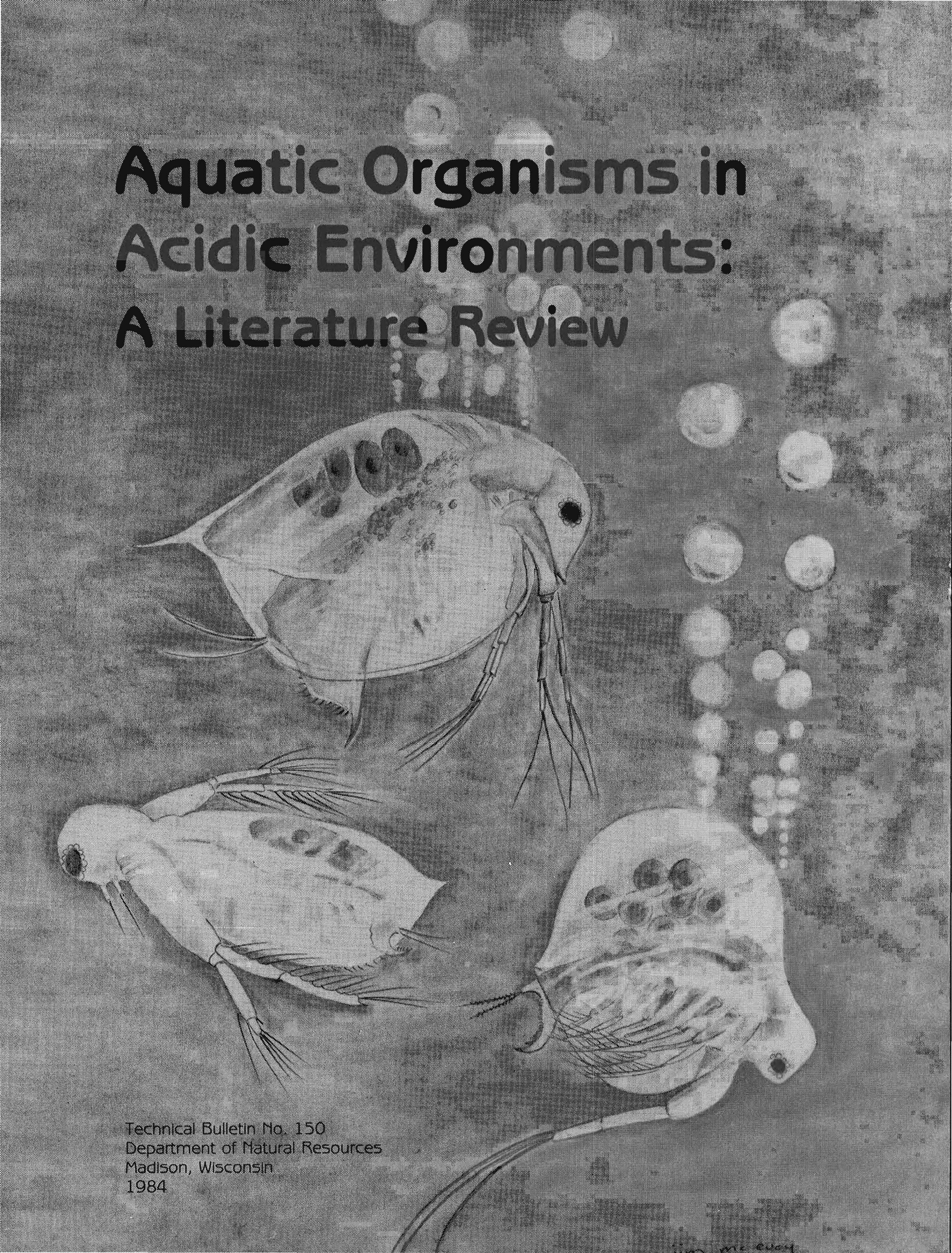
Aquatic Organisms in Acidic Environments: A Literature Review



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ABSTRACT

Acid deposition has aroused concern about aquatic organisms in soft water lakes and streams, as the loss of indigenous species is commonly observed when pH decreases. This literature review was initiated to intensively examine the distribution of invertebrates with respect to pH, in order to define the tolerance limits of various species in acidified waters and predict how acidification would alter distributions.

We hypothesized that two patterns would emerge from the data base constructed: 1) taxonomic groups with external calcium requirements, such as molluscs, would be poorly represented in acidic waters; and 2) taxonomic groups with a great diversity of species occupying many microhabitats would display broad response to pH.

Over 2,000 minimum pH values for 9 major taxonomic groups of aquatic organisms were compiled from the literature (on both field and laboratory studies). The range of minimum pH values within each group was quite broad, especially for the algae, aquatic insects, rotifers, and crustaceans. The organisms with the fewest observations in low pH environments were the molluscs and leeches; they rarely occurred below pH 5.7. In contrast, the median of the minimum pH values for fish was 5.6.

Several general patterns emerged from this review: 1) the greatest reduction in number of species for all groups occurred between the pH interval 6.1 and 5.2; 2) with the exception of cyprinids and darters, fish are not remarkably sensitive to acidic waters, which means other taxonomic groups would be more desirable as early indicators of stress caused by acidification; and 3) because of the large intraspecies variation in response to hydrogen ion concentration, it is difficult to predict biological response to acidification in one region based on the response observed in another region.

Caution must be exercised in interpreting minimum pH values derived from this work. Problems in interpretation include uncertainty about the accuracy of the pH measurements, correlation of other chemical parameters with pH, confounding biological factors, and biased information sources (such as surveys of hard water sites).

KEY WORDS: Acidic Environments, Aquatic Invertebrates, Aquatic Organisms, Literature Review, pH, pH Tolerance.

Aquatic Organisms in Acidic Environments: A Literature Review

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PREFACE

This work was initiated in 1981 in response to a request from the Environmental Research Laboratory-Duluth to synthesize the current state of knowledge on how aquatic organisms respond to acid stress. This report is an attempt to respond to that request, with emphasis on aquatic organisms found in Wisconsin. Primarily, the data base was compiled in 1981, with supplementary efforts in 1982 and 1984.

Because of the accelerated level of research in this field in recent years, many new studies have greatly expanded the information base. Given the unavoidable lag between completion and publication of a manuscript, it was inevitable that this literature synthesis would be dated by the time it became available. Consequently, conclusions in this report should be tempered by the wealth of information now available. Some of the many recent manuscripts that we were unable to include in this report are:

HENDREY, G.R. (ED.)
1984. Early biotic responses to advancing lake acidification. Acid Precipitation Series Vol. 6. Butterworth Publishers, Boston. 173 pp.

HOWELLS, G.D.
1984. Fishery decline: mechanisms and predictions. Phil. Trans. R. Soc. Lond. B 305:529-47.

MAGNUSON, J.J., J.P. BAKER, AND F.J. RAHEL
1984. A critical assessment of effects of acidification on fisheries in North America. Phil. Trans. R. Soc. Lond. B 305:501-16.

MAGNUSON, J.J., F.J. RAHEL, R. SINGER, J.H. PEVERLY, J.P. BAKER, K. FISCHER, C. DRISCOLL, AND G.C. SCHAFARN
1984. Effects on aquatic biology. Chapter E-5 *in* R.A. Linthurst, ed. The acidic deposition phenomenon and its effects. Critical Assessment Review Papers Vol. II, Effects Sciences. EPA-600/8-83-016BF. 196 pp.

RAHEL, F.J.
1984. Factors structuring fish assemblages along a bog lake successional gradient. Ecology 65:1276-89.

RAHEL, F.J. AND J.J. MAGNUSON
1983. Low pH and the absence of fish species in naturally acidic Wisconsin lakes: inferences for cultural acidification. Can. J. Fish. Aquat. Sci. 40:3-9.

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INTRODUCTION

Impacts of acid deposition on aquatic organisms in Scandinavia, Ontario, and New England (Wright et al. 1976; NRCC* 1981; Haines 1981) have aroused concern for the fate of biota in soft water lakes and streams in other susceptible regions. In the already affected regions, the loss of indigenous species is commonly observed as the pH of lakes and streams decreases.

The importance of pH as a controlling variable in chemical reactions at the cellular and subcellular level has been well documented (Giese 1968). However, as organisms become more complex, they are often able to adequately regulate their body chemistry despite unfavorable external conditions.

Despite the large number of early studies claiming to show the important role pH exerts on aquatic communities (Myers 1931, 1942; Bryant 1936; Lowndes 1952; Harrison 1958), these investigations often lacked adequate controls and, therefore, failed to conclusively link pH with aquatic organism response. Hutchinson (1941) and Hynes (1970) refer to claims linking pH and organism distribution as largely unsubstantiated, while Macan (1974) concludes his brief discussion on pH as a factor in the aquatic environment with the following statement: "Some protozoa are probably the only animals affected directly by the concentration of hydrogen and hydroxyl ions."

The present study was initiated to more intensively examine the distribution of invertebrates with respect to hydrogen ion concentration. Most of the reviews of the aquatic impacts of acidic deposition have focused on fish. Reviews by Fromm (1980), Haines (1981), and Howells et al. (1983) should be consulted for specifics on fisheries impacts related to acid deposition.

It is an accepted ecological principle that each species has an optimum environmental condition which favors its success (Cummins and Lauff 1969). Beyond that optimum condition, the species experiences stress that may result in greater expenditure of energy or some other competitive disadvantage with other species. We are attempting to define the range in hydrogen ion concentration in which this stress causes the organism to be eliminated. Water quality plays an important role in determining the success of aquatic species, and it seems reasonable to expect that hydrogen ion concentration is a major influence on the success of a species, because of its important role in a large array of chemical reactions.

Research on acid mine drainage conducted over the last two decades has supported the hypothesis that higher organisms are directly affected by hydrogen ion concentration (WRSIC* 1975). The large body of research on aquatic effects, collected in support of the National Acidic Precipitation Assessment Program, also provides support for this hypothesis. In particular, the experimental acidification of Lake 223 (Schindler and Turner 1982) provided direct evidence that elevated hydrogen ion concentration, in the absence of high metal concentration, can cause loss of fish species (fathead minnows) and zooplankton (*Mysis relicta, Epischura lacustris,* and *Diaptomus sicilus*).

Results from research on acid mine drainage and acidic deposition effects also suggest that certain taxonomic groups are more tolerant of acidic conditions. We approached the review of organism distribution in acidic environments expecting to observe two patterns from the data base: (1) certain taxonomic groups, particularly those with external calcium requirements such as molluscs, will tend to be poorly represented in acidic waters; and (2) taxonomic groups that are represented by a high diversity of species occupying many microhabitats, such as aquatic insects, will display a broad response to pH.

This review is only a preliminary step in understanding why various species respond differently to a water quality property such as hydrogen ion concentration. We are fully aware that species survival depends on an integrated response to a multitude of environmental factors. Our objective is not to identify all the interacting factors contributing to the distribution of aquatic organisms, but rather to use available information to predict what response we might anticipate should acidification occur. We hope that the validity of the observations from this exercise will be rigorously tested in field and laboratory acidification experiments.

*National Research Council of Canada.

*Water Resources Scientific Information Center.

METHODS

The information sources used to develop the data base on minimum pH values were identified, in part, by computer searches of biological abstracts. The following key words were used: animal distribution, aquatic invertebrata or vertebrata in conjunction with pH, acid, or water pollution. Followup searches were made under selected taxonomic groups. Bibliographies of research in acid deposition and acid mine drainage provided additional sources on the topic.

A third major literature area investigated was natural history surveys of regions known to contain acidic waters. With few exceptions, the sources used to compile the data base were published. Results from unpublished surveys were sought in several cases where the authors had personal knowledge of such data. No doubt, a large body of data (particularly unpublished data) exists which was either not readily available for this review or not known to the authors. In particular, the European data related to acid rain research may not be well represented here.

The sources included field (lakes and streams) and laboratory studies. Most of the field studies were collected across a gradient of pH values, although some were restricted to a small number of habitats with similar pH values. Each source was evaluated for the occurrence of observations in acidic waters and the taxonomic level to which the organisms were identified. Taxa identified above the generic level were excluded. All pH values were rounded to the nearest one-tenth of a unit. The minimum pH values from individual studies were categorized on the basis of field or laboratory investigation, habitat type, number of repeated observations and sites, possible interactions with metals, geographic region, life stage of organism, and type of pH measurement. The primary sources of information from which these values were derived and the taxonomic groups involved are shown in Table 1.

Analysis of the data was performed using MINITAB (Ryan et al. 1981). Cumulative frequency plots of species were generated to illustrate the distribution of observed minimum pH values for each taxonomic group. The algae, aquatic insects, molluscs, crustaceans, and fish were subdivided into lower taxonomic units.

The relative sensitivity of aquatic groups to acidic waters was compared using the median of the minimum pH values (the 50th percentile of the recorded minimum pH values for a group). The extremes or 'tails" of a distribution are difficult to characterize, especially for non-normal distributions. Therefore, we chose to characterize that portion of the population for which we have the most information. The use of the median of the minimum pH serves as a robust estimator for comparison and also avoids the problem caused by using a parametric estimator for a variable with a log-normal distribution (Boutilier and Shelton 1980).

RESULTS AND DISCUSSION

ORGANISM DISTRIBUTION IN RELATION TO pH

Comparisons Between and Within Groups

Table 2 shows summary statistics for the minimum pH values at which aquatic organisms have been observed, including field and laboratory values. Figure 1 shows the distribution of selected taxonomic groups with respect to pH of the field habitat.

The distribution of minimum pH values differed substantially among different taxa of aquatic organisms. The extreme field responses, from the snails and leeches (median minimum of pH 6.6 and 6.7, respectively) to that of the rotifers (5.0), indicated the variety of pH responses observed. However, the median of the minimum pH values for most of the aquatic groups was between 6.1 and 5.2. Three dominant functional groups in lentic environments—the algae, crustaceans, and fish—exhibited median minimum pH values within 0.3 pH units of each other (5.6 to 5.3). Although differences among the taxonomic groups were apparent, the significance of these differences remains undetermined.

The snails and leeches were much less likely to inhabit low pH waters than the remaining groups, and were rarely found below pH 5.7. In contrast, the algae and insects showed a remarkably broad distribution with respect to pH (minimum values of 1.5 and 2.0, respectively).

The crustaceans, represented primarily by the planktonic cladocerans and copepods, had a median minimum pH of 5.3. The median of the minimum pH values for the crustacean subgroups were similar to one another (pH 5.1-5.5), except for the ostracods (pH 6.2).

Figure 2 shows the distribution of the four dominant fish families by pH. The one family showing a significantly less tolerant distribution is the Cyprinidae, which exhibited a strong reduction in species below pH 6. This is consistent with the observations of Wiener et al. (1984), who observed that minnows were not present in acidic Wisconsin lakes (pH < 6.0). In contrast, the salmonids showed no major reduction until pH 5.0. There were no strong differences in acid tolerance within families except for the Percidae. The distribution of the darters was similar to the cyprinids, whereas the perch were among the most acid-tolerant fish.

Of the major taxonomic groups examined, the algae showed a more uniform distribution across the pH range, with the median minimum pH for five of the six subgroups less than or equal to 5.5. The observations for the two algae subgroups with extreme median minimum pH values—the Euglenophyta at 3.8 and diatoms, or Bacillariophyceae, at 6.2—may reflect the atypical conditions from which some of these data were derived. (The former were observed in very acidic streams receiving industrial wastes and some of the sources for the latter were surveys that poorly represented soft water environments.) However, these median minimum pH values were consistent with rankings of perceived habitat preferences for these two groups.

The tolerance of the remaining algae to acid stress is subject to considerable debate. We separated the desmids from the other green algae at the outset of this review, believing their occurrence in acid bogs would indicate a greater tolerance to acidity. The results did not support this assumption. The desmids averaged 0.9 pH unit higher than the other green algae.

Another unexpected result was the apparent tolerance of some species of blue-green algae to highly acidic waters. Contrary to reports that blue-green algae are intolerant of acid conditions (Brock 1973; Prescott 1962), blue-green algae were observed in waters down to pH 2.0 (Hargreaves et al. 1975). The majority of the diatom records were obtained from Lowe (1974), who compiled information on nearly 300 species from 48 original sources. Some of the diatom observations were likely derived from ambient water quality surveys, rather than from studies specifically focused on soft water environments. This may act as a positive bias on the pH distribution of the diatoms.

It is widely recognized that diatoms are important indicators of pH as shown by their extensive use in reconstructing the pH history of lakes (Charles 1982; Van Dam et al. 1981; Davis and Berge 1980; Del Prete and Schofield 1981; Nygaard 1956; Renberg and Hellberg 1982). The widespread use of this technique reinforces

TABLE 1. *Summary of information sources for nine taxonomic groups in the study.*

Taxonomic Group	Observations**	Literature Sources	Predominant Area	Comments on Site Characteristics
Algae	349			
Chlorophyta	59	Warner 1971; Moss 1973; Hargreaves et al. 1975; Kwiatkowski and Roff 1976	U.S., England, Ontario	Includes polluted stream sites
Desmidiaceae	11	Warner 1971; Moss 1973; Kwiatkowski and Roff 1976	U.S., England, Ontario	Soft water lakes and bogs
Euglenophyta	4	Warner 1971; Moss 1973; Hargreaves et al. 1975; Kwiatkowski and Roff 1976; Yan and Stokes 1978	Ontario	Includes polluted stream sites
Chrysophyta	244			
Xanthophyceae	14	Kwiatkowski and Roff 1976	Ontario	Soft water lakes
Bacillariophyceae	230	Warner 1971; Lowe 1974*; Hargreaves et al. 1975; Kwiatkowski and Roff 1976	U.S.	Includes many hard water sites
Cyanophyta	31	Warner 1971; Moss 1973; Hargreaves et al. 1975; Kwiatkowski and Roff 1976	U.S.	Soft water lakes
Porifera	49	Old 1932; Jewell 1935; Ward 1949; Moore 1953; Penny 1954; Poirrier 1969; Harrison 1971	Wisconsin and others	Some soft water sites
Rotifera	80	Lansing 1942; Edmondson 1944; Roff and Kwiatkowski 1977;Hobaek and Raddum 1980	Wisconsin, New England, Ontario	Soft water lakes
Hirudinea	99	Gresers 1928; Bere 1931; Laurie and Jones 1938; Bennike and Boisen 1943; Tucker 1958; Herrmann 1970; Klemm 1972; Nilssen 1980	U.S.	Few soft water sites
Mollusca	196			
Gastropoda	113	Morrison 1932; Bryant 1936; Kalkowski 1948; Harman and Berg 1971; Nilssen 1980	Wisconsin and New York	Soft water lakes
Pelecypoda	83	Morrison 1932; Harrison 1958; Roff and Kwiatkowski 1977; Nilssen 1980; Okland, K. 1980; Okland and Kuiper 1980	Wisconsin	Soft water lakes
Crustacea	383	Lowndes 1952; Costa 1967; Davis and Ozburn 1969; Carter 1971; Sutcliffe and Carrick 1973; Capelli and Magnuson 1975; DeCosta 1975; Sprules 1975; Borgstrom and Hendrey 1976; Roff and Kwiatkowski 1977; Torke 1979; Fryer 1980; Hobaek and Raddum 1980; Malley 1980; Okland, K. 1980; Parent and Cheetham 1980; Havas and Hutchinson 1982; Malley et al. 1982; Marmorek 1982; Morgan and McMahon 1982; Schindler and Turner 1982; Walton et al. 1982; Confer et al. 1983	England, Ontario, Wisconsin, Scandinavia	Soft water lakes
Insecta	586			
Ephemeroptera	52	Gaufin 1973; Sutcliffe and Carrick 1973; Roback 1974*; Fiance 1978; Nilssen 1980	U.S.	Some acid mine drainage sites
Plecoptera	30	Bell 1971; Gaufin 1973; Roback 1974; Butler et al. 1973	U.S.	Some acid mine drainage sites
Trichoptera	250	Harrison 1958; Bell 1971; Gaufin 1973; Roback, 1974; Wiederholm and Eriksson 1977; Harris and Lawrence 1978*	U.S.	Includes polluted stream sites
Odonata	74	Harrison 1958; Bell 1971; Butler et al. 1973; Roback 1974*; Wiederholm and Eriksson 1977	Pennsylvania	Mostly stream sites
Diptera	73	Gaufin 1973; Roback 1974; Roff and Kwiatkowski 1977; Wiederholm and Eriksson 1977; Hobaek and Raddum 1980	U.S. and England	Includes sites with acid mine drainage
Coleoptera	44	Roback 1974*; Wiederholm and Eriksson 1977; Nilssen 1980	Pennsylvania	Soft water streams and lakes
Hemiptera	63	Roback 1974*; Wiederholm and Eriksson 1977; Nilssen 1980; Raddum 1980	Pennsylvania, Scandinavia	Soft water streams and lakes
Teleostei	156	Trama 1954; Cairns and Scheier 1959; Bishai 1960; Lloyd and Jordan 1964; Schofield 1965; Beamish 1972; Jensen and Snekvik 1972; Butler et al. 1973; Dunson and Martin 1973; Mount 1973; Almer et al. 1974; Daye and Garside 1975; Huckabee et al. 1975; Johansson and Kihlstrom 1975; Kwain 1975; Milbrink and Johansson 1975; Beamish 1976; Johansson and Milbrink 1976; Menendez 1976; Craig and Baksi 1977; Daye and Garside 1977; Johansson et al. 1977; Ruby et al. 1977; Runn et al. 1977; Smith 1977; Trojonar 1977b; Grande et al. 1978; Swarts et al. 1978; Ultsch 1978; Carrick 1979; Daye and Garside 1979; Grande et al. 1980; Gunn and Keller 1980; Harvey 1980; Lee and Gerking 1980; McDonald et al. 1980; Miller and Mackay 1980; Nilssen 1980; Peterson et al. 1980; Rahel and Magnuson 1980; Ryan and Harvey 1980; Graham and Wood 1981; Haya and Waiwood 1981; Roush 1981; Baker and Schofield 1982; Duplinsky 1982; Schindler and Turner 1982; Zischke et al. 1983	Wisconsin, Ontario, New York	Soft water lakes
Amphibia	17	Gosner and Black 1957; Huckabee et al. 1975; Cooke and Frazer 1976; Pough 1976; Pough and Wilson 1976; Mathews and Larson 1980; Schlichter 1981	New Jersey	Soft water ponds

*Compilation of sources.
**Corresponds to the number of investigators reporting a minimum pH value for a taxon; does not reflect the number of observations by an investigator.

TABLE 2. *Range of pH values and median of the minimum pH values for the taxonomic groups in the study (for observations between pH 3.0 and 7.0).*

	Field Observations*												Lab Observations*			
	Lakes				Streams				All							
Taxon	N*	Range	Med. Min. pH	95% C.I.	N*	Range	Med. Min. pH	95% C.I.	N*	Range	Med. Min. pH	95% C.I.	N*	Range	Med. Min. pH	95% C.I.
Algae (total)	71	3.8-6.3	4.6	±0.19	22	3.0-4.7	3.1	±0.30	264	3.0-7.0	5.5	±0.18	22	3.6-7.0	4.9	±0.33
Chlorophyta	23	4.1-6.3	5.5	0.30	9	3.0-4.5	3.1	0.37	29	3.0-6.3	4.6	0.41	13	4.6-7.0	5.0	0.48
Desmidiaceae	3	-	5.5	-	0	-	-	-	3	-	5.5	-	7	3.6-5.6	4.9	0.30
Euglenophyta	1	-	3.8	-	0	-	-	-	1	-	3.8	-	1	-	3.6	-
Chrysophyta (total)	19	4.1-6.3	4.6	0.36	10	3.0-4.7	3.1	0.72	203	3.0-7.0	6.0	0.19	0	-	-	-
Xanthophyceae	14	4.1-5.5	4.6	0.42	0	-	-	-	14	4.1-5.5	4.6	0.42	0	-	-	-
Bacillariophyceae	5	4.3-6.3	4.6	1.34	10	3.0-4.7	3.1	0.72	189	3.0-7.0	6.2	0.16	0	-	-	-
Cyanophyta	25	4.1-6.3	4.5	0.44	3	-	3.1	-	28	3.1-6.3	4.5	0.35	1	-	5.6	-
Porifera	0	-	-	-	8	4.2-6.6	4.2	0.95	14	5.0-6.9	6.4	0.64	0	-	-	-
Rotifera	67	3.5-7.0	5.0	0.31	0	-	-	-	67	3.5-7.0	5.0	0.31	1	-	5.4	-
Hirudinea	22	5.1-7.0	6.6	0.54	1	-	6.6	-	46	5.1-7.0	6.7	0.16	1	-	4.5	-
Mollusca (total)	80	4.7-7.0	6.2	0.18	0	-	-	-	92	4.7-7.0	6.4	0.16	1	-	5.0	-
Plecypoda (total)	49	4.7-7.0	6.2	0.24	0	-	-	-	50	4.7-7.0	6.2	0.25	0	-	-	-
Unionidae	9	6.0-7.0	6.9	0.11	0	-	-	-	9	6.0-7.0	6.9	0.11	0	-	-	-
Sphaeriidae	40	4.7-7.0	6.1	0.20	0	-	-	-	41	4.7-7.0	6.1	0.20	0	-	-	-
Gastropoda (total)	31	5.4-7.0	6.2	0.28	0	-	-	-	42	5.4-7.0	6.6	0.20	1	-	5.0	-
Pulmonata	26	5.4-7.0	6.3	0.22	0	-	-	-	37	5.4-7.0	6.6	0.19	1	-	5.0	-
Prosobranchia	5	5.7-7.0	5.9	0.88	0	-	-	-	5	5.7-7.0	6.5	0.81	0	-	-	-
Crustacea (total)**	98	3.9-7.0	5.5	0.24	1	-	5.8	-	185	3.0-7.0	5.3	0.19	9	4.0-6.4	4.3	0.50
Ostracoda	0	-	-	-	0	-	-	-	19	3.0-6.8	6.2	0.54	0	-	-	-
Cladocera	55	3.9-7.0	5.5	0.36	0	-	-	-	74	3.4-7.0	5.5	0.28	3	4.3-5.0	4.3	0.64
Copepoda (total)	37	3.9-6.8	5.4	0.32	0	-	-	-	72	3.4-7.0	5.2	0.24	1	-	4.3	-
Cyclopoida	18	4.2-6.8	5.3	0.39	0	-	-	-	47	3.4-7.0	5.1	0.21	0	-	-	-
Calanoida	19	3.9-6.8	5.5	0.47	0	-	-	-	25	3.9-7.0	5.4	0.41	1	-	4.3	-
Insecta (total)	48	3.9-7.0	4.2	0.16	181	3.0-7.0	6.4	0.14	370	3.0-7.0	6.3	0.10	19	3.6-6.6	5.2	0.47
Ephemeroptera	6	4.2-7.0	4.9	1.03	24	5.5-7.0	6.6	0.13	30	4.2-7.0	6.6	0.35	5	5.1-6.4	5.9	0.53
Plecoptera	0	-	-	-	11	5.5-6.7	6.0	0.43	11	5.5-6.7	6.0	0.43	9	4.1-6.6	5.2	0.55
Trichoptera	1	-	3.9	-	21	4.0-7.0	6.4	0.34	163	3.8-7.0	6.3	0.11	2	4.0-4.7	4.4	-
Odonata	2	-	3.9	-	48	4.0-7.0	6.4	0.18	50	3.9-7.0	6.4	0.20	2	3.8-5.2	4.5	-
Diptera	14	3.9-4.6	3.9	0.02	33	3.0-7.0	5.6	0.29	47	3.0-7.0	5.5	0.55	1	-	3.6	-
Coleoptera	11	3.9-7.0	4.2	0.10	13	5.5-7.0	6.6	0.57	24	3.9-7.0	5.6	0.80	0	-	-	-
Hemiptera	14	3.9-7.0	4.6	0.98	31	4.4-7.0	6.3	0.34	45	3.9-7.0	6.0	0.38	0	-	-	-
Teleostei (total)**	34	4.3-6.3	5.0	0.18	46	4.5-6.4	6.0	0.16	66	4.3-6.4	5.6	0.24	15	3.6-6.4	4.7	0.53
Cyprinidae	9	4.5-6.3	5.5	0.40	18	4.6-6.4	6.0	0.13	23	4.5-6.4	6.0	0.20	2	4.0-4.5	4.3	-
Percidae	5	4.4-5.4	5.2	0.64	7	5.5-6.2	6.0	0.12	10	4.4-6.2	5.9	0.51	1	-	5.0	-
Salmonidae	8	4.4-5.2	4.8	0.31	3	4.5-5.3	4.6	0.73	9	4.4-5.3	5.0	0.34	5	4.0-6.0	4.5	0.92
Centrarchidae	5	4.6-5.5	4.7	0.32	6	4.6-6.4	6.0	1.11	7	4.6-6.4	5.1	1.02	1	-	3.6	-
Amphibia	0	-	-	-	1	-	4.6	-	4	4.0-6.0	5.3	1.46	11	3.8-6.0	4.3	0.24

*N = Number of species.
**Minor subclasses and families with few observations are not shown.

the hypothesis that some groups of aquatic organisms display pH preferences.

The overall distribution of the aquatic insects with respect to pH was quite similar to that for the algae. The Plecoptera, Coleoptera, Hemiptera, and Diptera had median minimum pH values at or below pH 6.0. The major outlier among the insects, the Diptera, had a median minimum pH value of 5.5. Within the dipterans, the Chironomidae typically were found in the most acidic environments (as low as pH 2.8).

The relative tolerance of the common orders of insects appears to conflict with observations by Vangenechten et al. (1979), Raddum (1980), and Nilssen (1980), who reported the dominance of Hemiptera, Coleoptera, Odonata, and Diptera in acidified lakes. Although the median of the minimum pH values for the Hemiptera, Coleoptera, and especially Odonata were higher than might be expected in light of the observations from Scandinavian lakes, the apparent conflicts can be easily resolved—if one considers that, in extremely acidic conditions, very few taxa in each of these orders were represented. Therefore, the increased acidification suggested a response for the insects similar to that observed under eutrophication, namely a reduction in species richness.

The plots showing the percent reduction in number of species should be interpreted with this in mind. For example, Figure 3 indicates a low probability of finding a mollusc community rich with diversity below pH 6.0. Also, the probability of finding molluscs (other than Sphaeriidae) below pH 5.5 is low, but one cannot necessarily draw any inferences about the abundance of those species that might be present in acidic waters. Conversely, lack of change in species richness cannot be used as evidence that the aquatic community has not been affected. For example, Mills (1984) reported the substitution of the formerly rare pearl dace species for the acid-intolerant fathead minnow when Lake 223 was acidified to pH 5.4.

With few exceptions, the minimum pH tolerated by individual taxonomic groups in the laboratory was lower than that observed in the field, typically by ≥1 pH unit. Similarly, the taxa occurring in the lakes usually were found at lower pH values than those found in streams (within the same order or family). The major exception to this pattern was the salmonids, which were found in quite acidic streams. For this taxa, the laboratory minimum pH was also much closer to the field minimum pH compared to most other taxonomic groups.

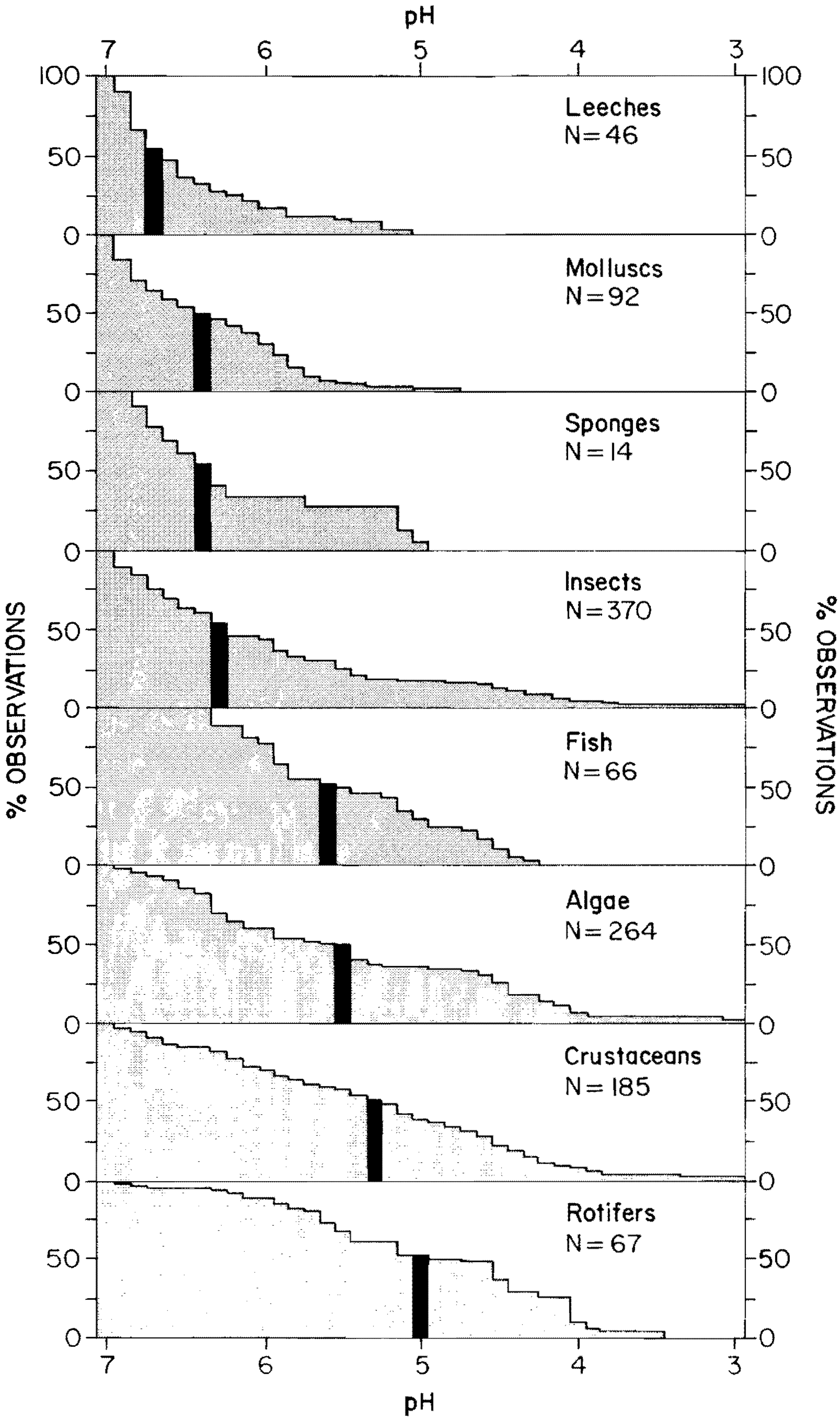

FIGURE 1. *Cumulative frequency distribution of minimum pH values for field observations of aquatic taxa, showing percent reduction in species along a pH continuum. (The median minimum pH value is indicated by the solid bar.)*

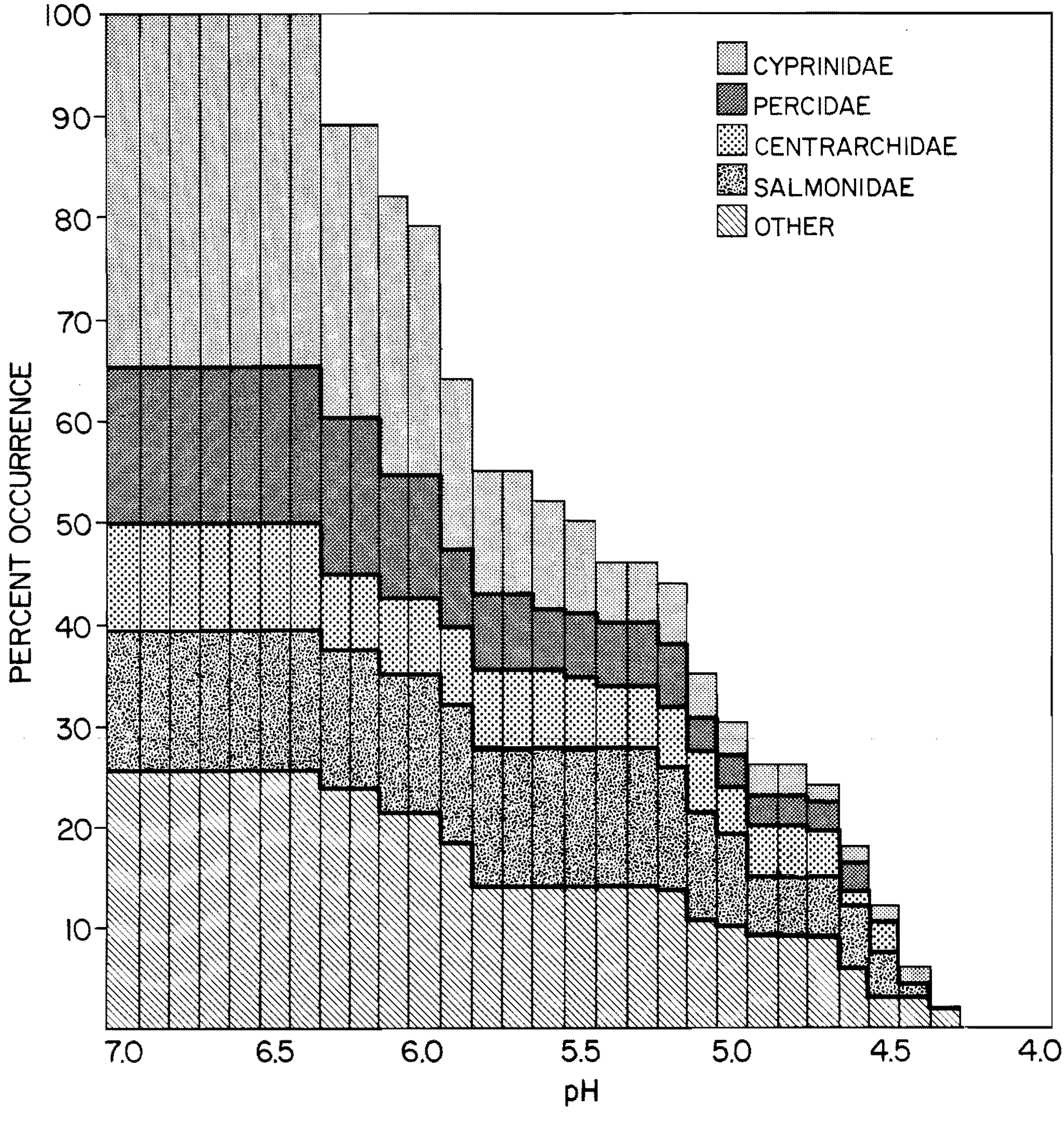

FIGURE 2. *Cumulative frequency distribution of minimum pH values for field observations of fishes, showing percent reduction in species along a pH continuum.*

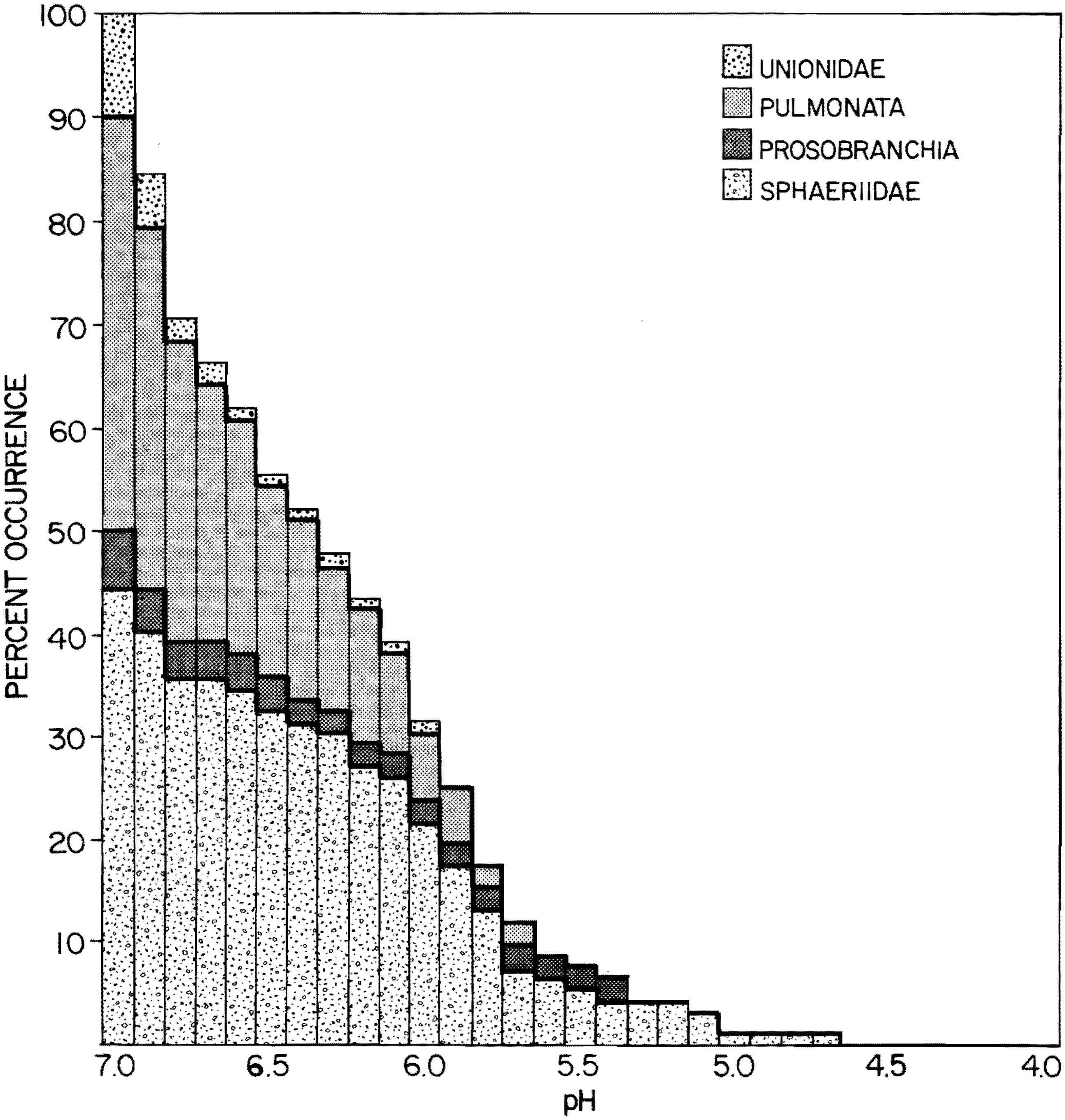

FIGURE 3. *Cumulative frequency distribution of minimum pH values for field observations of molluscs, showing percent reduction in species along a pH continuum.*

Variability Within Species

An indication of the reliability of the minimum pH values can be obtained by examining pH differences for individual species with observations from two or more investigators. Results of differences in multiple observations for the same species were shown in Table 3. The average differences for the fish (0.5) were significantly smaller than the differences within the other groups. The average differences for the snails, stoneflies, and crustaceans were intermediate between the values for the fish and those for the remaining groups. Data for the crustaceans were derived from similar field surveys of soft water habitats but, in the case of the stoneflies, also included some laboratory studies.

The comparison of snails was based on surveys of Wisconsin lakes (Morrison 1932) and New York sites (Harman and Berg 1971). The Wisconsin survey covered a broad range of lake chemistries, whereas the New York survey was restricted to sites with pH > 6. Consequently, the paired minimum pH values for the mollusc species did not represent an optimum comparison.

The average differences for the other five groups ranged from 1.1 pH units for the caddisflies to 2.4 for the diatoms. These groups had higher differences, probably because much of the data were from general surveys or studies conducted as part of organic pollution investigations not necessarily associated with soft water environments. Consequently, the observed minimum pH values from these regions dominated by relatively hard water may not represent the lowest pH the taxa may be able to tolerate.

LIMITATIONS ON INTERPRETING SPECIES TOLERANCE TO LOW pH

Organism presence or absence is subject to a host of water quality variables, of which pH is only one. In addition, the presence of an organism is affected by numerous biological variables such as age and predation. Without an understanding of the limitations of the original data applied to this analysis, we must exercise considerable caution in interpreting these results. Problems in interpretating the influence of pH on these groups are arranged into two categories: (1) problems specific to the data base, primarily the validity of using such data to determine pH tolerance; and (2) problems related to lack of knowledge of the organisms, especially their environmental preferences and response to stress.

The Data Base

The first concern is the accuracy of the published pH values. In more recent studies, pH meters with the capability of providing accurate measurements have been used. However, some of the earlier investigators had to rely on less accurate, colorimetric techniques.

Fortunately, the pH data for most of the groups was relatively recent and should be of acceptable accuracy. The data for the molluscs are based on colorimetric techniques and may not be as precise. However, an analysis of the errors associated with colorimetric data (Haines et al. 1983) provided sufficient evidence for concluding that colorimetric pH is reasonably accurate (± 0.2 pH units), particularly for values above pH 5.6.

Assuming the pH was measured accurately, the recorded value may not be representative of the water to which the organism was exposed. This is particularly true of the many benthic organisms that live on or in the substrate. For example, Harp and Campbell (1967) found chironomid larvae were able to survive in lake waters of pH 2.8 by residing in the less acidic substrate. The problem of measuring the pH to which the organisms are exposed may be difficult to resolve, especially for stream investigations where the benthos may represent a large portion of the community.

The design of the investigation plays a major role in determining if the minimum pH to which the organism was exposed was actually measured. Many of the studies were either surveys or short-term investigations (one year or less) and were conducted at a limited number of sites. Because pH varies throughout the day and on a seasonal basis, it is unreasonable to assume the minimum pH value observed during a given field study was necessarily the minimum value experienced by the organism. In addition, the central limit theorem shows that the probability of recording extremely low pH values increases with increasing sample size.

The use of a minimum pH value also failed to address the question of how rapid fluctuations in pH or duration of exposure to the minimum pH affect organism response. Jeffries et al. (1979) documented rapid pH depression of streams and lakes during spring snow melt and speculated on its possible impacts on the biota. One might expect that short-term pH depression would have a greater impact on the lotic community (excepting the hyporheic organisms) compared to a lentic community because of the increased opportunity to avoid low pH water in the lake. Muniz and Leivstad (1980) discussed habitat selection as a means of avoiding acidic waters. This behavioral response may explain why some organisms survive in waters known to have periods of high acidity.

Ideally, comparisons of organism distributions should be derived from a single study that included all taxa being considered. However, this review relies on a variety of studies representing a mix of environmental gradients and taxonomic groups. The probability that the correct distribution of a given taxa or taxonomic group is related to the number of observations made across the environmental gradient. Therefore, if either the level of effort for taxonomic groups or the ranges cov-

TABLE 3. *Differences in minimum pH for species observed by more than one investigator.*

Taxonomic Group	No. Species with Multiple Field Observ.	Avg. Difference Between Observations	Range of Differences
Algae			
Chlorophyta	4	2.1*	0.9-3.7
Euglenophyta	1	0.5	-
Bacillariophyceae	16	2.4	0-4.0
Rotifera	4	0.3	0.2-0.3
Hirudinea	25	1.0	0.1-2.5
Mollusca	15	0.9	0-2.3
Crustacea	58	1.1	0-3.7
Insecta			
Plecoptera	3	1.0	0.5-1.3
Trichoptera	15	1.1	0-3.0
Odonata	2	1.4	0.4-2.4
Hemiptera	6	0.7	0.4-1.2
Teleostei	18	0.5	0-1.3

*pH units.

ered for the taxonomic groups are not equal, then the comparisons among taxonomic groups will suffer from some undefined bias.

Knowledge of the Organisms

Although the problems mentioned above are not trivial, they are overshadowed by problems stemming from our lack of knowledge of the organisms. The first of these problems arises from our inability to precisely identify which factors are responsible for an organism's absence. Many early researchers, from whom these values were derived, expressed doubt about linking pH, or any other single variable, to organism presence or absence.

A number of investigators found that bicarbonate, alkalinity, calcium, or total hardness were more important than pH in explaining organism distribution. Jewell (1939) considered calcium to be the most important factor governing the survival of sponges, whereas Racek (1969) identified hydrogen ion concentration as the most important factor. Although Myers (1931, 1942) attributed the differences in distribution of many rotifers to pH, Edmondson (1944) suggested rotifer distribution was affected by both pH and alkalinity, but seldom by pH alone. Much of the mollusc literature discussed the importance of alkalinity (Shoup 1943) or calcium (McKillop and Harrison 1972) in determining limiting habitats, but seldom was pH mentioned as a factor (Bryant 1936).

Recent investigations, such as that of Okland and Okland (1980), showed there were no definite fixed limits of any variable that suggest species tolerance. Although the abundance and number of snail species declined with pH, those species existing near the lower pH tolerance limit were also inhabiting lakes with elevated calcium concentrations. J. Okland (1980), studying over 1,000 lakes in Norway, noted that within the same calcium concentration, the number of snail species decreased with pH. Howells et al. (1983) reported fish tolerance to low pH was modified by both calcium and aluminum concentrations. These observations indicated pH tolerance for a given taxon was not a fixed value, but rather varied as a function of the interacting variable(s).

Important biological factors affecting organism distribution include species acclimation (Jewell and Brown 1924; Trojonar 1977*a*), predator/prey relationships (Raddum 1980; Eriksson et al. 1980), available habitat (Harp and Campbell 1967), and genetic variability within species (Gjedrem 1980). Raddum et al. (1979) attributed the observed biological simplification in acidified lakes primarily to reduced competition resulting from the loss of fish in addition to physiological stress from hydrogen ion concentration. Harp and Campbell (1967) found that the distribution of *Chironomus plumosus* in acid lakes was restricted not by pH, but rather by the presence of leaf litter.

The variation in minimum pH among closely related taxa is perhaps one of the major problems in acidification impact studies. In keeping with the need to consider organism response at the lowest taxonomic unit possible (Resh and Unzicker 1975; Stoermer 1978), the vast majority of observations used in this analysis are at the species level. However, even within species, considerable variation can occur.

Gjedrem (1980) reported a 60% variation in survival rates among strains of brown trout exposed to low pH waters. Beebee and Griffin (1977) also noted large differences in tolerance to acid waters between strains of Natterjack toads *(Bufo calamita)*. Rahel and Magnuson (1980) attributed variation in acid tolerance of yellow perch *(Perca flavescens)* to genetic differences rather than acclimation. McCormick et al. (1980) showed that reproductive failure of fathead minnows in acidified artificial channels, measured by the proportion of pre-ovulatory corpora atretica, varied considerably between individuals. Again, this suggests that the ability to tolerate low pH conditions is, in part, attributable to genetic differences.

Life stage at the time of exposure is another key biological factor governing response to stress. Daye and Garside (1975), Menendez (1976), and Kwain (1975) showed that tolerance to low pH among fish was highly dependent on the life stage of the test organism. Similarly, Bell (1971) found that aquatic insects were more sensitive to low pH during the period of emergence than during the last instar. Most studies of the Unionidae indicate sizable populations are found only above pH 6.0. Brown and Jewell (1926) observed complete survival of unionid mussels after 46 days exposure to a pH level of 4.4, but there was significant corrosion of the shell. They attributed this latter effect to be the acidity or low calcium content of the water and concluded that young mussels would not grow or secrete a shell under these conditions.

Thus far, much of the discussion has assumed pH exerts its primary impact through direct physiological stress. However, many organisms may be able to survive low pH, yet still face elimination because of their dependence on more sensitive species. Nilssen (1980) noted the disappearance of leeches in his study lakes coincided with the loss of the gastropods and suggested that the leeches disappeared because they lacked adequate prey. Nilssen's observation is also consistent with the median of the minimum pH values reported here for the snails and leeches (6.6 and 6.7). Predator/prey relationships are often difficult to observe, yet a modification of these interspecific interactions may be a common effect of acidification for many aquatic organisms (Hendrey et al. 1976). Therefore, using laboratory tolerance data could overestimate community tolerance to acid conditions in the natural system.

Another potential problem with the median minimum pH approach is the use of presence/absence data from regional surveys. For example, presence/absence of fish from a lake in the process of acidification may fail to reveal the inevitable loss of species when recruitment is zero due to cessation of reproduction (Mills 1984).

Lastly, the question of habitat type (lentic vs. lotic) complicates the interpretation of organism distribution by pH. We observe in Table 2 that for taxonomic groups with both lake and stream representatives, the median of the minimum pH value is usually lower for the lentic taxa compared to the lotic taxa. This pattern is particularly striking when comparing the values for the insects and fish. The lake taxa pH values are less than the stream taxa values by 2.2 and 1.0 units, respectively.

IMPLICATIONS FOR BIOLOGICAL MONITORING AND WATER QUALITY CRITERIA

The results indicate many fish taxa are more tolerant of low pH than a variety of other aquatic organisms such as molluscs, leeches, and several orders of insects. Dramatic changes in the aquatic ecosystem have occurred before economically important game fish have been lost (Schindler 1980). Biological monitoring established to detect early signs of acidification should reflect this observation.

The high intraspecies variability in pH response serves to caution against monitoring one or two sensitive species. Exclusive reliance on the presence or absence of "indicator" species only documents species extirpation and may result in false indications of damage or may fail to detect damage altogether. Investigators attempting to determine the biological effects of lake and stream acidification should consider the use of factorial designs (or other appropriate designs) to more clearly establish the importance of potentially confounding variables.

*European Inland Fisheries Advisory Commission.
**U.S. Environmental Protection Agency.

The pH criteria for water quality, particularly as it applies to fisheries, has been reviewed extensively by EIFAC* (1969), EPA** (1976), and Katz et al. (1979). The results presented here are in general agreement with the following EIFAC conclusion: "There is no definite pH range within which a fishery is unharmed and outside which it is damaged, but rather there is a gradual deterioration as the pH values are further removed from the normal range." However, the fixed pH minimum criteria of 6.5 for freshwater aquatic life (cited in both EPA and Katz) does not reflect the fact that many soft water lakes and streams have normal ranges well below pH 6.5. More realistic criteria should be formulated based on tolerable deviations from the normal range, with the recognition that there are errors associated with the collection of environmental data (Hunter 1977).

SUMMARY

In this report, the aquatic community response to acidic conditions was a compilation of organism responses from various regions and illustrated general patterns associated with acidification. Our results are as follows:

1. With over 2,000 minimum pH values in 9 major taxonomic groups of aquatic organisms, the range of minimum pH values within each group was broad, especially for the algae, aquatic insects, rotifers, and crustaceans.

2. The median of the minimum pH values of the major groups ranged from 6.7 for the leeches to 5.0 for the rotifers. The snails and leeches were much less likely to inhabit low pH waters than the remaining groups, and were rarely found below pH 5.7. In contrast, the algae and insects showed a remarkably broad distribution with respect to pH, with minimum values of 1.5 and 2.0, respectively.

3. The median of the minimum pH values for most of the aquatic groups was between 6.1 and 5.2. Three dominant groups in lake environments—the algae, crustaceans, and fish—exhibited median pH values within 0.3 pH units of each other (5.6 to 5.3). While differences among the taxonomic groups was apparent, the significance of these differences remains undetermined.

4. The crustaceans, represented primarily by the planktonic cladocerans and copepods, had a median minimum pH of 5.3.

5. The response of various fish families showed a somewhat homogeneous response similar to that of the crustaceans. The one fish family showing significantly less tolerance for acidic waters was the Cyprinidae, which exhibited a strong reduction in species below pH 6.0. In contrast, the salmonids showed no major reduction until pH 5.0. The distribution of the darters was similar to the cyprinids, whereas the perch were among the most pH-tolerant fish.

6. Of the major taxonomic groups examined, the algae showed a more uniform distribution across the pH range. The desmids averaged 0.9 pH unit higher than the other green algae, despite the fact that they occur in acid bogs. Blue-green algae were observed in waters down to pH 2.0.

7. The overall distribution of the aquatic insects with respect to pH was quite similar to that for the algae. The Plecoptera, Coleoptera, Hemiptera, and Diptera had median minimum pH values at or below pH 6.0. Diptera had a median minimum pH value of 5.5.

8. Although the median of the minimum pH values for the Hemiptera, Coleoptera, and especially Odonata, were higher than might be expected in light of the observations from Scandinavian lakes, the apparent conflicts can be easily resolved if one considers that, in extremely acid conditions, very few taxa in each of these orders were represented. Therefore, the increased acidification suggested a response for the insects similar to that observed under eutrophication, namely a reduction in species richness.

9. With few exceptions, the minimum pH measured in the laboratory was lower than that observed in the field, typically by ≥ 1 pH unit. Similarly, the taxa occurring in the lakes usually were found at lower pH values than those found in streams (within the same order or family). The major exception to this was the Salmonidae, which were found in quite acidic streams.

10. Problems interpreting the presence or absence of an organism fall into two categories: the data base and lack of knowledge about the organisms.

11. Problems with using the data base to generalize about species distribution include: a) questionable accuracy of published pH values (early investigators had to rely on less advanced measurement techniques); b) representativeness of the measured pH values in terms of the organism's actual environment, since some organisms live in the less acidic substrate; c) rapid fluctuations in pH or duration of exposure to the minimum pH could affect organism response; and d) focus of some studies was only on a portion of the biota under very site-specific conditions.

12. Lack of knowledge about the organisms themselves also makes it difficult to interpret their presence or absence. Many early researchers expressed doubt about linking pH, or any single variable, to organism presence or absence. A number of investigators found that bicarbonate, alkalinity, calcium, or total hardness were more important in explaining organism distribution. In addition, biological factors affecting organism distribution include species acclimation, predator/prey relationships, available habitat, genetic variability within species, and life stage at the time of exposure.

13. Many organisms may be able to survive low pH, yet still face elimination because of their dependence on more sensitive species. Therefore, using laboratory tolerance data could overestimate community tolerance to acid conditions in the natural system.

14. Type of habitat can influence organism distribution in relation to pH. The study showed the median of the minimum pH value is usually lower for the lake taxa compared to the stream taxa, especially for insects and fish.

CONCLUSIONS

Despite problems in applying the data to determine tolerances to low pH, we conclude:

1. Aquatic community response to increasing acidity is evident at all levels below pH 7.0, and any pH reduction greater than that normally associated with a given lake or stream will most likely cause loss of indigenous species.

2. The loss of aquatic species appeared to be gradual throughout the pH range 7.0 to 4.0, although many investigators noted the greatest reduction in number of species occurring between pH 6.1 and 5.2.

3. Considerable emphasis is being placed on monitoring the fish community's response to acidification. If the objective of a biological monitoring program is to detect early impacts of acidification, there are other aquatic groups which will better serve this purpose. In this review, molluscs and leeches showed the greatest sensitivity to low pH.

4. The high intraspecies variability in pH response serves to caution against monitoring one or two sensitive species. Exclusive reliance on the presence or absence of "indicator" species only documents species extirpation and may result in false indications of damage or may fail to detect damage altogether. Investigators attempting to determine the biological effects of lake and stream acidification should consider the use of factorial designs (or other appropriate designs) to more clearly establish the importance of potentially confounding variables.

5. The large variation in a species' response to low pH can limit the accuracy of predicting acidification impacts on that species in regions not yet affected by acidic deposition.

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