological work* has been done since 1990, and only one current Adirondack monitoring program, the Adirondack Effects Assessment Program has a biological component.

4 The EPA's *Northeastern Lakes Program*, which ran from 1992 to 1994, produced interesting regional estimates of ecological stresses and fish diversity. Its stress estimate suggests that there is no region in the Northeast where 50% of the lakes are free from ecological stress. Mercury pollution is a problem throughout the region; acidification is severe in the Adirondacks, and eutrophication and shoreline development severe in the northeastern lowlands. Cyprinid minnow diversities and the percentage of native species are low in much of the Northeast. If they are, as the EMAP researchers suggest, good proxies for naturalness or ecological health, then the only area in which the majority of the lakes sampled were natural or in good health was northern Maine.

NOTES

For general reviews of aquatic biology see Baker et al., "Biological effects of changes in surface water acid-base chemistry," 1990; Baker and Christensen, "Effects of acidification on biological communities in aquatic ecosystems," 1991; and Ecological Society of America, "Acid deposition: The ecological Response", 1999.

p. 176 Papers in the chronology not cited later in the chapter are: Schofield, "Acid precipitation: Effects on fish," 1976; Driscoll et al., "Effect of aluminum speciation on fish in dilute acidified waters," 1980; Schindler et al., "Long-term ecosystem stress: The effects of years of experimental acidification on a small lake," 1985; Brezonik et al., "Experimental acidification of Little Rock Lake, Wisconsin," 1986; Johnson et al., "In situ toxicity tests of fishes in acid waters," 1987; and Sutherland, ed., *Field Studies of the Biota and Selected Water Chemistry Parameters in 50 Adirondack Mountain Lakes*, 1990.

p. 178 For aquatic vascular plants see Jackson and Charles, "Aquatic macrophytes in Adirondack (New York) lakes: patterns of species composition in relation to environment," 1988.

p. 180 For fish in acidic streams see Colquhoun et al., *Preliminary Report of Stream Sampling for Acidification Studies – 1980*, 1981; Driscoll, Yatsko, and Unangst, "Longitudinal and temporal trends in the water chemistry of the North Branch of the Moose River," 1987; and Sharpe et al., "The relation of water quality and fish occurrence to soils and geology in a region of high hydrogen and sulfate ion deposition," 1987. For the RILWAS biological studies see: Johnson et al., "In situ toxicity tests of fishes in acid waters," 1987

p. 181. For the results of the Episodic Response Project see the last note on p. 127.

p. 185. For the design of the EMAP lake studies see Whittier and Paulsen, "The surface waters component of the Environmental Monitoring and Assessment Program (EMAP): An overview," 1992.

Monitoring Programs, 1963–2003

1963 The Hubbard Brook Experimental Forest in northern New Hampshire begins monitoring precipitation and runoff chemistry.

1976 The U.S. Department of Energy opens the first four precipitation monitoring stations of the Multistate Atmospheric Power Production Pollution Study Network.

1978 A consortium of state and federal agencies and private research organizations opens the first 22 precipitation monitoring stations in the National Trends Network.

1981 Researchers at the New York Department of Environmental Conservation begin the monitoring of several Adirondack streams.

1982 The Regionalized Integrated Lake-Watershed Acidification Study begins the monthly monitoring of 20 Adirondack lakes. Seventeen of these are taken over by the Adirondack Long-Term Monitoring Program in 1985 and have been monitored ever since.

1982 Researchers at Huntington Forest begin monitoring the element balances of Arbutus Lake.

1986 The Environmental Protection Agency establishes the National Dry Deposition Network, later the Clean Air Status and Trends Network, with 50 stations.

1987 The New York State Department of Environmental Conservation opens the first 15 stations in its Atmospheric Deposition Monitoring Network.

1990 The Episodic Response Project (ERP) begins monitoring 13 streams in New York and Pennsylvania.

1991 The Environmental Protection Agency's TIME program begins the annual monitoring of 43 Adirondack lakes, 30 New England lakes, and 30 streams in the mid-Atlantic region.

1992 The Adirondack Long-Term Monitoring Program adds 35 lakes and 3 streams, giving it a total of 55 monitored waters.

1992 The first analysis of LTM data for the eastern United States by Newell finds significant decreases in sulfate at many sites in the Catskills, Adirondacks, and Vermont.

1993 The Mountain Cloud Acid Deposition Program begins to monitor cloudwater chemistry at three sites.

1993 Driscoll and Van Dreason examine 8 years of Adirondack LTM data from 17 lakes. They report statistically significant decreases of sulfate in 13 lakes, significant increases of nitrate in 9 lakes, and significant decreases of ANC in 5 lakes. They speculate that the decreases in ANC are being controlled by the increases in nitrate.

1994 The national Mercury Deposition Network begins with 13 precipitation stations, and the Adirondack Effects Assessment Program begins the biological monitoring of 30 Adirondack lakes.

1995 Driscoll et al. extend the analysis of the Adirondack LTM lakes, using data through 1994. They find that the concentration of sulfate in lakes is decreasing more slowly than the concentration of sulfate in precipitation and speculate that this may be caused by the release of sulfates stored in soil. Despite decreases in sulfate there are no systematic increases in ANC or pH.

1999 Stoddard et al. provide the first comparison of regional trends in Europe and eastern North America. They find widespread decreases in sulfate. ANCs are increasing in Europe, Britain, and Scandinavia but in only a few parts of North America

2001 Mitchell et al. summarize 16 years of mass-balance data from the Arbutus watershed. The watershed is retaining nitrogen and hydrogen ion and exporting sulfate and base cations.

2002 Driscoll et al. summarize Adirondack LTM data through 2000. They report, for the first time, decreases in nitrate and increases in pH, ANC, and DOC.

2002 Lawrence, Momen, and Roy report on the first 11 years of monitoring the three Adirondack LTM streams. They report a complex relation between ANC and flow, in which ANC increases were observed but were not synchronous between the three streams and were not directly related to trends in deposition.

2003 Stoddard et al. analyze the long-term monitoring data for the eastern United States. They find large decreases in sulfate and base cations, smaller decreases in nitrates, widespread increases in ANC, and almost no changes in hydrogen ion.