Indicators of Ecological Stress and Their Extent in the Population of Northeastern Lakes: A Regional-Scale Assessment

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The last few decades have witnessed phenomenal growth in the amount of environmental data available for broad-scale assessments. Concurrent with this information explosion has been the resolution of many local environmental problems. As these problems are addressed, broader-scale issues, such as nonpoint source pollution, biodiversity loss, and alien species invasions, have presented ever more complex and difficult regional-scale challenges, especially with respect to evaluation of these issues' relative importance. Fortunately, understanding of the importance of geographic and temporal scales in the related fields of ecology, conservation and restoration biology, and environmental protection and management is growing.

Historically, much of the research and application of knowledge in these fields has, of necessity, been done at local scales. As data collected by narrowly focused studies at local sites accumulate, the need to place this knowledge in landscape, regional, and historical contexts grows (Landres et al. 1999, Poiani et al. 2000). There have also been increases in the diversity and power of spatial analysis tools, most prominently the introduction of faster, smaller computers with ever more powerful software applied to ever larger databases. Perhaps less obvious, but nonetheless important, are conceptual tools such as ecoregions, which are used to describe the geographic context of large areas (Omernik 1987, Omernik and Bailey 1997); indices of biological integrity that extract assessments of condition from complex species assemblage data (Karr 1981, 1991); and statistically rigorous survey designs (Stevens 1994, Urquhart et al. 1998, Olsen et al. 1999).

Despite these advances and decades of monitoring and research, it is rarely possible to answer with any confidence such seemingly simple questions as, What percentage of lakes in a region are eutrophic? or even, How many lakes are there?

> ALTHOUGH STRESSORS SUCH AS NONNATIVE FISH INTRODUCTIONS, MERCURY CONTAMINATION, AND SHORELINE ALTERATION ARE NOT GENERALLY CONSIDERED SUBJECTS FOR ENVIRONMENTAL MANAGEMENT, THEY ARE AS WIDESPREAD AS EUTROPHICATION, AND MORE EXTENSIVE THAN ACIDIFICATION, IN THE LAKES OF THE NORTHEASTERN STATES

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Nor is it generally possible to provide anything more than a best-judgment assessment of the relative extent of the various environmental problems. Yet answers to these sorts of questions are essential for effective environmental protection and resource management.

The inability to address the issues described above stems from the way in which environmental data traditionally have been collected. First, most sampling programs collect data for only a few indicators (often only one), usually as part of an issue-focused survey limited to the legal mandate of an agency or to the research expertise of an investigator. Second, very few monitoring or research programs use statistically based designs to select sampling sites. Without well-designed surveys, one must rely on modeling approaches to describe the condition of ecosystems other than those that have actually been sampled. Nevertheless, data from subjectively selected sites are often applied directly to the entire population of the ecosystem type, as though the data were known to be representative (Paulsen et al. 1998). To use the vast amount of existing data to quantify, at a regional scale, the ecological condition of a resource, one must combine sets of data of unknown representativeness, collected at different sets of sites and times, using a variety of sampling protocols.

To begin addressing these kinds of issues, the US Environmental Protection Agency (EPA) initiated the Environmental Monitoring and Assessment Program (EMAP) in 1989 (Larsen et al. 1991, Hughes et al. 2000). One of EMAP's first projects was a survey of lakes in the eight states of the northeastern United States: Connecticut, Maine, Massachusetts, New Hampshire, New Jersey, New York, Rhode Island, and Vermont. This survey was the first regional-scale attempt to use a probability-based design to collect biological assemblage data along with a broad range of physical and chemical indicators of stress to lake ecosystems.

We use the data from this survey to determine the extent to which northeastern lakes are affected by nutrient enrichment, acidification, metals contaminants in fish tissue, nonnative invasions, and riparian disturbance—problems that can impair or even destroy lake ecosystems. We focus on estimates of the extent to which the population of lakes in the Northeast was either in impaired condition or was subject to ongoing stress. These estimates provide a previously unavailable kind of information that we believe is needed to develop a relative ranking of stressors to northeastern lakes, which can help guide restoration efforts and policy.

Program approach

The EMAP approach combines two components that distinguish it from most broad-scale environmental monitoring programs. The first is the use of multiple indicators of ecological condition that combine assemblage-level biological data with chemical and physical measures of each lake, augmented by landscape-scale assessments of the watersheds. The second is a regional-scale, probability-based survey design. The objectives of this approach were to be able to characterize at a regional scale, with known statistical confidence, the sampled attributes of the population (or subpopulations) of lakes in the Northeast and to characterize the ecological condition of these lakes and the extent of threats to their ecosystems.

Every summer from 1991 to 1996, EPA collaborated with the US Fish and Wildlife Service in a survey of 345 lakes in the Northeast (Figure 1). In order to make inferences about all lakes in the region, the lakes were selected using a stratified, randomized design (Larsen et al. 1991, 1994, Stevens 1994). Each lake was visited during a sampling window extending from July to mid-September. Lakes were sampled for a broad range of characteristics: biological (fish, zooplankton, littoral macroinvertebrate, riparian bird, and sediment diatom assemblages), chemical (water-column nutrients and chemistry, chlorophyll *a*, and fish tissue contaminants), and physical (dissolved oxygen and temperature profiles, and littoral and riparian physical habitat) (Baker JR et al. 1997). Unless

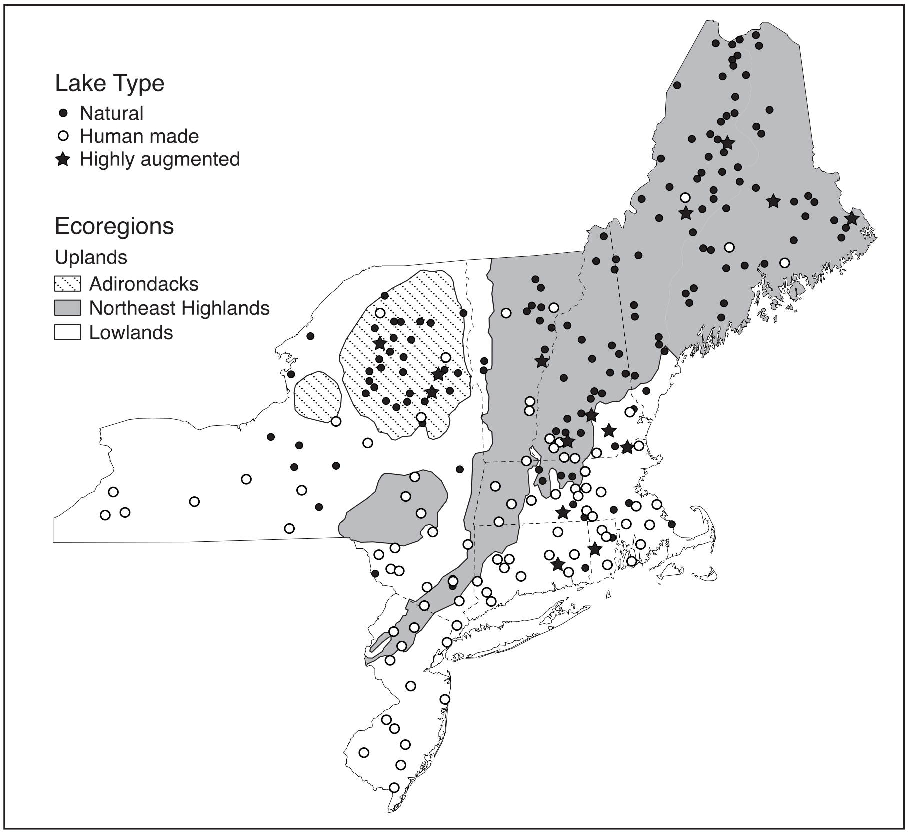

Figure 1. Locations of natural and human-created lakes sampled by the Environmental Monitoring and Assessment Program (EMAP) in the Northeast, 1991–1996. (Ecoregions based on Omernik 1987 and McMahon et al. 2001.)

stated otherwise, we report results as estimates (with 95% confidence intervals) of the condition of the population of northeastern lakes, rather than as data from individual lakes or sets of sampled lakes. The procedures for calculating estimates of numbers and percentages of lakes in the population are based on sampling theory, using the Horvitz-Thompson estimate of variance, rather than on standard parametric statistics (Stevens 1994). Thus, no data transformations are applied.

To provide a geographic framework, we divided the Northeast into two ecological regions based on Omernik's (1987) and McMahon and colleagues' (2001) ecoregions: the Uplands, regions of higher elevation or conifer forests, and the Lowlands, regions of lower elevation or agricultural and urban land uses. For some indicators (e.g., acidification, nonnative fish species), we further divided the Uplands into the Adirondacks and the Northeast Highlands (Figure 1).

Lake resource characterization

A probability-based design requires an explicit population from which to draw a sample. Our population of interest was all lakes in the Northeast with a surface area of 1–10,000 hectares and a depth of at least 1 meter. However, lakelike water bodies span a continuum that includes natural lakes without anthropogenic modifications, ponded wetlands, human-constructed lakes intended to mimic natural lakes, and "run-of-the-river" reservoirs created by damming rivers. We included all lentic water bodies. As our sampling frame, we used the digital version (Digital Line Graphs, or DLG) of the US Geological Survey 1:100,000 map series. That database catalogued about 16,500 water bodies in the Northeast coded as lakes or reservoirs with surface area greater than or equal to 1 ha. Expecting that there would be some errors in the DLG (Burch Johnson et al. 1989), we drew a sample larger than the one we planned to visit in the field. After a variety of data quality checks, including field reconnaissance and sampling visits to more than 350 lentic water bodies, we estimated the actual number of lakes, impoundments, and water-filled quarries in the Northeast at 11,088 (± 1615, 95% confidence interval).

For each sampled lake, we used a variety of information, including field data, topographic maps, and sediment diatoms, to determine whether it was natural, human made, or highly augmented (Whittier et al. forthcoming). We classified water bodies into four types: (1) quarry lakes, (2) impoundments (lakes created intentionally by impounding flowing water, e.g., millponds; artificial residential, agricultural, or recreational lakes; and reservoirs), (3) highly augmented lakes (existing lakes that had been deepened by more than 30%), and (4) natural lakes (lakes whose hydrology, depth, and shape had not been greatly altered by humans).

We estimated that 47% (± 9%) of the northeastern lentic water bodies were human made and that an additional 2% of lakes had been highly augmented (Figure 1). Of the human-made lakes, 93% (± 9%) were impoundments, and 7% were quarries. Of the natural lakes, 87% (± 10%) were drainage lakes, and 13% were seepage lakes (i.e., lakes lacking outlet streams). Natural and human-made lakes were not evenly distributed. In the Uplands, 69% (± 12%) of lakes were natural, whereas in the Lowlands only 27% (± 13%) were. All but two of our sample lakes in New Jersey, Connecticut, and Rhode Island were impoundments. Many natural lakes had somewhat modified hydrologies; 22% of natural lakes had either a small dam or an outlet stream road crossing, or both. As expected, small lakes were far more numerous than large lakes, with a median surface area of 9 ha and an interquartile range of 3–25 ha. Impoundments tended to be smaller (median = 7 ha, interquartile = 2–15 ha) than natural drainage lakes (median = 13 ha, interquartile = 6–36 ha).

Anthropogenic stresses to lake ecosystems

Eutrophication (nutrient enrichment) and acidification have been the most studied types of lake degradation processes (Cooke et al. 1993). The role of other airborne chemical pollutants or chemicals transferred via overland or groundwater flow are less well understood in terms of their effect on lakes. The overall impact of biotic invasions is likewise less well understood in lake systems, as are effects of human activity in the watersheds and on the lakeshore.

Nutrient enrichment. Overenrichment (eutrophication) of lakes can result in algal blooms, loss of water clarity, noxious odors, oxygen depletion, and fish kills (Cooke et al. 1993). The degree of nutrient enrichment (trophic state) is a multidimensional condition indicated by algal biomass, littoral vegetation, nutrient loads, and water transparency. In lakes, it is often measured with some combination of total phosphorus (TP, usually the limiting nutrient), Secchi disk transparency (a measure of water clarity), and chlorophyll *a* (used to estimate algal biomass) (Wetzel 1983, Cooke et al. 1993). Largely because chemical measurements can be obtained with relative ease, and because there is a predictable relationship between TP and chlorophyll *a*, TP is often is used as a surrogate to estimate phytoplankton biomass and overall lake trophic state.

In northern temperate lake districts such as the Northeast, eutrophic (TP ≥ 30 micrograms per liter) and hypereutrophic (TP ≥ 60 µg per L) lakes are generally considered to be adversely enriched (NALMS 1990, Peterson et al. 1998). An estimated 22% (± 8%) of lentic water bodies in the Northeast were eutrophic or hypereutrophic. A regional-scale assessment of whether these lakes are trophically degraded must address whether the lakes are naturally eutrophic—that is, whether there is evidence of cultural eutrophication. Ecoregional and water-body-type differences in trophic state can help answer this question. Only 12% of the Uplands lakes were eutrophic and none were hypereutrophic, while 17% of Lowlands lakes were eutrophic and an additional 22% were hypereutrophic (Figure 2a). Within the Uplands, there were no differences in trophic state patterns between the Adirondacks and the Northeast Highlands (Peterson et al. 1998). There were, however, clear differences in trophic state between the populations of natural lakes and human-made lakes (Figure 2b), with

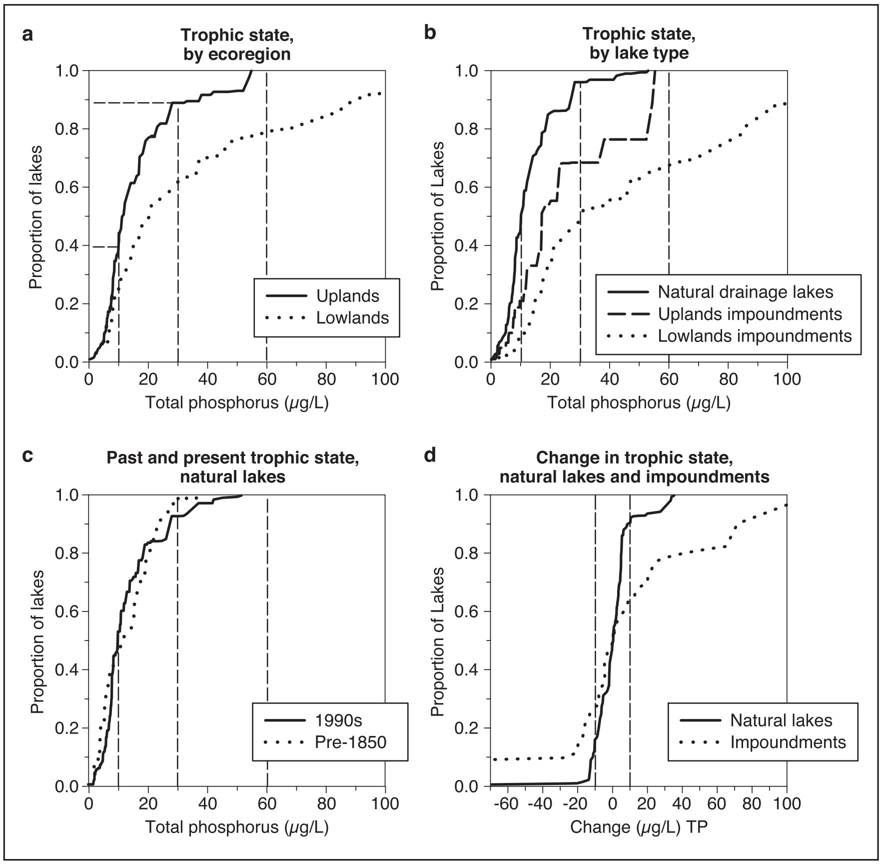

Figure 2. Trophic status of the population of northeastern lakes, illustrated by cumulative distribution functions (CDF) for total phosphorus (TP) concentrations. Vertical reference lines (in panels a, b, c) mark oligotrophic, mesotrophic, eutrophic, and hypereutrophic lake conditions. (a) CDFs of ecoregional differences in trophic state. Horizontal lines show that 39% of Uplands lakes have TP < 10 μg per L, and about 12% have TP greater than 30 μg per L. (b) CDFs of lake type differences in trophic state. (c) CDFs of present (early 1990s) and past (pre-1850s, diatom-inferred TP) trophic state for natural lakes. (d) CDFs of changes in trophic state (individual lakes) for natural lakes and impoundments. Positive values (horizontal axis) indicate increases in TP from past to present. The area within the vertical reference lines denote changes in TP of 10 μg per L or less.

83% of eutrophic or hypereutrophic lentic water bodies being impoundments. Lowlands impoundments were more eutrophic than Uplands impoundments (Figure 2b).

To estimate changes in trophic state over time, we compared TP values from the past, which were inferred from diatom assemblages in sediments in the core bottoms (Dixit et al. 1999) with current TP values. For nearly all natural lakes, core-bottom sediments dated from before 1850, thus predating the industrial period. The distribution of TP values for the population of natural lakes in the 1990s differed very little from the distribution of diatom-inferred, pre-1850s TP (Figure 2c), although the upper tails (TP > 20 μg per L) indicated that there were more eutrophic lakes in the 1990s. Regionally, about 80% of natural lakes changed less than 10 μg per L of TP (Figure 2d). The lower tail indicated that almost no natural lakes had lost more than 20 μg per L of TP since the preindustrial period, while the upper tail indicated a greater magnitude of relatively large TP increases. Finally, nearly all natural lakes with TP greater than 20 μg per L in the 1990s showed TP increases from the diatom-inferred values, with greater increases in the more eutrophic lakes.

Assessing change in impoundments was more complex than assessing change in natural lakes. Sediment cores could not be obtained from 8% of the impoundments because of hard or sandy bottoms, and 86% of impoundment core bottoms were post-1850s. Thus, diatom-inferred estimates of past TP of impoundments were based on a subset of the sampled impoundments and represented more recent conditions. In addition, the preimpoundment ecosystem type is generally not known. Diatom-inferred TP data indicated much greater variability in change than in natural lakes, with about 60% of impoundments showing change of greater than ± 10 μg per L TP (Figure 2d).

We drew several conclusions about the trophic state of the population of northeastern lakes in the early to mid-1990s. First, only a small proportion of natural lakes, in both the Uplands and the Lowlands, were eutrophic. Second, a large majority of eutrophic systems were Lowlands impoundments (Whittier et al. forthcoming). Third, in general the trophic state of the population of natural lakes had changed very little since before 1850. From that we would argue that about half of the natural lakes should be expected to be oligotrophic (TP < 10 μg per L; Figure 2c), and about half should be mesotrophic (TP < 30 μg but > 10 μg per L). Fourth, most of the currently eutrophic natural lakes have become so within the last 150 years, which we take as evidence of cultural eutrophication.

Acidic deposition. Portions of the Adirondacks and the Uplands in New England are among the areas of the United States most affected by acidic deposition (Baker LA et al. 1991). Many lakes in these areas have watersheds with thin till soils that provide very little acid buffering capacity (Driscoll et al. 1989, Stoddard et al. 1998). Although pH is a common measure of acidity in lake water, acid-neutralizing capacity (ANC) is a more robust measure of the susceptibility of lakes to acidic deposition. Lakes with summer ANC less than or equal to 0 μeq per L are considered chronically acidic (typically pH less than 5.5) and often have elevated inorganic monomeric aluminum concentrations (Al_{im}) that are toxic to fish. Lakes with ANC between 0 and 50 µeq per L are classified as acid sensitive, because they often become briefly acidic during high-flow periods such as spring snowmelt.

An estimated 2% of northeastern lakes were acidic in the 1991–1994 period; an additional 12% (± 5%) were acid sensitive (Figure 3a). In the Adirondacks, 10% of the lakes were acidic and another 25% were acid sensitive (Figure 3b). All of the acidic lakes in the Adirondacks had anionic composition dominated by sulfate from deposition (Baker LA et al. 1991). More than half of these acidic lakes (52%) had Al_{im} greater than 100 µg per L, levels considered toxic to fish (Baker JP 1982, Baker JP et al. 1993). In the remainder of the Northeast, less than 1% of lakes were acidic, and about 9% were acid sensitive (Figure 3b). In all of those lakes, Al_{im} was less than 100 µg per L. Most (84%) of the acidic conditions in lakes outside the Adirondacks were probably caused by organic acids (dissolved organic carbon > 15 mg per L).

Diatom fossil assemblages in lake sediments from before the 1850s indicate that the population of Adirondack lakes was less acidic in the past than it is now (Figure 3c). For example, in the 1990s an estimated 40% of Adirondack lakes had pH less than or equal to 6.0, while only 17% of these lakes had been in that range in the past. Below a pH of 6, sensitive fish species such as trout and minnows begin to disappear from lakes in the Adirondacks (Baker JP et al. 1993). Analyses of diatom-inferred change in pH in individual lakes showed that most currently acidic and acid-sensitive lakes have become more acidic since preindustrial times (Cumming et al. 1992, Dixit et al. 1999).

Fish tissue contaminants. The possibility that contaminants may have entered the food chains in lakes leads to concerns about whether one can safely eat fish caught in the lakes and whether contaminant levels pose a risk to the lake ecosystem. Assessments of fish tissue contaminants can become enmeshed in additional questions about the species and size of fish (Somers and Jackson 1993), the frequency of consumption, and the consumer of the fish (adults, children, pregnant women, or wildlife). While these questions are best addressed with traditional toxicological methods, the question of what contaminants are of regional concern can be addressed with probability-based synoptic surveys. In particular, one can address the issues of frequency and spatial extent of high contaminant levels (i.e., how many lakes in the region have fish with elevated levels? Are high levels widespread, or regionally or locally clumped?), and which, if any, contaminants frequently occur at high levels.

We analyzed metals in tissue samples composited from whole fish collected in 167 lakes. On a regional basis, mercury appeared to be the only metal contaminant in fish tissue of concern in the Northeast (Yeardley et al. 1998). No contamination at the action level or critical level was detected for cadmium, nickel, or selenium. In 6% or fewer of northeastern lakes, concentrations of arsenic, chromium, copper, lead,

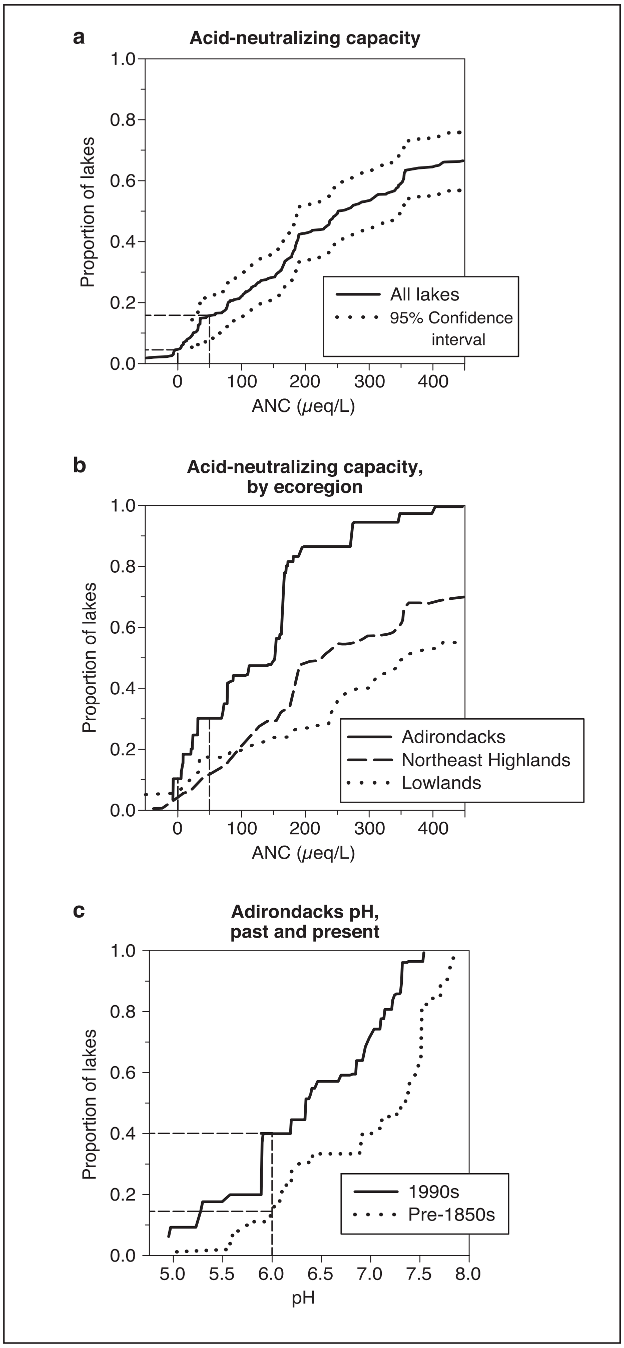

Figure 3. Acid-neutralizing capacity (ANC) and pH status of the population of northeastern lakes. (a) ANC for all lakes. The solid line is the cumulative distribution function (CDF) for the population of lakes; dotted lines mark the 95% confidence interval. Vertical reference lines mark acidic and acid-sensitive lake condition. Horizontal reference lines show that 2% of northeastern lakes were acidic (ANC < 0 µeq per L) and an additional 12% were acid sensitive (ANC = 0–50 µeq per L). (b) CDFs of ecoregional differences in ANC. (c) CDFs of present (1990s) and past (pre-1850s, diatom-inferred) pH in the population of Adirondacks lakes, indicating a general acidification of lakes.

Cumulative Distribution Function Plots

Data distributions typically are represented by histograms. This information is often better depicted by cumulative distribution function (CDF) plots (also called cumulative frequency distribution plots). Although CDFs are not as intuitively interpreted, they have three advantages over histograms: (1) The value of any percentile of interest (e.g., a median or quartiles) is easily located in the distribution. (2) The display does not require choosing ranges of values to display as bars. Broad or poorly chosen ranges may hide interesting features in the data, and narrow ranges result in many small bars that are difficult to interpret. (3) Different distributions can be more directly compared.

Interpretation of CDF plots. In a CDF, the range of values a variable can take are plotted on the horizontal axis. The vertical axis usually represents the proportion of all the data, ranging from 0 to 1 or, if percentages are being used, 0 to 100; it may also represent a count of all instances in the data, ranging from 0 to *n*, where *n* equals the number of data values. The cumulative frequency distribution is then plotted, usually as a line, by the accumulating proportions or numbers represented at each increasing *x* value. In this form, a CDF always rises to the right. For any *x* value, the height of the line represents the proportion (or number) of data points having values equal to or less than *x*. When describing the proportion of values greater than *x*, one needs to take the (initially counterintuitive) step of subtracting the height of the plot line from 1 (or 100 or *n*). Areas along the *x*-axis with a sharply rising line have a relatively large proportion of data in that range. CDF lines that shift to the right indicate that greater proportions of the data have higher *x* values.

Examples. Identifying medians: In Figure 2b, the median total phosphorous (TP) concentration in natural drainage lakes was 10 µg per L, while it was 18 for Uplands impoundments and 30 for Lowlands impoundments (i.e., half of the natural lakes were oligotrophic whereas half of the Lowlands impoundments were eutrophic or hypereutrophic). Comparing distributions: Figure 8b shows that 31% of the Northeast Highlands lakes had no nonnative fish, while only 5% of the Adirondacks lakes and 11% of the Lowlands lakes had no nonnatives. There was not a great difference between the Adirondacks and Lowlands ecoregions in frequency of low values (i.e., values below a threshold of about 25% nonnative species). At higher proportions of nonnatives, the Lowlands and Northeast Highlands lakes had essentially the same frequency: In nearly 70% of the lakes in both ecoregions, 20%–50% of the fish were nonnative species.

and zinc exceeded only one of the three action levels or critical levels cited by Yeardley and colleagues (1998). In contrast, elevated levels of mercury (Hg) in fish tissue were widespread. Mercury concentrations exceeded a level of concern for human consumption (0.2 µg per gram) in an estimated 26% (± 8%) of lakes in the Northeast (Figure 4), and exceeded levels of concern to other piscivorous mammals (0.1 µg per g) in 51% (± 11%) of lakes. There were no ecoregional or water-body type differences in the distribution of Hg concentrations. The widespread distribution of mercury contaminants in the lakes of the Northeast indicates a common regional airborne source, rather than local discharges or soil conditions (Rudd 1995).

Habitat alteration. Riparian and littoral habitat structure serves as both an indicator of ecological condition and a context for interpreting biological information. These habitat components are important to lake biological assemblages, providing refuge from predation, living and egg-laying substrates, and food. Shoreline structure also affects nutrient cycling, littoral production, and sedimentation rates. Human activities along lakeshores often adversely affect these ecosystem functions by reducing habitat complexity. In midwestern lakes, there were negative associations between lakeshore cabin development and the density of riparian trees and littoral coarse woody debris (Christensen et al. 1996), and cumulative negative effects on fish assemblages as riparian alteration increased (Jennings et al. 1999). In the

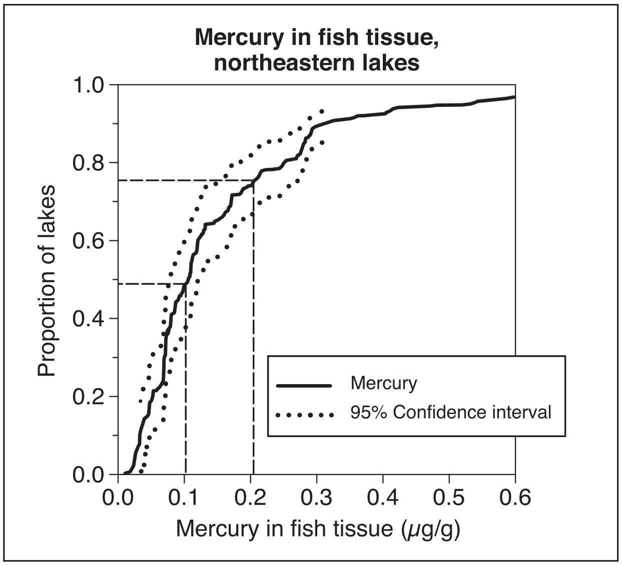

Figure 4. Cumulative distribution function of concentrations of mercury (solid line) in fish tissue in the population of northeastern lakes. The vertical reference lines mark values of mercury concentrations judged to pose a risk to the health of human and other piscivorous mammals (Yeardley et al. 1998). The horizontal reference lines indicate that mercury concentrations in fish tissue exceed those values in 26% to 51% of lakes in the Northeast.

Northeast, shoreline disturbance has been associated with the decline of species richness of native minnows and with an increase in nonnative predator fish species (Whittier et al. 1997).

The shoreline survey recorded no direct evidence of human activities in 27% (± 9%) of the lakes in the Northeast (Figure 5a). At lakes with no anthropogenic riparian disturbance, the median canopy-layer tree cover was 67%, with a median combined canopy-layer, midlayer, and ground-layer woody cover of 170% (of a possible 300%), indicating substantial structural complexity and the potential for sustaining that complexity over time. At the other end of the spectrum, 23% (± 10%) of lakes had at least one type of human structure or activity at half or more of the shoreline stations. This human activity was associated with reduced canopy-layer cover (median = 35%) and three-layer woody cover (median = 82%). Half of these lakes had buildings at more than a third of the shoreline stations. Habitat complexity, in the form of woody snags, overhanging trees, and aquatic plants, was markedly reduced at lakes with higher levels of human activity along the shoreline. There were ecoregional and water-body type differences in level of riparian disturbance, with larger proportions of Uplands lakes and natural lakes having low levels of riparian disturbance (Figure 5b, 5c).

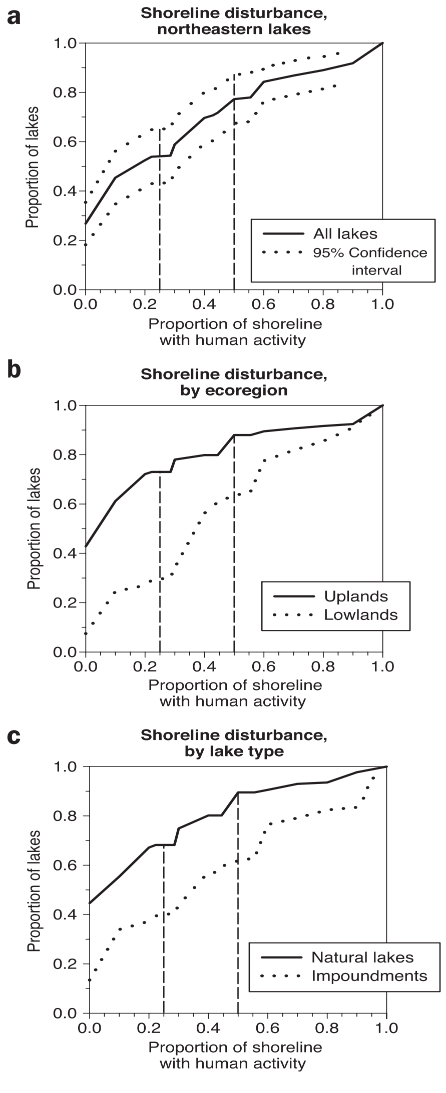

Figure 5. Cumulative distribution functions (CDFs) of shoreline disturbance as measured by the proportion of shoreline stations with visible indications of human activity: (a) for the population of northeastern lakes (CDF and 95% confidence interval), (b) by ecoregion, and (c) by lake type. Vertical reference lines mark possible criteria for highly and moderately disturbed riparian habitat.

Biological invasions. In the last few decades, growing concerns about species extinction and loss of biodiversity have led to greater study of the role of nonnative species introductions in those processes (Vitousek et al. 1996). There is evidence that many introductions fail, and some species introductions seem to have little or no detectable ecological effect (Moyle and Light 1996). However, some introductions have resulted in local extirpation and even the extinction of native species, as well as regional and global homogenization of species assemblages, resulting in reduced broad-scale diversity (Vitousek et al. 1996, Lodge et al. 1998, NRC 2000, Rahel 2000). Some invasions by nonnative species (e.g., goats and rats on islands, zebra mussels in the Great Lakes) have caused major changes in ecosystem structure and function.

Zebra mussels. Perhaps the most notorious invasion by a nonnative species in recent years was that of the zebra mussel *(Dreissena polymorpha)*, which was probably introduced by ballast water into the Great Lakes in the mid-1980s. By the early 1990s, the mollusk seemed poised for a major invasion of inland aquatic ecosystems in the Northeast, having spread throughout the Great Lakes and into many large water bodies in New York. However, zebra mussels require moderately alkaline waters (i.e., water with calcium levels greater than 12 to 15 mg per L), while much of the Northeast has low-alkalinity lakes (the reason acid deposition is a concern there). Integrating acid sensitivity maps of low-alkalinity areas with the EMAP water chemistry data, Whittier and colleagues (1995) estimated that 74% (± 8%) of lakes in the Northeast were in mapped low-alkalinity areas, with only 5% of lakes in those areas having calcium levels greater than 12 mg per L (i.e., calcium levels that put them at risk of zebra mussel invasion; Figure 6). Regionwide, an estimated 25% (± 8%) of lakes have calcium levels greater than 12 mg per L. A review of 466 zooplankton samples taken at 342 of the lakes in our sample through 1994 found zebra mussel veligers in only one lake (Richard Stemberger [Dartmouth College, Hanover, NH], personal communication). During the limited sampling in 1995 and 1996, no veligers were found in 124 zooplankton samples from 84 lakes, 13 of which had calcium levels greater than 12 mg per L.

Current US Geological Service databases (USGS 2002) also indicate that, with the exceptions of the New York Finger Lakes and Lake Champlain, zebra mussels generally have

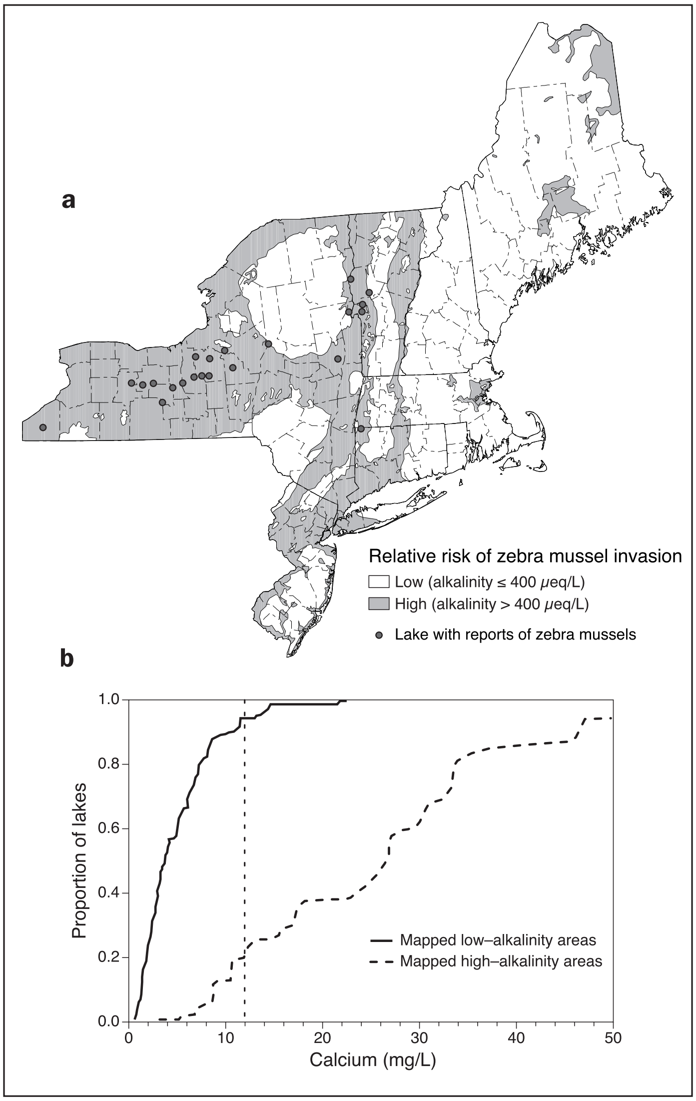

Figure 6. (a) Areas of lower (white) and higher (shaded) risk for zebra mussel invasion in the Northeast, based on mapped surface water alkalinity. In general, only a few, mostly large, inland lakes, had been invaded by zebra mussels by 2000 (New York Finger Lakes, Lake Champlain, and six others). All of these lakes are in the higher risk areas. (b) Shown in this panel are cumulative distribution functions of calcium concentrations in lakes in the low-risk (solid line) and higher-risk (dashed line) areas. Vertical reference line indicates the hypothesized minimum concentration (12 mg per L Ca) required for zebra mussel invasion.

not invaded inland lakes in the Northeast. There are zebra mussel reports for 17 New York lakes, including a dozen of the Finger Lakes; three lakes in western Vermont; and one lake in the northwestern corner of Connecticut (Figure 6). All of these are within areas predicted to have sufficient calcium levels to support zebra mussels (Whittier et al. 1995).

Nonnative fish. Although the Northeast is lake rich, the native lake fish assemblages, especially in New England, are species poor in comparison with those of the lake-rich Great Lakes region (Schmidt 1986, Underhill 1986). Before Europeans settled in the Northeast, Lowlands lake fish assemblages there generally included one or two sunfish (Centrarchidae), one top predator (chain pickerel, *Esox niger*), a few minnows (Cyprinidae), one or two bullheads (*Ameiurus* spp.), yellow perch (*Perca flavescens*), white sucker (*Catostomus commersoni*), and few other species, while small Uplands lakes had brook trout (*Salvelinus fontinalis*) and numerous minnows. These represent unique lake fish assemblages not generally found in other lake districts (Tonn and Magnuson 1982).

Over the last century and a half, widespread introductions, particularly of game fish, as well as transfers from the Lowlands to the Uplands, have greatly altered the Northeast's lake fish assemblages (Whittier et al. 1997, 1999, Whittier and Kincaid 1999). For example, four centrarchids—largemouth bass (*Micropterus salmoides*), bluegill (*Lepomis macrochirus*), smallmouth bass (*M. dolomieu*), and black crappie (*Pomoxis nigromaculatus*)—are not native to most of the Northeast, yet they were, respectively, the 6th, 8th, 9th, and 12th most widespread fish in the EMAP sample, being collected in 55%, 32%, 31%, and 22% of the sampled lakes (Whittier et al. 1999). Of the 88 fish species collected, 9 were judged nonnative in all lakes, and 30 others have been introduced to lakes outside their native ranges within the region. Sixteen species were judged nonnative more often than not (Whittier and Kincaid 1999).

Only an estimated 21% (± 10%) of northeastern lakes retained an all-native fish assemblage. A majority of the all-native fish lakes were in Maine or in the Great Lakes drainages of western New York, where many of the Centrarchidae are native (Figure 7). An estimated 15% (± 8%) of lakes had more introduced species than native species (Figure 8a), while introduced individuals outnumbered natives in 31% of lakes (Whittier and Kincaid 1999). The extent and magnitude of nonnative fish species invasions varied by ecoregion and lake type (Figure 8b, 8c). Although the Adirondacks and the Northeast Highlands have similar lake types, trophic states, riparian disturbance levels, and general land uses, these two areas were least similar relative to nonnative species. Few Adirondack lakes (5%) had all-native fish assemblages, and 61% were dominated by nonnative species, while 32% of Northeast Highlands lakes had only natives and 14% were dominated by nonnatives. The high proportion of nonnative fish in the Adirondacks is the result of a long history of active sport-fisheries management. Although this kind of management continues, it is just part of a complex mix of factors—biological (e.g., the nature of current fish assemblages), physical (e.g., degree of proximity to population centers and paved roads), and cultural (e.g., patterns of landownership, local fishing preferences)—that have contributed to the current differences in nonnative fish invasions (Whittier et al. 1997).

Certain types of introduced species, particularly predators, are more likely to eliminate native species (Moyle and Light 1996). Strong circumstantial evidence suggests that species that

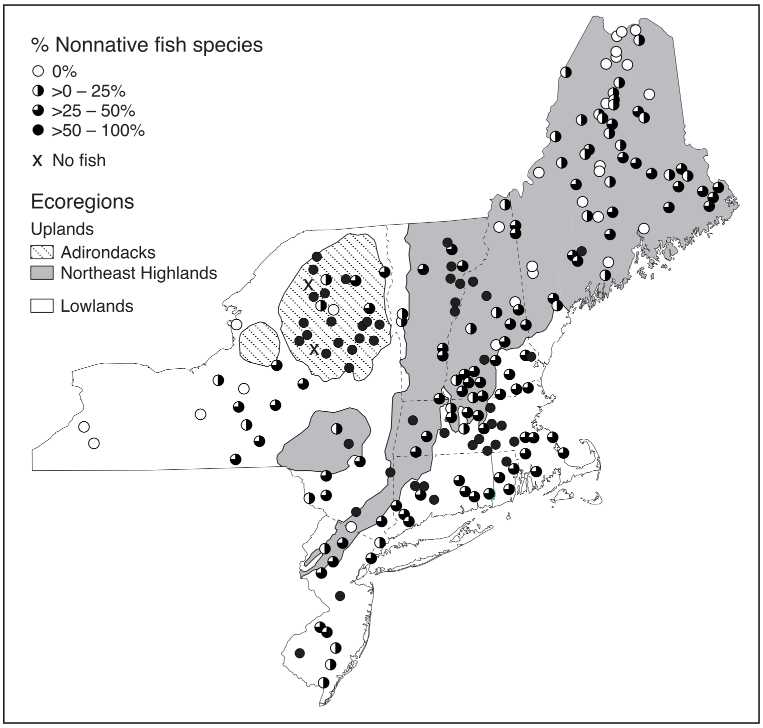

Figure 7. Geographic distribution of nonnative fish species in Environmental Monitoring and Assessment Program lakes sampled in the summers of 1991 through 1996. Open circles indicate lakes where all collected species were judged to be within their native ranges.

are small or soft finned are at greater risk of local extirpation by introduced predators (Tonn and Magnuson 1982, Chapleau et al. 1997, Whittier et al. 1997, Whittier and Kincaid 1999). Most of the susceptible species in northeastern lakes are currently found in cold-water and cool-water lakes; the primary nonnative predators are mostly warm-water species. Of the predators, the smallmouth bass has the greatest potential to spread further into these cooler systems, partially because of its temperature tolerances and its appeal to sportfishers. Five locally common minnows, burbot (*Lota lota*), and four species of sticklebacks (Gasterostidae) were not collected in any lakes with smallmouth bass. Brook trout also appear to be intolerant of smallmouth bass in lakes; of the five sampled lakes where they co-occurred, the trout were maintained by stocking in three, and only one individual was collected in each of the other two.

Management implications of this approach. To move toward rational, broad-scale management of ecological resources, environmental resource managers and policymakers need at least two tools that are generally unavailable. The first is data known to be representative of the larger population of ecosystems. The second, which relies on the first, is the ability to rank the relative importance of various stresses and risks. The probability-based design, multiple indicators, and broad-scale sampling used by EMAP provide some of the components and information needed to develop those tools.

Representative data. The ability of environmental resource managers to make informed decisions is often impaired because they do not have data that are representative of larger populations of systems (Paulsen et al. 1998, Peterson et al. 1999). Those managers nevertheless often presume that their data are regionally representative. One source of such data is hand-picked, fixed sampling stations, essentially a judgment sample assumed to be representative. For example, since 1950 the Oregon Department of Fish and

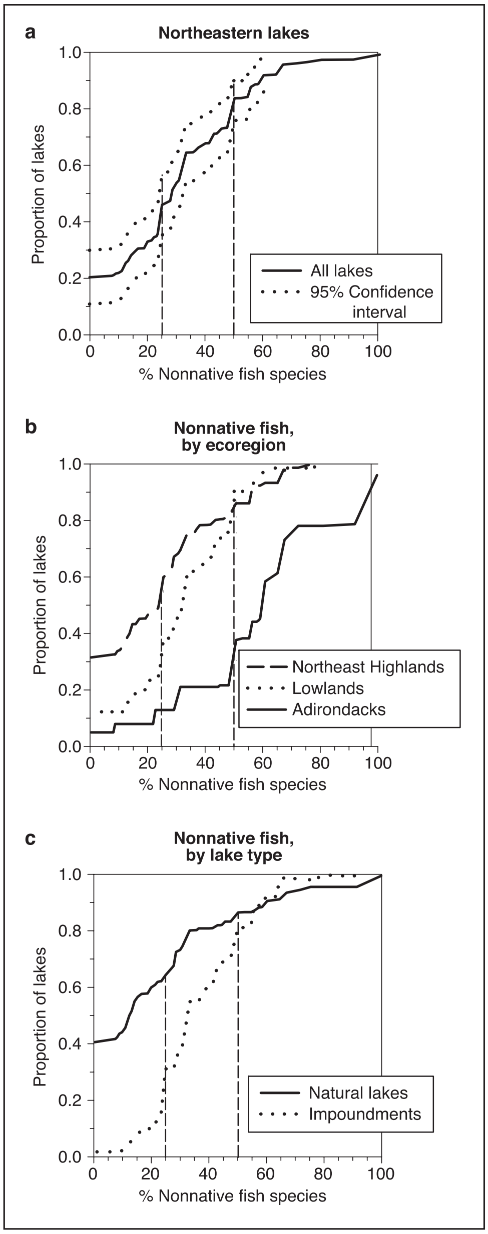

Figure 8. Cumulative distribution functions of the proportions of fish species judged as nonnative: (a) for northeastern lakes (cumulative distribution function and 95% confidence interval), (b) by ecoregion, and (c) by lake type. Vertical reference lines mark possible criteria for highly and moderately disturbed fish assemblages.

Wildlife has made adult spawner counts of coho salmon *(Oncorhynchus kisutch)* at 50 nonrandomly selected, fixed-station sites and extrapolated the results to 4764 coastal stream miles. In 1990, Jacobs and Cooney (1995) began comparing these estimates to data from randomly selected sites. The probability-based data consistently indicated that the fixed-station extrapolations overestimated coho salmon populations by nearly two-thirds (Paulsen et al. 1998).

Large, nonrandomly selected data sets are a second source of potentially misleading information if it is assumed that a big sample makes up for a lack of statistical design. Peterson and colleagues (1998) evaluated this assumption for northeastern lakes by comparing the proportion of lakes in various trophic states estimated from the EMAP probability sample with estimates derived from two much larger data sets. One of these estimates was a compilation from 4210 lakes assessed by the eight northeastern states in their 1994 reports to Congress (required under section 305[b] of the Clean Water Act); the other was from data compiled by Rohm and colleagues (1995) on 2758 lakes. Regionwide, the extrapolated estimates from Rohm and colleagues were within the EMAP confidence intervals, but the reliability of the estimates declined at the subregional scale. Despite the larger number of lakes evaluated, the 305(b) reports overestimated the number of eutrophic lakes by nearly 20%.

Relative ranking of lake stressors. Most ecosystems experience multiple anthropogenic stresses, and the relative importance of stresses varies within and among regions. One way stresses may be ranked is by severity; that is, on the basis of which stresses most intensely disrupt ecosystems. This complex task involves multiple judgments to rank effects that may not be directly comparable, such as those required by the following questions: Is the potential loss of trout and minnows due to acidification more severe than the periodic anoxia and obnoxious odors that result from eutrophication? Is habitat simplification more severe than the loss of minnows attributable to predator introductions? Ultimately, such rankings will have to integrate scientific knowledge with societal values.

Another way to rank stresses is by extent, that is, by determining which stresses have adversely affected the greatest number of ecosystems. A synoptic, multiple-indicator survey can provide the data to support such a ranking. We have devised a preliminary regional-scale ranking of the extent of five anthropogenic stresses to northeastern lakes. The first step was to choose cutoff values above (or below) which we considered indicator values to be highly stressful to lakes in the Northeast. All such cutoffs are necessarily somewhat arbitrary. No matter how well studied a stressor may be, judgment is always used to some degree in setting criteria, and complete consensus among experts is rarely achieved. Thus, we present two criteria for each stressor, to indicate a range of possible cutoff values and how those choices affect one's estimate of the number of lakes that are highly or moderately stressed.

Eutrophication and acidification are well studied and have generally agreed-upon classification schemes defining impaired lake condition (NALMS 1990, Baker LA et al. 1991). For trophic state, the diatom-inferred TP data (Figure 2) indicate that very few northeastern lakes are naturally eutrophic. Thus, we judged the 13% of lakes and impoundments that were eutrophic to be highly stressed and the 9% of lakes that were hypereutrophic to be severely stressed (Figure 9). We treat the latter group as a subset of the population of lakes highly stressed by nutrient enrichment. Because the diatom-inferred TP data indicated that, regionally, about half of the lakes were naturally mesotrophic in the past, we view the currently mesotrophic lakes as generally in acceptable trophic state; thus, we do not evaluate a moderately stressed class for eutrophication.

For acidification, lakes with ANC less than 0 μeq per L are generally considered highly stressed, and lakes with ANC between 0 and 50 μeq per L are considered moderately stressed. However, in some cases acidic conditions are natural. Although low-pH bog lakes (lakes with levels of dissolved organic carbon greater than 10 mg per L) are undoubtedly stressful environments for many fish species, we judged that they were naturally acidic (Kaufmann et al. 1992). We judged

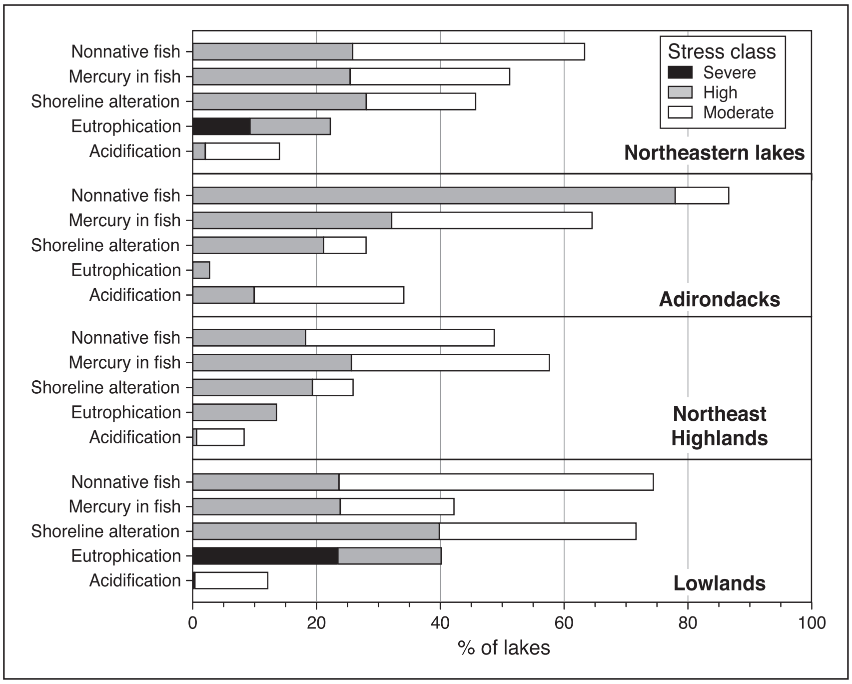

Figure 9. Comparison of the percentage of lakes subject to moderate to high levels of stress from five sources of stress regionwide in the Northeast and in the Adirondacks, Northeast Highlands, and Lowlands ecoregions. The bars show the percentage of lakes classed as experiencing each stress level for each attribute.

that 2% of northeastern lakes were highly stressed by acidification, with nearly all of these in the Adirondacks (Figure 9). Another 12% were moderately stressed. Although some small lakes whose watersheds have thin till soils have always been acidic, the diatom-inferred pH data indicate that their acidification stress has generally increased since 1850. These data suggest that if anthropogenic acidification were to cease completely and lakes were to recover to their preindustrial state, perhaps one-third to one-half of the currently acidic Adirondack lakes would continue to have pH levels stressful to sensitive fish such as trout and minnows.

Because the appropriate cutoff level for mercury in fish tissue is less clear, assessments of the prevalence of highly stressed lakes can vary widely. The mercury concentration level appropriate to trigger advisories on fish consumption has been under discussion for years. Currently, those levels range from 0.1 to 0.5 µg per g, depending on which state or agency is issuing the advisory. We use levels from Yeardley and colleagues (1998): The 0.2 µg per g level indicates high stress and the 0.1 µg per g level moderate stress. Using those values, 26% of northeastern lakes experience high stress from mercury contamination, while 25% experience moderate stress.

Stresses caused by nonnative fish species and shoreline disturbance are less well studied, and there is no consensus on what constitutes high levels of stress. Thus, our cutoff levels for these stresses are less firmly supported than those for acidification and mercury contamination, but these levels, we believe, clearly indicate adverse conditions. For fish, we judged that assemblages in which half or more of the species were nonnative were stressed by introductions, and those with 25%–49% nonnative species were moderately stressed. We used the proportion of shoreline stations with observable human activity (e.g., buildings, lawns, docks) as a measure of disturbed riparian areas. We judged that lakes with visible human activity in at least half of the shoreline stations had highly disturbed shoreline habitat, while lakes with human activity at 25%–49% of the stations had moderately disturbed shoreline habitat (Figures 5, 8, and 9).

Of these five indicators—eutrophication, acidification, mercury in fish tissue, presence of nonnative fish species, and shoreline disturbances—high stress caused by acidification clearly affected the fewest northeastern lakes (Figure 9). The proportions of northeastern lakes highly stressed by the other four factors did not differ substantially from each other. The proportions of lakes highly stressed by all of the indicators, except for mercury in fish, were lower for lakes in the Northeast Highlands than for those in the Lowlands. Although acidification has been a major concern in the Adirondacks and the proportions of acidified lakes are higher there than in other areas, far more lakes in that ecoregion were stressed by nonnative fish, mercury contamination, and shoreline alteration. Regionwide, 34% (± 10%) of lakes were highly stressed by more than one of the five factors. In the Northeast Highlands, 21% of the lakes were subject to multiple high stresses. In the Adirondacks and Lowlands, 45% and 44% of the lakes, respectively, were subject to multiple high stresses. In contrast, regionwide, 37% of the lakes were judged not to be highly stressed by any of the five indicators.

The EMAP survey results have implications for protection and restoration of northeastern lakes, at a variety of scales. Some stressors, such as atmospheric acidification and atmospheric deposition of mercury, are known to operate at large scales. The EMAP survey and others have helped to demonstrate the large scale of mercury contamination. Protection of lake resources from these stressors requires the kind of regional or national perspective on the extent and degree of the problem that such surveys can provide.

Other stressors, such as eutrophication, are often viewed as local problems requiring solutions at that scale. However, a large-scale perspective has much to offer environmental resource managers in that it can define the scope of the problem, which helps elucidate possible solutions. For example, the water quality standards for phosphorus were based, in part, on the National Eutrophication Survey in the 1970s. Our data can facilitate trophic state management by providing a regional context, thus narrowing the scope of the problem, and by demonstrating associations among trophic state, lake morphometry, and land use. The diatom-inferred TP data indicated that for natural lakes in the Northeast a water quality standard with a goal of oligotrophic waters for all lakes would be unrealistic; about half the lakes are naturally mesotrophic. Some past lake restoration projects have failed, in part because regional lake quality data were not available and the restoration goals were unrealistic for that region (Peterson et al. 1995).

Regionally, lake eutrophication is overwhelmingly a problem of small, shallow impoundments, primarily in the Lowlands. Human land uses in these watersheds are more intense than for natural lakes or Uplands impoundments. A phosphorus-loading model indicated that urban areas in impoundment watersheds exported more than twice as much phosphorus as urban areas in natural lake watersheds and that forested lands around Lowlands impoundments exported twice as much phosphorus as forested watersheds of natural lakes and Uplands impoundments (Whittier et al. forthcoming). Thus, trophic state management in the Northeast should consider the effects of homes in forested areas, as well as urban and suburban wastewater and storm water, on the region's waterways.

Finally, we believe that comparative information on the extent of stressor effects has important policy and management implications. Restoration and protection of lake quality over broad geographic regions should benefit from knowing which stressors are impacting the greatest number of lakes. For example, in the Northeast, eutrophication is not significantly more extensive—and in some areas is less extensive—than mercury in fish tissue, shoreline alteration, and nonnative fish introductions. The latter two stressors are examples of topics that have not traditionally been the subjects of concern for environmental protection agencies but are now emerging as significant threats to the overall health of lake ecosystems.

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