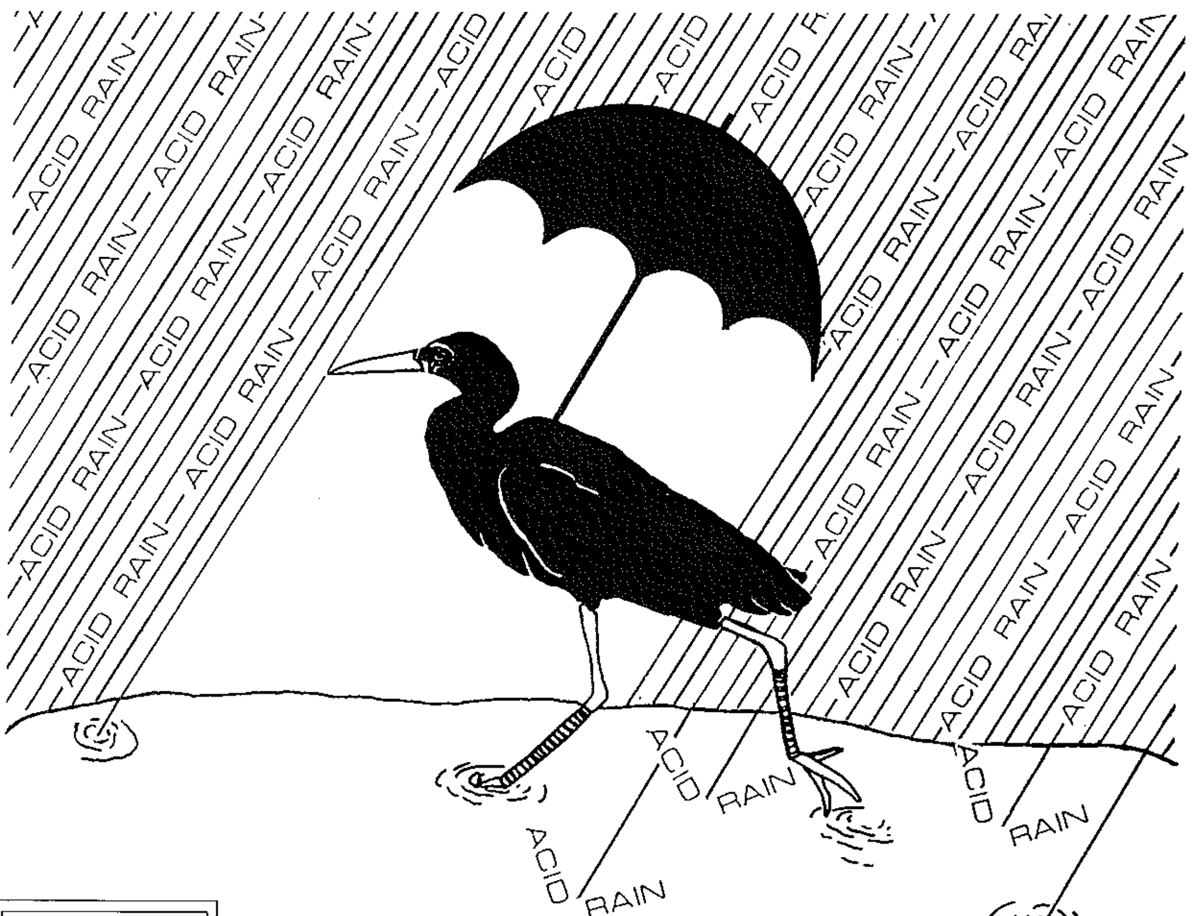
ACIDIC DEPOSITIONS: EFFECTS ON WILDLIFE AND HABITATS



THE WILDLIFE SOCIETY

Technical Review 93-1

November 1993

Acidic Depositions: Effects on Wildlife and Habitats

The Wildlife Society

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Technical Review 93-1
November 1993

Foreword

Presidents of The Wildlife Society occasionally appoint ad hoc committees to study and report on selected conservation issues. This has worked reasonably well, but experience indicated a need to standardize the procedures. On advice from the Publications Committee in 1989, the Society's governing Council agreed to refine its oversight role, to appoint an editor or editors to assist committees, and to establish standard formats for the committee reports.

The reports ordinarily appear in 2 related series called either Technical Review (formerly "White Paper") or Position Statement. The review papers present technical information and the views of the appointed committee members, but not necessarily the views of their employers or The Wildlife Society. Position statements are based on the review papers, and the preliminary versions ordinarily are published in **The Wildlifer** for comment by society members. Following the comment period, revision, and Council's approval, the statements are published as official positions of The Wildlife Society.

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This report may be cited as: Longcore, J. R., et al. 1993. Acidic depositions: Effects on wildlife and habitats. Wildl. Soc. Tech. Rev. 93-1. 42pp.

Acknowledgments

We thank T. A. Haines, L. J. Garrett, and P. W. Manning for providing access to documents for this review. W. M. Healy, D. H. Rusch, and H. Salwasser composed the Steering Committee and reviewed an early draft of this Technical Review.

Cover art generously provided by the Publications Section, Public Affairs, the University of Maine, Orono.

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SYNOPSIS

The phenonmenon of "acid rain" is not new; it was recognized in the mid-1800s in industrialized Europe. In the 1960s a synthesis of information about acidification began in Europe, along with predictions of ecological effects. In the U.S. studies of acidification began in the 1920s. By the late 1970s research efforts in the U.S. and Canada were better coordinated and in 1980 a 10-year research program was undertaken through the National Acid Precipitation Assessment Plan (NAPAP) to determine the causes and consequences of acidic depositions.

Much of the bedrock in the northeastern U.S. and Canada contains total alkalinity of <200 μeq l^{-1}, thus, it lacks acid-neutralizing capacity. In the U.S. about 5% of the land area and in Canada about 43% of the land area is sensitive to acidic depositions. Further, these areas receive $\geq$20 kg/ha/yr of wet sulphate depositions and are vulnerable to acidifying processes.

Acidic depositions contribute directly to acidifying processes of soil and soil water. Soils must have sufficient acid-neutralizing capacity or acidity of soil will increase. Natural soil-forming processes that lead to acidification can be accelerated by acidic depositions. Long-term effects of acidification are predicted, which will reduce soil productivity mainly through reduced availability of nutrients and mobilization of toxic metals. Severe effects may lead to major alteration of soil chemistry, soil biota, and even loss of vegetation. Several species of earthworms and several other taxa of soil-inhabiting invertebrates, which are important food of many vertebrate wildlife species, are affected by low pH in soil. Loss of canopy in declining sugar maples results in loss of insects fed on by certain neotropical migrant bird species.

No definitive studies categorically link atmospheric acidic depositions with direct or indirect effects on wild mammals. Researchers have concentrated on vegetative and aquatic effects. Circumstantial evidence suggests that effects are probable for certain species of aquatic-dependent mammals (water shrew, mink, and otter) and that these species are at risk from the loss of foods or contamination of these foods by metals, especially methylmercury. Continued acidification of terrestrial habitats, to the extent that earthworm populations are broadly reduced, might expose some fossorial mammalian species to risk because of decline in their major prey species.

Acidic deposition affects primarily aquatic habitats of avian species by disrupting food webs (ecological effects) and increasing amounts of available heavy metals (mercury, aluminum, cadimum) in prey of avian species (toxicological effects). The ecological effects of acidifying wetlands are to reduce acid-intolerant prey (invertebrates) and to change prey quality from high-calcium bearing prey to low-calcium bearing prey. The toxicological effects are to increase contamination by heavy metals, especially methlylated mercury, in foods of breeding waterbirds. The combination of these 2 types of effects results in potentially lower survival of adults and reduced production, growth, or survival of young of many bird species.

Effects of acidification on herpteofauna and their habitats are mainly reproductive failure of susceptible species and reduced or metal-contaminated foods for both amphibians and reptiles.

INTRODUCTION

Fish and wildlife have served for decades as barometers of environmental contamination. One of the earliest uses was that of canaries to warn coal miners of toxic gases. Under protocols of the National Contaminant Biomonitoring Program (O'Shea and Ludke 1979, Jacknow et al. 1986) analysis of wings of hunter-harvested waterfowl for organochlorine contaminants began in 1964 and analysis of whole carcasses of starlings (*Sturnus vulgaris*) and freshwater fish started in 1967 and has continued. These programs are now under review and the emerging *Biomonitoring of Environmental Status and Trends (BEST)* program probaby will be focused to monitor a broad array of lands, species, and contaminants (C. M. Bunck, U.S. Fish and Wildl. Serv., pers. commun.). Herring gulls (*Larus argentatus*) have been monitored to determine dynamics of contaminants in the Great Lakes (Mineau et al. 1984), and aquatic mammals have served as monitors of heavy metals (Newman and Schreiber 1984, Wren 1986*a*). Clark et al. (1988), using wildlife species, stressed the importance of establishing quantitative links between contaminant emissions, abiotic concentrations, concentrations in wildlife, and ecological viability. Fish and wildlife, especially fish, have served as the biological "red flag" manifesting adverse effects of wetland acidification from anthroprogenic acidic depositions.

Purpose and Scope

A review of effects of acidic depositions on wildlife is appropriate under the 2 primary objectives of The Wildlife Society (TWS): (1) to develop and promote sound stewardship of wildlife resources and the environments upon which wildlife and humans depend and (2) to undertake an active role in preventing human-induced environmental degradation. In 1987 TWS President Lytle Blankenship formed the *Acid Rain on Wildlife Technical Advisory Committee (Ad Hoc)* and in his letter to the Chairman charged that "The basic responsibility of this committee is to prepare a technical report (review paper) based on current information available on the effect of acid precipitation (acid rain) on wildlife, with special emphasis on the terrestrial ecosystem." Although the emphasis was to be directed toward the terrestrial ecosystem, data from wildlife species (mostly migratory birds) associated with aquatic ecosystems are included because more specific data existed for these organisms in aquatic habitats.

A number of terms in this review require definition. *Acidic deposition* is the deposition of airborne contaminants commonly known as *acid rain* or *acid precipitation* that is in 2 forms: *dry deposition* by absorption of gases or by particle collection at surfaces, and *wet deposition* by chemical scavenging and deposit via precipitation (rain, snow, fog) (Ulrich 1982, Gibson 1984, Hidy 1987, Schwarz 1987). The *pH (acidity)* is the negative logarithm of the hydrogen ion concentration that ranges from 14 (alkaline/basic) to 0 (acidic). Substances (water, soil) with *low* pH are acidic; a decrease of 1 pH unit indicates *10 times more* acidity. *Acidification* is the phenomenon of coupled chemical reactions: one that produces hydrogen ions (acidifying process) and the other that consumes hydrogen ions (neutralizing process) (Paces 1985). Concentration of hydrogen ions is usually small, thus rate of production and consumption of hydrogen ions is of utmost importance. Before the industrial era and use of fossil fuels, the weathering process maintained hydrogen ions in a relatively balanced state through production of neutralizing cations. About 150 years ago the balanced state was disrupted when burning of fossil fuels and smelting of ores began producing large amounts of sulfur and nitrogen oxides (Paces 1985). *Acid Neutralizing Capacity (ANC)* is the capacity of a substance to neutralize added acids by reaction of hydrogen ions with inorganic or organic bases (bicarbonate or organic ions). *Alkalinity*, also referred to as "buffering capacity" (see Norton 1980, Norton et al. 1982), is the measure (in $\mu eq\ l^{-1}$) of a substance's (water, soil) ability to neutralize acid, as determined by titration with a known strong acid (Lerman 1978). A large alkalinity value indicates a large "buffering capacity". The inflection point Gran method is the acceptable method for determining alkalinity (Hendrey et al. 1980*a*). *Wildlife* is considered vertebrate organisms (mammals, birds, amphibians, and reptiles, excluding fish) that inhabit aquatic and terrestrial ecosystems. Of necessity, fish and organisms of lower taxonomic order (invertebrates) will be discussed only as needed to depict effects on wildlife.

Historical Perspective of Acidic Depositions

History of the "acid rain" phenomenon is detailed by Cowling (1982, 1983) and others (Gordon 1987, Schwarz 1987), who documented key events, people, and progress through 1981 toward understanding acidic depositions. The following points are paraphrased from

Cowling's (1982) review. (1) Acid rain is not a recent phenomenon as Smith (1852, cited in Cowling 1982; Smith 1872) first coined the term "acid rain" and expressed many ideas about sources, processes, and effects of acid rain. (2) Gorham (1955, 1957, 1958, 1961) built the major foundations for our understanding of the causes of acidic depositions and their effects on aquatic ecosystems. Gorham (1981) also prepared a detailed analysis of Smith's pioneer work. (3) In the late 1960s the first major synthesis of information about acid precipitation in the fields of limnology and agricultural and atmospheric chemistry was achieved by Oden (1968) who clearly documented that (a) acid precipitation was a large-scale regional phenomenon in much of Europe with well-defined source and sink regions, (b) both precipitation and surface waters were becoming more acidic, (c) long-distance (100-2,000 km) transport of sulfur- and nitrogen-containing air pollutants was taking place among various nations of Europe, (d) there were marked seasonal trends in deposition of major ions and acidity, and (e) long-term trends in acidity could be detected in many countries of Europe. Oden also predicted ecological consequences: changes in surface water chemistry, decline in fish populations, leaching of toxic metals from soils into surface waters, decreased forest growth, increased plant diseases, and accelerated damage to materials.

Scientific debate followed publication of Oden's (1976) ideas and 2 major scientific initiatives resulted. In 1972 the Norwegian Interdisciplinary Research Programme called "Acid Precipitation---Effects on Forest and Fish" (SNSF Project) was established with 2 goals: (1) to establish as precisely as possible the effects of acid precipitation on forests and freshwater fish, and (2) to investigate the effects of air pollutants on soils, vegetation, and water to the extent required to support the primary objective. The second initiative was by the Organization for Economic Cooperation and Development (OECD) during 1973-75. It began study of the long-range transport and deposition of atmospheric sulfur in eastern and western Europe.

In the U.S. the first studies of precipitation chemistry were completed by MacIntire and Young (1923). Research and monitoring accelerated (see Cowling 1982) and now Canada and the U.S. have long-term programs for chemical analysis of precipitation. *The Canadian Network for Sampling Precipitation* began in 1976 (Cowling 1982) and in the U.S. *The National Atmospheric Deposition Program (NADP)* was started in 1978 (Galloway and Cowling 1978).

In the late 1970s more effort was made to coordinate research programs between Canada and the United States within North America. In 1977 a document for *A National Program for Assessing the Problem of Atmospheric Deposition (Acid Rain)* was developed (Galloway et al. 1978). In 1980 a 10-year program of research on the causes and consequences of acid precipitation was called for and enacted through the Energy Security Act (PL 96-264) under the *National Acid Precipitation Assessment Plan (NAPAP)*. Research on all aspects of acid rain has continued and expanded since Cowling's (1982, 1983) reviews. Many recent findings were presented at the *International Symposium on Acidic Precipitation* held at Muskoka, Ontario in 1985. The final report and review for the NAPAP is now available (NAPAP, 1991). The preceding brief history is only a sketch of some of the influential scientists and events in the acid rain investigations.

SENSITIVITY OF NORTH AMERICAN HABITAT TO ACIDIC DEPOSITIONS

Effects of acidic depositions on ecosystems are variable and depend largely upon the type of underlying bedrock that affects capacity of the drainage basin bedrock to assimilate acid (H^+ ions) during chemical weathering (Kramer 1976, Norton et al. 1982). Acid-neutralizing capacity (ANC) is related to mineral solubility and kinetics of solution and ion-exchange properties of soil. Consequently, presence of any carbonate mineral yields essentially infinite buffering (ANC). Galloway and Cowling (1978) depicted most of northeastern North America and the Rocky Mountain area as sensitive (total alkalinity <200 μeq l^{-1}) to acidic deposition (also see Likens et al. 1979). Norton et al. (1980, 1982) refined sensitivity predictors and Hendrey et al. (1980*b*) tested bedrock as predictors of sensitivity in Maine, N.H., N.Y., Va., and N.C. and reported that alkalinities were low, <200 μeq l^{-1}. Also, he documented that marked declines in alkalinity and pH occurred in sensitive waters of N.C. and N.H. For the lower 48 states of the U.S. about 5% of the land area (91% in the northeastern and southeastern states) is sensitive to acidic deposition using the threshold of sensitivity as alkalinity of ≤ 200 μeq l^{-1} (Omernik and Powers 1982, Omernik and Kinney 1984, Omernik and

Griffith 1985). In Canada, 46% of the land area is considered sensitive to acidic deposition (Anon. 1988), mostly in eastern Canada. Many of these sensitive areas also receive enough wet sulphate deposition ($\geq$ 20 kg/ha/yr) so that they are acidified (Wisniewski and Keitz 1983, Pearse et al. 1985).

CHANGES IN ACIDIC DEPOSITIONS IN NORTH AMERICA

Documentation of the degree and timing of changes in acidic depositions has been tentative and criticized (see Hansen and Hidy 1982, Stensland and Semonin 1982) because early measurements of pH and alkalinity were less reliable and data sets were often incomplete. This prevented calculation of ionic balances, which is the currently accepted method to verify chemical accuracy (Schindler 1988). Data have documented, however, since the 1950s that rainfall was acidic in northeastern United States (Herman and Gorham 1957, Gambell and Fisher 1966, Granat 1972, and Likens et al. 1972). Cogbill and Likens (1974) and Cogbill (1976) reported that acid precipitation has occurred throughout the northeastern United States since 1950-55 and, assuming a stoichiometric formation process, 65% of the acidity was caused by H_2SO_4 and 30% by HNO_3. Later, after criticism by Stensland (1979) and by Hansen and Hidy (1982), Likens and Butler (1981) reported that the trend of increasing acidity of precipitation in the northeastern United States from 1955-56 to 1965-66 was substantiated (Cogbill et al. 1984) by use of an error analysis of these data (Liljestrand and Morgan 1979). Further, the 1975-76 data of Likens and Butler (1981) revealed that the area receiving acidic precipitation has expanded substantially southward and westward with intensification of acidity in the northeastern and southeastern regions of the U.S. since the 1950s. These published trends in acid rain were questioned by Hansen and Hidy (1982) and Stensland and Semonin (1982), but validity of the trends was further substantiated by Cogbill et al. (1984) and supported by studies of Battarbee and Charles (1986) and Dixit et al. (1987) through reconstruction of diatomaceous fossils. Also, Schindler (1988:154) stated that analyses of SO_4^{2-} and NO_3^- in ice cores from south Greenland revealed increases in deposition of these ions from 1900 onward, thereby supporting the thesis of Likens and colleagues.

Recently, decreases in SO_2 emissions have been associated with decreased concentration of SO_4^{2-} in precipitation at the Hubbard Brook Experimental Forest (HBEF) in New Hampshire (Hedin et al. 1987), but increases in NO_3^- and concentration of base cations and Cl^- have obscured trends in acidity. The authors concluded (p. 246), however, that "... decrease in SO_4^2 content of precipitation at HBEF generally attributed to decreases in SO_2 emissions has resulted in large scale decreases in both concentration and deposition of H^+, thereby diminishing the potential effects of acidification on organisms, water and soil." Driscoll et al. (1989) later cautioned that, although elevated sulfur loadings clearly have affected water quality, including at the HBEF, atmospheric deposition of basic cations also may alter the acid-base status of surface waters. In eastern Canada significant decreases in amounts of SO_2 in air and sulphate in precipitation (up to 30%) have been recorded in the last decade, particularly at sites in or downwind of regions in which SO_2 emissions have decreased by >10 percent (RMCC 1990). Associated with decreased SO_2 emissions in the Sudbury, Ontario area after restrictions on industry have been signs of recovery of surface waters and biota (Gunn and Keller 1990, Keller et al. 1992). However, the long-term benefits of reductions in SO_2 may be partly eroded by NO_x depositions. Although NO_x depositions have been low relative to those of sulphate, nitrates in eastern Canada have changed little in precipitation during the 1980s, consistent with constant nitrogen oxide emissions.

EFFECTS ON WILDLIFE HABITAT

Soils

Soils constitute the interface between the atmosphere and lithosphere over much of the terrestrial portion of the earth's crust. They are produced by interactions of complex geologic and biological processes over thousands to millions of years. Soils form the substrate that provides, directly or indirectly, most of the food and many of the materials on which our civilization depends. Even the chemical quality of streams and lakes is influenced by soil-forming processes. Throughout most of geologic time, the major acidic agent involved in weathering and soil-forming processes has been carbonic acid. As a consequence, a by-product of these reactions is bicarbonate alkalinity, which is delivered to surface waters. The acid/base chemistry of most natural waters has been dominated by the dissolved carbon system and throughout geologic time organisms have evolved within the range of pH dictated by that system. With the beginning of the industrial revolution, additional anthropogenic acidic components (H_2SO_4, HNO_3) have composed greater amounts of atmospheric depositions. Initially effects were observed locally around heavily industrialized cities (Smith 1872). Now, virtually every industrialized nation is receiving "acid rain" over large regions that are not confined to the vicinity of industrial development (Cowling 1982).

Concern has been raised that acid rain may adversely affect soil productivity and other soil characteristics. Soils can respond to acidic additions in a variety of ways. A primary concern is that soils may become so acidified that they can no longer support vegetation. Acidification develops through the leaching of alkali and alkaline earth cations (base cations) by acid depositions (Reuss and Johnson 1985). Base cations on exchange sites in soils are replaced by hydrogen ions from acid rain leading to a decrease in base saturation and an increase in soil acidity (McFee et al. 1977). Replenishment of base cations on soil exchange sites simply cannot keep pace with the loss.

Aluminum and trace metals are mobilized from soil minerals as soils become increasingly acid (Cronan and Schofield 1979). Acid soils and elevated amounts of dissolved aluminum in soil water combine to interfere with proper transfer of nutrients and electrolytes across root membranes, thereby inhibiting growth of vegetation (Ulrich et al. 1980). Increased concentration of trace metals may exacerbate these inhibiting effects. In agricultural areas where fertilizer and lime are commonly added to soil, this is not of serious consequence, but it may be serious on nonagricultural lands such as forests. Water from lakes and streams that drain watersheds where soil is acidified may contain dissolved aluminum at concentrations that are toxic to fish (Schindler and Turner 1982).

Loss of vegetation from watersheds may lead to increased soil erosion and an increased sediment load in streams that drain these watersheds. Elevated sediment loads in streams may adversely affect aquatic organisms. Soil loss, on a human time scale, is essentially an irreversible process. Other less extreme effects of acid rain, however, may have long-term implications relative to soil productivity. Decreases in decomposition of organic matter and carbon mineralization have been observed as a result of soil acidification (Francis et al. 1980, Lohm 1980, Moloney et al. 1983). Microbial communities shift from bacteria to fungi, which are better adapted to tolerate acidic conditions (Lohm 1980). Nitrification and ammonification are diminished in acid soils (Alexander 1980, Francis et al. 1980). Among inorganic constituents of soil, Al-hydroxy interlayers of clay minerals increased under acidic conditions (Jackson 1963). Cation exchange capacity is decreased by clay alumination (Sawhney 1968). Base saturation decreases and soil acidity increases as acidification develops (Abrahamson 1980, Paces 1986). Leaching of aluminum and heavy metals increases with acidification and nutrient cations are lost from soil. When mobilized in soil waters, aluminum and heavy metals eventually reach streams and lakes where they adversely affect aquatic life. Similar changes take place in soils whether they are acidified by the activities of man or by natural processes, but on different time scales and to different intensities. Many natural soil-forming processes commonly lead to acidification, however, rate of acidification may be increased by acidic atmospheric deposition (Rosenqvist 1978, Krug and Frink 1983, Ulrich 1983). Thus, soils are an indispensible part of the basic life-support system for virtually all terrestrial organisms; any contamination of them may have broad ecological effects.

Water

The status of acidification of North American surface waters (lakes, ponds, and streams) has been determined during local and regional surveys. In Minnesota, all of 85 lakes sampled had pH of $\geq$6.0, but alkalinities ranged from a low of 2.7 μeq l^{-1} to 85.6 (Glass and Loucks 1980). For 265 wetlands sampled in northwest Wisconsin, 16 (6%) were in the 5.0-6.0 pH range and 249 (94%) were >6.0 and all alkalinities were $\geq$21 μeq l^{-1} (Lillie and Mason 1980). In the Adirondack Mountains area, 212 (25%) of 849 lakes had a pH of <5.0, 255 (30%) had a pH of 5.0-6.0, and 382 (45%) had a pH of >6.0 (Pfeiffer and Festa 1980). Alkalinities were similarly lower for 692 lakes with 284 (41%) $\leq$20 μeq l^{-1}, and 297 (43%) $\geq$200 μeq l^{-1}. In New England, 8 (18%) of 226 (193 lakes, 33 streams) surface waters sampled were <5.0 pH, 47 (21%) in the 5.0-6.0 range and 160 (71%) >6.0 pH (Haines and Akielaszek 1983). Fifty-two (23%) had alkalinities $\leq$20 μeq l^{-1} and 68 (30%) had akalinities of $\leq$ 200 μeq l^{-1}. For 9 (lst-3rd order) Atlantic salmon (*Salmo salar*) streams in Maine and Connecticut pH was 5.31, which for the 1st-order streams approaches the negative effect level (Haines and Akielaszek 1984).

The National Surface Water Survey was initiated in 1983 and included a National Lake Survey and a National Stream Survey (Landers et al. 1988). For the Eastern Lake Survey, the Northeast Region was estimated as having 326 lakes (4.6%) with ANC ≤ 0, which generally corresponds to a pH of ≤ 5.2 (Landers et al. 1988) and 4,258 (60%) lakes with ANC ≤ 200 $\mu eq\ l^{-1}$. In the Upper Midwest Region 148 (1.7%) lakes had an ANC ≤ 0, and in the Southern Blue Ridge subregion there was only 1 lake with pH <6.0. Florida had the largest percentage (12.4%), number (259) and surface area (7,936 ha) of lakes with pH ≤ 5.0. Note that the study areas for this survey were restricted to areas where most lakes were expected to have ANC <400 $\mu eq\ l^{-1}$. Also, small lakes (<4 ha up to 10 ha) are not included or poorly represented in the sample.

For the Western Lake Survey (Landers et al. 1987) pH values were not low: 99% of the lakes had a pH of ≥ 6.0 and ranged from a median of 6.94 in California to 7.6 in the Southern Rockies. Likewise, ANC was generally greater than in the Eastern Lake Survey with the lowest values (ANC ≤ 50 $\mu eq\ l^{-1}$) in the California subregion (800 lakes, 36.7%) and the Pacific Northwest (333 lakes, 19.5%). No lakes in the west had ANC ≤ 0 $\mu eq\ l^{-1}$, except for 1 lake associated with a hot spring (Landers et al. 1987).

In 1986 the U.S. Environmental Protection Agency (Kaufmann et al. 1988) conducted a National Stream Survey (NSS) in Mid-Atlantic (MA) and Southeast (SE) U.S. to determine how many streams had low ANC or were now acidic. Stream "reaches" (either just above the downstream point of confluence or just below the upstream point of confluence) with drainages <155 km^2 (60 mi^2) were sampled (500 reaches per each of the nine subregions).

Excluding Florida, 51% (18,542) of MA reaches and 52% (9,642) of SE reaches had ANC ≤ 200 $\mu eq\ l^{-1}$ at their upstream ends. In the MA region 7.4% (2,677) of the reaches were acidic (ANC ≤ 0 $\mu eq\ l^{-1}$) at their upstream ends and 3% (1,098) were acidic at their downstream ends. Among the subregions of the MA region the greatest number of acidic stream reaches were in the MA Coastal Plain where 12% of the upper reach ends had pH between 5.0 and 5.5. In other MA subregions (Poconos/Catskills, Valley and Ridge, and Northern Appalachians) relatively few reaches were acidic at downstream ends. Among the Interior Southeast subregions, excluding Florida, acidic reaches were found only in the Southern Appalachians where 120 reaches (2%) were acidic at their upstream ends. The Florida subregion stands out with a relatively high percentage of acidic, low ANC, and low pH streams, i.e. at upstream ends an estimated 678 (39%) of the reaches were acidic (ANC ≤ 0 $\mu eq\ l^{-1}$) and another 531 (31%) had ANC between 0 and 50 $\mu eq\ l^{-1}$. At the upstream ends an estimated 539 reaches (31%) had pH ≤ 5.0; another 324 (19%) were between pH 5.0 and 5.5. Of the currently acidic streams based on the NSS, 26% are acidic because of acid mine drainage and 27% because of organic acids (NAPAP 1990). Further, atmospherically derived sulfate was the dominant non-sea salt anion in the remaining 47% of the acidic streams: these were streams in forested, higher elevation areas (>300 m), mountainous catchments with watershed area <30 km^2.

In Canada several studies have documented numbers of acidified wetlands. For lakes in the La Cloche Mountains of Ontario, 42 (28%) of 152 lakes had a pH of <5.0 and 52 (34%) lakes were in the 5.0-6.0 range (Beamish and Harvey 1972). In the Sudbury region of Ontario 20 (13%) of 150 lakes had pH <5.0 and 22 (15%) in the 5.0-6.0 range (Conroy et al. 1976). In central Ontario 2 (8%) of 26 lakes had pH <5.0 and 15 (58%) were in the 5.0-6.0 range (Scheider et al. 1979*a*). In Nova Scotia 11 (52%) of 21 wetlands had a pH of <5.0 and 5 (24%) were in the 5.0-6.0 pH range (Watt et al. 1979). In Quebec 3 (12%) of 25 surface waters had pH <5.0 and 10 (40%) in the 5.0-6.0 pH range (Jones et al. 1980). Kelso et al. (1986) estimated that in Canada 14,000 lakes were acidified (i.e., pH <5.0 and 150,000 lakes with pH <6.0) and an estimated 5% of the lakes in eastern Canada have ANC of ≤ 0 (NAPAP 1990). The federal/provincial Research and Monitoring Coordinating Committee (RMCC 1990) assessment report for 1990, as paraphrased in the following paragraph details current aquatic resources at risk in Canada.

Forty-three percent of Canada's land area (generally corresponding to the Canadian Shield) is sensitive to acidic depositions. The area of primary concern for adverse effects in aquatic systems is where sensitive terrain is overlapped by acidic depositions, namely the area east of the Manitoba-Ontario border (about 95° W longitude) and south of the 10 kg/ha/yr wet sulphate deposition isopleth (about 52° N latitude), just south of James Bay. In an area slightly smaller than the region of concern delineated above, an inventory identified 800,000 water bodies >0.18 ha, with 53.7% <1.0 ha.

By analysis of chemical data from 8,505 lakes in 324 tertiary watersheds, for lakes >0.18 ha 31,000 were acidic and for lakes >1.0 ha 14,000 were acidic (i.e. ANC ≤ 0). Except for regions containing SO_2 emitters (e.g. Sudbury and Noranda), the Atlantic provinces contain the highest proportion of acidic lakes, reflecting their greater sensitivity. Acidification of lakes in eastern Canada is from depositions of atmospheric sulphate and not from nitrogen depositions or natural organic acids and sulphide minerals in bedrock. Hence, the highest median sulphate amounts in lakes coincide with the areas of greatest depositions (i.e. central and southern Ontario and southern Quebec). Acidification from land-use changes is considered insignificant. In western and northern Canada the meager data available suggest that the current low amounts of acidic depositions have not altered water chemistry in that region, although local pollution sources have acidified some wetlands. Furthermore, some waters are temporarily acidified during spring snowmelt because of either storage of acids within the winter snowpack or temporary storage of sulphate in the catchment, particulary in wetlands, during dry seasons.

In addition to the regional variability in occurrence of acidic wetlands related to bedrock sensitivity, wetland acidity may be dominated by strong, anthropogenic acids or weak, naturally occurring organic acids (Kahl et al. 1989). Thus, some seepage lakes with high amounts of dissolved organic carbon may be acidic because of organic acids, i.e. humic and fulvic acids (LaZerte and Dillon 1984, Malcolm 1985, Bourbonniere 1987).

Terrestrial Vegetation

Although acid deposition may affect the productivity of crop and forest plants by direct or indirect means (tissue necrosis or lessening soil nutrients), there is little unequivocal evidence that, at ambient levels, acid precipitation is deleteriously affecting terrestrial vegetation (Evans 1982, 1984; Barnard et al. 1990). Further, Evans concluded that the level of injury, if injury occurs, is less than the year-to-year changes from differences in natural climatic factors, e.g. precipitation or temperature. Irving (1983) also reported that most of the agricultural crop species studied in field and controlled environment experiments exhibited no effect on growth or yield as a result of simulated acidic rain. A year later, Amthor (1984:5) reached a similar "no clear evidence" conclusion after reviewing the experimental evidence of direct phytotoxic effects of acid rain, including effects on metabolic leaching, acid-rain induced lesions, growth and productivity, interaction of acid rain with gaseous pollutants, and long-term responses. Amthor (1984) acknowledged, however, that long-term detrimental effects were possible because of interaction of acid rain with ozone, the primary gaseous air pollutant, which is known to adversely affect vegetation (Linzon 1986).

In 1978, Hutchinson (1978:617) concluded that "...there is little solid evidence to date of the occurrence of visible or even detectable damage to terrestrial ecosystems caused by the acid precipitation events of the past twenty years." The issue of forest "dieback," however, has been linked to acid rain, but Krause et al. (1986:661) concluded that "... no clear statement of a true cause-effect relationship in respect to novel forest decline in Europe can be made at the present time." For North America, Linzon (1985:21) concluded that, although "...there is no conclusive proof that air pollutants, including acid deposition, are directly responsible for the forest declines there is substantial circumstantial evidence linking the two." Linzon (1985:21-23) then detailed 17 items of circumstantial evidence that linked air pollution and forest decline. More recently, The American Forestry Association (Anon. 1987:Abst.) published *A White Paper on the Forest Effects of Air Pollution* and concluded "...that further control of sulfur and nitrogen oxides, hydrocarbons, ozone, and toxic metals is now warranted to protect the forest ecosystem." This concern is in contrast to earlier inaction by the forest products industry (Postel 1984), which believed that evidence linking forest damage to acid deposition was not sufficient to warrant action. Manion (1987) cautions that there are no absolutes for the recent forest decline of northeastern United States and Europe and that it is inappropriate to assume that all the dieback and mortality in 1 forest is caused by the same agent.

Nevertheless, effects on forest vegetation seem to affect avian species, although documentation is difficult. For example, declines in northern parula warbler (*Parula americana*) populations seem linked to declines in amount of pollution-sensitive lichen (*Usnea* sp.), which is required for nests (Arbib 1980). Similarly, changes in habitat structure in declining sugar maple (*Acer saccharum*) forests in southern Quebec (DesGranges et al. 1987, Darveau et al. 1992) seem related to fewer passerine species (e.g. red-eyed vireo [*Vireo olivaceus*]) that rely on the forest canopy for food and shelter and greater numbers of ground-dwelling species (e.g. black-throated blue warbler [*Dendroica caerulescens*]). Some of these changes are attributed to shifts in assemblages of invertebrates when stands of healthy maple declined, but the substantial year-to-year variability does not now suggest long-term alterations in habitat use or in population densities as birds move in from nearby healthy stands (Darveau et al. 1992). In the Netherlands where forest decline is evident, several species of cavity-nesting birds, (e.g. great tit [*Parus major*]) do not lay eggs or they have eggshells of inferior quality (Drent and Waldendorp 1989). These authors hypothesize that acidic depositions have depressed the calcium:aluminum ratio in soil and thus in leaves of the forest trees. In turn caterpillars, which feed on these tree leaves and are low in calcium, are eaten by the birds that consequently do not acquire enough calcium to form adequate eggshells. Eggshell effects were noted in resident, cavity-nesting species, but not migrants (e.g. pied flycatcher [*Ficedula hypoleuca*]), which can store calcium on wintering areas and moblize calcium during breeding. This phenomenon has not been noted among birds of North American forests, although low dietary calcium is a concern for wildlife in acidified environments (Scheuhammer 1991).

Aquatic Macrophytes

In freshwater environments acidification has caused reduced growth and productivity of plants, reduced numbers or diversity of vascular macrophytes (Almer et al. 1974, Grahn et al. 1974, Wile and Miller 1983, Roberts et al. 1985, Wile et al. 1985, Grahn 1986, Hunter et al. 1986*a*, Arts et al. 1990), replacement of macrophytes by *Sphagnum* sp. (Grahn 1977, Hendrey and Vertucci 1980, Hultberg and Grahn 1976), and increased metal residues in plant tissues (Dietz 1973, Miller et al. 1983, Andersson 1988, Lehtonen 1989, Crowder 1991), which may influence macrophyte occurrence (Gorham and Gordon 1963, Wile and Miller, 1983). Acidic lakes that are fertilized, however, produce lush macrophyte communities (even *Potamogeton* spp.) (Kerekes et al. 1984) suggesting that effects of acidificiation on macrophytes (Kerekes and Freedman 1989) may be indirect, through nutrient impoverishment (i.e. oligotrophication; Grahn et al. 1974).

Macrophytes are essential substrate for many aquatic invertebrates (Rosine 1955, Moyle 1961, Krull 1970, Voigts 1976) and luxuriant growths of plants in quiet, shallow waters most often have the largest invertebrate populations (McGaha 1952). Generally, macrophytes of acidic lakes are morphologically reduced (often in rosette form), with few leafy-stemmed species (Roberts et al. 1985, Wile et al. 1985), and this situation might result in reduced invertebrate numbers. Krecker (1939) and Andrews and Hasler (1943) have reported that usually the greater the leaf dissection of a submerged aquatic plant, the larger the animal population associated with it. Therefore, changes in macrophytes to that of species typical of acidic lakes along with direct intolerance of species to low pH (Eilers et al. 1984) adverserly affects aquatic invertebrates, which are essential for higher trophic predators, i.e. fish, amphibians, and birds, especially waterfowl (Schroeder, 1973, Kaminski and Prince 1981). Other data, e.g. Schell and Kerekes (1989), however, depict the importance of nutrients in affecting numbers and biomass of macroinvertebrates, irrespective of pH.

EFFECTS ON MAMMALS

Direct Effects

Direct effects on the health of mammals from acid rain have not been reported. Mammals, in contrast to amphibians and fish, are not solely dependent on the physical/chemical aquatic environment for growth, reproduction and survival. Changes to the physical/chemical "water" environments, e.g. change in lake water pH caused by acid rain, do not seem to directly affect mammals, but there may be subtle indirect effects.

Indirect Effects

Indirect effects on mammals from acid rain have been reported by Bevanger and Albu (1986), Wren et al. (1980) and hypothesized by others (Singer and Fischer 1984, Wiener 1987, Schreiber and Newman 1988). Acid rain can cause degradation of habitat and changes in quantity or quality of available foods. Effects of these changes might cause shifts in distributions of mammals or even losses of individuals from populations because of effects on health.

Loss of Habitat

Forest dieback observed in red spruce and other tree species has been attributed to acid rain, ozone, or a combination of these and other variables (see **Terrestrial Vegetation** section). This phenomenon has been observed at high elevations in mountain regions of Vermont (Siccama et al. 1982), New Hampshire and New York (Johnson et al. 1984) and Virginia (J.

Bennett, National Park Service, pers. commun.). Mammals in these regions, however, are not directly dependent upon these affected forest plant species for survival. Nevertheless, forest dieback, if extensive, might affect local sites used by bats (*Lasiurus* sp.) that roost in foliage. These roost sites, however, are considered temporary and are used by solitary or small groups of bats (Kunz, 1982, Mattsson and Kunz 1982). The red spruce dieback is not extensive enough to be critical to mammalian populations living in these forests.

Changes in Quantity of Foods

The decline and loss of animals (e.g. fish and invertebrates), which has been documented in aquatic habitats (Bell 1971, Altshuller and Linthurst 1984, Eilers et al. 1984) might result in adverse effects to mammals that depend upon these organisms as food (Schreiber and Newman, 1988). This risk will be greater for obligate consumers and for small mammals that have restricted habitats or home ranges where foods have been reduced or eliminated. Lower food availability also may elicit adverse effects on reproduction (Sadleir 1969). One or more foods usually compose most of the diets of some mammals, especially seasonally. If these foods are adversely affected by acid rain then mammalian species, especially aquatic species that rely on fish (O'Connor and Nielsen 1981), may be affected.

Lichens are sensitive to acid rain and their abundance has decreased in some regions because of air pollutants, including acid rain (Fritz-Sheridan 1985, Gilbert 1986, Sigal and Johnston 1986*a,b*). A few mammals are dependent on lichens for food (Richardson and Young 1977), especially caribou and voles. The distribution of caribou (*Rangifer tarandus*) in Eastern Canada (Hall and Kelson 1975) overlaps areas affected by acid rain and caribou are dependent on lichens as their primary foods in winter (Thompson and McCourt 1981); lichens usually exceed 50% of their diets.

Several lichen species, including *Alectoria* spp. and *Bryoria* spp., *Evernia mesomorpha, Hypogymnia physodes*, and *Usnea* spp. are eaten by North American woodland caribou. Caribou also eat species of *Umbilicaria* where it is abundant on rock outcrops. Scott and Hutchinson (1987), through experimental acid rain episodes, have determined short-term declines in photosynthesis of the lichens, *Cladina stellaris* and *C. rangiferina*, used by caribou. They hypothesize that substantial restriction in growth and dry-matter accumulation of these species can be caused by acid rain. Although widespread decline in lichens from effects of acid rain has not been reported in these regions, continued acid rain might place caribou at risk from loss of their primary winter food (Singer and Fischer 1984). Several species of rodents including the heather vole, *Phenacomys intermedius*, and hoary marmot, *Marmota caligata*, eat lichens, primarily *Lobaria oregana, Peltigera* spp., and *Caldonia* spp.. Heather voles use lichens for food and nest-building. Three subspecies of the heather vole, which is considered one of the rarest of North American mammals (Banfield 1974), inhabit regions either affected by or with potential to be affected by acid rain. The subspecies *Phenacomys intermedius ungava* lives in Eastern Canada, *P. i. intermedius* in the Rocky Mountains and *P. i. laingi* in the Pacific Northwest (Banfield 1974). Hoary marmots occur in western Canada where acid rain is not considered a concern. Relative to the caribou, loss or reduction in lichens (if that should happen) is inconsequential for these rodents. Although rodents would need to change to alternate foods, these foods are available as well as nest-building materials.

Some aquatic invertebrates that are important foods of some mammals are sensitive to acidification (Haines 1981). Where pH of streams has been reduced below 6.0 macroinvertebrates have declined in Norwegian lakes (Okland and Okland 1980). Similarily aquatic invertebrates have declined in streams in New York (Hall and Likens 1980; Hall et al. 1980) when pH in streams was reduced from 5.4 to 4.0. Generally, numbers of invertebrate species in lakes and streams decline as pH declines with marked changes between pH 6.0 and 5.0 (Eilers et al. 1984). These effects on aquatic organisms have been reported for lakes and streams in the Adirondack region of New York and the LaCloche Mountain region of Ontario. Potential biological changes have been identified for headwater streams in Pennsylvania, North Carolina, the Muskoka-Halburton region of Ontario, and coastal areas of Nova Scotia (Altshuller and Linthurst 1984). Sensitive aquatic systems have been identified in much of Eastern Canada and New England, parts of the Allegheny, Smoky, and Rocky Mountains and the Northwest and North Central United States (Altshuller and Linthurst 1984). Mammals (shrews, mink, and otters) that are dependent upon aquatic foods and whose ranges include areas known to be affected by acid rain are at risk.

Shrews, especially the northern water shrew (*Sorex palustris*), are potentially sensitive to the indirect effects of acid rain because they have a high metabolic rate that requires them to eat more food than their body weight per day. The water shrew, is more restricted in its habitat requirements than most other species of shrews. It inhabits borders of ponds, streams, meadows, marshes, and woods (Conaway 1952, Conaway and Pfitzer 1952, Sorenson 1962, Brown 1967, Banfield 1974, Hall and Kelson 1975) and is considered an uncommon species (Hooper 1942, Johnson 1951, Wrigley 1969).

Primary foods of water shrews are insects, including a high percentage of aquatic larva, e.g. stoneflies, caddisflies, and mayflies (Conaway 1952, Sorenson 1962, Banfield 1974). The water shrew also eats amphibians and small fish, such as sculpin in streams (Nussbaum and Maser 1969) and salmon parr. It has been reported to eat fish eggs from hatchery pools (Banfield 1974). Four subspecies inhabit regions of North America (Banfield 1974, Hall and Kelson 1975) that either have been affected by acid rain or are sensitive to acid rain. *Sorex palustris punctulatus* lives in the Smoky and Allegheny Mountains; *S. p. albilarbis* in New England, New York and Eastern Canada; *S. p. gloveralleni* occurs in Nova Scotia; and *S. p. navigator* inhabits the Rocky Mountains. Thus, local populations of water shrews are at risk from indirect effects of acid rain because of their high metabolic requirements, comparatively narrow habitat requirements, and dependence on prey known to be sensitive to acid rain.

Some soils and invertebrates, including earthworms, are sensitive to acidification (see **Effects on Birds** and *Changes in Soil pH and Invertebrates*). Fossorial mammals, especially terrestrial species of shrews, might be at risk locally if earthworm populations are reduced substantially.

Mink (*Mustela vison*) in North America could be affected by acid rain. A decline in populations of Norwegian mink caused indirectly by acid rain has been reported by Bevanger and Albu (1986) who used statistical techniques to correlate ($r^2 = 0.865$, $P < 0.001$) geographic areas of Norway with declining mink populations to areas with declining fish populations attributed to acid rain. Gerell (1967) reported that in Norway during winter mink depend on fish as their primary (>50%) food. In North America mink are opportunist feeders consuming terrestrial as well as aquatic animals. Mink are considered semiaquatic mammals associated with streams, lake shores, and river banks (Allen 1986). In winter fish and other aquatic organisms, such as crayfish, comprise 30-40% of the diet of mink (Hamilton 1936, Sealander 1943, Korschgen 1958, Gilbert and Nancerkivell 1982). Two subspecies inhabit regions affected by acid rain. *Mustela vison vison* occurs in New England, New York, the Smoky Mountains, and Eastern Canada. *M. v. energumenos* occurs in the Rocky Mountains (Hall and Kelson 1975). Assuming that Bevanger and Albu's correlation is valid, then effects on mink are possible in watersheds adversely affected by acid rain in North America. Generally, because of their diverse diet in North America mink are not considered at risk from acid rain, although some local populations might be affected. In contrast, otters (*Lutra canadensis*) may be more at risk than mink from indirect effects of acid rain because they depend directly on fish and other aquatic organisms for food. Fish make up 50-100% of an otter's diet (Greer 1955, Sheldon and Toll 1964, Knudsen and Hale 1968). Otters have a wider geographical distribution than mink but are more restricted to stream and lake habitats. They also inhabit regions of North America exposed to acid rain, including New England, New York, the Smoky Mountains, Eastern Canada, and the Rocky Mountains.

Changes in Quality of Foods

The third type of indirect effect of acidification involves changes in quality of foods through contamination by heavy metals. Scheider et al. (1979*a,b*), Suns et al. (1980), and Johnson (1987) reported large amounts of mercury, cadmium, and lead in surface waters in Ontario. Schofield (1978) and Bloomfield et al. (1980) have reported similar findings for the Adirondack region of New York. Mammals that live in these regions and eat aquatic organisms from the surface waters might accumulate, through their diet (Wren et al. 1983, 1986*c*), greater amounts of the metals that are mobilized by acidification. Fish in many low-pH or low-alkalinity waters contain elevated amounts of mercury and other metals (Wren et al. 1983). Methylmercury, the primary form of mercury in these fish, is a highly toxic form (Wiener 1987) and is known to accumulate in mammalian food webs (Jenkins 1980). The formation of methylmercury in low-pH lakes is affected by several envrironmental variables (Winfrey and Rudd 1990) so severity of methylmercury contamination varies among wetlands.

Although conclusive evidence that mammals are adversely affected by metals mobilized by acid rain is lacking, circumstantial evidence suggests risk to certain mammalian species. Elevated amounts of cadmium have been found in tissues of moose (*Alces alces*), roe deer (*Capreolus capreolus*), and hares (*Lepus* spp.) in Southern Sweden (Frank et al. 1981, Mattsson et al. 1981), in Ontario (Crete et al. 1987, 1989), and in Maine and Norway (Scanlon et al. 1986). Also, cadmium has been found in wildlife near industries, particularly smelters (Sileo and Beyer 1985, Froslie et al. 1986). Cadmium acculmulation in tissues is greater in animals from acid-sensitive regions where acidification of soils might have increased amounts of cadmium in plants eaten by wildlife (Crete et al. 1987, Glooschenko et al. 1988). Herbivorous mammals, especially moose, deer, and caribou, accumulate enough cadmium in liver and kidney tissues to be a health risk to human consumers (Crete et al. 1987, 1989; Glooschenko et al. 1988*a*, Brazil and Ferguson 1989). Mercury has been detected in raccoons (*Procyon lotor*), beaver (*Castor canadensis*), and otters (*Lutra canadensis*) in Canada (Wren 1984, Wren et al. 1980) where mobilization of metals by acidification is considered probable. Livers of raccoons from sensitive areas contain 5 times more mercury than livers of raccoons from areas with non-acidic waters. Weiner's (1987) review of consequences of metal contamination of fish in low-pH lakes and implications for piscivorous wildlife, including mammals, suggest that acidification of poorly buffered lakes may increase dietary uptake of methylmercury, cadmium, and lead in wildlife that consume fish from low-alkalinity lakes. This is especially true for methylmercury, which has a greater "biomagnification" potential than cadmium or lead (Jenkins 1980, Wren et al. 1983, Weiner 1987). Mink and otter accumulated 10 times more mercury than predatory fish from the same drainage areas in Manitoba (Kucera 1983). Mink are considered sensitive to mercury (Linscombe et al. 1982) and are good indicators of mercury contamination (Kucera 1983). In the northeastern United States mean (SE) amounts of methylmercury in livers of mink ranged from 0.73 (0.13) to 1.2 (0.27) ppm and in otters from 1.12 (0.19) to 2.14 (0.34) ppm, wet weight (O'Connor and Nielson 1981). Individual mink contained up to 4.08 ppm and otter contained up to 5.12 ppm in the liver. Large amounts of mercury and toxic effects of mercury have been reported in mammals that occur downstream from industrial sources (Wren 1986*c*, Blus et al. 1987).

Another effect of acid rain involves the availability of essential elements to mammals. Although selenium deficiencies (known as "white muscle disease") have not been documented in wild mammals, concern has been raised regarding the relationship between availability of selenium and acid rain (Shaw and Cocks 1982, Shaw 1983, Singer and Fischer 1984, Schreiber and Newman 1988). Solubility of selenium in water declines with decreasing pH and amounts of selenium in forage are reduced in areas with sensitive soils that receive acidic deposition. White muscle disease in cattle has been observed when fertilizer containing sulfur is used in areas naturally deficient in selenium. Reproductive failure, including abortions, infertility, and mortality of neonates have been observed. Although studies of this potential effect are incomplete, herbivorious mammals in sensitive areas might be at risk. Similar concerns for other essential elements, such as molybdenum, also have been raised (Singer and Fischer 1984.)

EFFECTS ON BIRDS

During the past 10 years, scientific understanding of the effects of acid precipitation on the environment has increased greatly. Much of the research conducted on effects of acid precipitation on wildlife in North America and Europe has dealt with aquatic environments and has focused primarily on aquatic birds. Definitive statements about known effects of acid rain on forest birds are difficult to make, although inferences can be drawn from parallel processes observed in aquatic ecosystems (Table 1).

Recent reviews by Blancher and McAuley (1987), DesGranges et al. (1987), Eriksson (1987), McNicol et al. (1987*b,c*), Ormerod and Tyler (1987), Schreiber and Newman (1988), Diamond (1989), Mitchell (1989), Goriup (1989), RMCC (1990), Scheuhammer (1991) and Blancher (1991) essentially conclude that effects of airborne pollutants, including acid-causing emissions, on birds probably result from a primary effect on habitat that leads to disruptions in food webs and possible contamination of foods. Birds, unlike plants, invertebrates, fish, and amphibians are not affected directly by acidic deposition or the resulting decrease in the pH of their habitats. However, conclusive evidence exists that acidification of aquatic ecosystems causes both direct and indirect effects on organisms fed upon by birds. Birds may be affected by alterations in food webs in 2 ways: (a) *toxicologically*, as prey species ingest toxic metals released by processes of acidification these potentially toxic substances move up the food chain to birds, and (b) *ecologically*, as prey species sensitive to acidification are replaced by those that are

Table 1. Bird species probably affected by long-term effects of acidic depositions on their foods in aquatic environments (Schreiber and Newman 1988) and expected effects of maple dieback on forest bird communities (modified from DesGranges 1987).

Potential Effect	Feeding Habitat	Species
	AQUATIC ENVIRONMENT	
Reduced biomass of fish, aquatic invertebrates, amphibians	Lakes	Common loon Common merganser
	Littoral zone	Great blue heron American bittern Belted kingfisher Hooded merganser Common merganser
Reduced biomass of aquatic invertebrates	Littoral zone	Common goldeneye Ring-necked duck Black duck Virginia rail
Reduced biomass of aquatic invertebrates with adult stage terrestrial invertebrates	Riparian wetlands	Spotted sandpiper Eastern kingbird Eastern phoebe Tree swallow Barn swallow Bank swallow Yellow-rumped warbler Blackpoll warbler Palm warbler Common yellowthroat
	MAPLE DIEBACK	
Reduced biomass of invertebrates associated with canopy and trunk	Overstory	Red-eyed vireo Scarlet tanager Rose-breasted grosbeak American redstart Great crested flycatcher Least flycatcher Eastern wood-pewee
	Trunk	White-breasted nuthatch Pileated woodpecker Yellow-bellied sapsucker
Increased biomass of invertebrates associated with shrubs and ground	Shrubs	Wood thrush Hermit thrush Black-throated blue warbler Canada warbler
	Ground	Veery Ovenbird White-throated sparrow Yellow-shafted flicker

tolerant to lower pHs resulting in changes in the quality, quantity, and diverstiy of prey communities.

Toxicological Effects

Direct effects of acidification are defined as direct toxicity to 1 or more life stages of an organism, which causes a decline in the abundance of the species (RMCC 1990). Acute effects of air pollution on terrestrial wildlife have been reported (Newman and Schreiber 1984, Schreiber and Newman 1988). They arise when accumulation of toxicants by potential wildlife foods is sufficient to be acutely toxic. Among birds, there are examples of granivores, insectivores, and carnivores whose exposure to gaseous pollutants has resulted in adverse effects ranging from mortality to signs of chronic exposure, such as reproductive dysfunction or patterns of abnormal behavior. Most of these incidents are local and usually are not a consequence of long-range transport of pollutants. Acidic depositions increase the exposure of biota to toxic metals in 3 ways. First, sources of acidic emissions (principally metal smelters and fossil-fuel-fired power stations) produce trace metals, which may be transported long distances and deposited with the acids (Schroeder et al. 1987, Nriagu and Pacyna 1988). Among the trace metals discharged into the atmosphere are arsenic, cadimum, chrominum, copper, mercury, molybdenum, nickel, lead, selenium, vanadium, and zinc. Second, acidification of sensitive terrain increases the solubility and mobility of such metals as aluminum, cadmium, and zinc in soils and ground water (LaZerte 1986). Third, acidification of soils and lake waters often results in increased concentrations of biologically available metal species (Dickson 1980, Yan and Dillon 1984, Campbell and Stokes 1985, Dillon et al. 1988, Steinnes 1989). At the same time, acidification of watersheds may reduce the concentration of certain essential elements, such as selenium and calcium in prey, both of which reduce the toxicity of metals (Wren and Stokes 1988).

Metals generally considered most important in terms of toxicology to wildlife in acid-sensitive environments are mercury, aluminum, cadmium, and lead (Scheuhammer 1987*a,b*). Elevated amounts of these toxic substances in prey from acidic environments might seriously affect higher trophic levels, including fish, birds, and mammals. In this section we discuss only birds and the evidence for toxic effects acting through contamination of food webs.

Published data indicating direct toxic effects of acidification on birds is sparse. Although mobilization of toxic metals often follows acidification (Campbell and Stokes 1985), accumulation (Weiner and Stokes 1990) of metals by wildlife prey organisms rarely exceeds levels known to be acutely toxic to birds. Instead, lower dietary metal concentrations most often manifest subtle effects on reproduction in birds as a result of chronic, low-level exposure to contaminants. Scheuhammer (1987*a*) reviewed the effects of chronic toxicity of aluminum, cadmium, mercury and lead in birds, and others (Doyle 1977, Demayo et al. 1982, Eisler 1985*a,b*, 1987, 1988, Krueger et al. 1985, Wren 1986*a,b*) have reviewed biological effects of toxic metals in a variety of organisms. More recently, Scheuhammer (1991) critically evaluated the potential for increased exposure to the 4 metals named above in birds and mammals that inhabit acid-sensitive environments, and he assessed the increased risk of reproductive impairment.

Mercury.--Among the toxic metals mobilized by acidification, mercury has the greatest potential to affect avian reproduction. In its methlylated form (MeHg) (Miller and Akagi 1979, Xun et al. 1987, Wiener et al. 1990, Gilmour and Henry 1991) mercury is readily absorbed and can "biomagnify" in aquatic food chains (Scheuhammer 1987*a*, Scheuhammer 1991). In particular, fish concentrate MeHg in muscle tissue (Hesse et al. 1975; Lindberg and Odsjo 1983; Doi et al. 1984; Wren 1986*a,b*; Braune 1987), whereas invertebrates (e.g. insects, crustaceans except crayfish and molluscs) typically contain $<50\%$ of total Hg as MeHg (Wren and Stephenson 1991). In contrast, plants contain barely detectable levels even from highly contaminated environments (Gardner et al. 1978, Hildebrand et al. 1980, Cappon and Smith 1981).

Several facts convince researchers that fish-eating birds (loons (Gaviidae), mergansers (*Mergus* spp.), ospreys (*Pandion haliaetus*), kingfishers (*Ceryle alcyon*), herons (Ardeidae), bald eagles (*Haliaeetus leucocephalus*) and fish-eating mammals (mink and otter) are at risk from dietary mercury, and that acidification of wetlands increases that risk (Wiener 1987). First, several studies in North America and Scandinavia have shown that amounts of mercury are greater in several fish species from acidic lakes than in circumneutral lakes (Hakanson 1980, Sloan and Schofield 1983, Wren and MacCrimmon 1983, Bjorklund et al. 1984, Kelso and Gunn 1984, Hamilton and Haines 1989, McMurtry et al. 1989, Cope et al. 1990, Wiener et al. 1990, Spry and Wiener 1991). For example, yellow perch (*Perca flavescens*) accumulated almost twice as much mercury in the experimentally acidified basin of Little Rock Lake, Wisconsin as in the control basin (J. G. Wiener, U.S. Fish and Wildl. Serv., pers. commun.). Levels of mercury in tissues of fish from acidic lakes often exceed dietary levels (0.5 ug/g, wet wt.) that are known to cause neurological impairment and reproductive dysfunction in a wide variety of birds (Fimreite 1971; Heinz 1974; Barr 1986; Scheuhammer 1987*b*, 1988). Mercury is known to affect survival and reproduction of birds and mammals, and piscivores tend to accumulate the greatest amounts of mercury (Wren 1986*a,b*; Scheuhammer 1987*a*; Spry and Wiener 1991).

Laboratory studies have revealed that reproductive success of birds can be decreased by as much as 50% following exposure to dietary MeHg at dosages that are insufficient to cause intoxication in adult birds (Heinz 1974, Scheuhammer 1987*b*).

Whereas the major effects of MeHg contamination are neurological (impaired vision, muscle weakness and clumsiness) (Annau and Eccles 1987), secondary effects, which compromise the ability of visual predators to obtain food in the wild, are equally important and may ultimately cause emaciation and increased susceptibilty of birds to disease, predation, or other environmental stresses (McIntyre 1989). Large amounts of mercury have been detected in dead and moribund loons, particularly adults wintering along the northern Gulf of Mexico (Alexander 1987). Mercury accumulated on the breeding areas might increase usual levels of mortality in winter associated with the energetic costs of feather replacement (McIntyre 1989). Along the mercury-contaminated English-Wabigoon River system in northwestern Ontario, the reproductive success of Common Loons (*Gavia immer*) was affected (reduced egg laying and nest fidelity) at levels of 0.3-0.4 ug/g (ppm) in their prey (fish and crayfish), an amount frequently observed in small fish from acidic lakes (Scheider et al. 1979*a*, Wren and MacCrimmon 1983). These levels of exposure are substantially lower than those associated with impaired hatching success and hatchling mortality in experimental studies using pheasants (*Phasianus colchicus*) (Fimreite 1971), mallards (*Anas platyrhynchos*) (Heinz 1974, 1976) and ringed turtle-doves (*Streptopelia risoria*) (Scheuhammer 1987*b*). Amounts of mercury in liver tissue of common merganser (*Mergus merganser*) ducklings in Ontario equalled 1.6-1.9 ug/g (Scheuhammer 1991), a level much higher than was observed in nonpiscivorous ducklings, but as high as amounts detected in loon chicks from Barr's (1986) study, where reproduction was impaired.

Also in acid-stressed habitats, the availability of selenium, a trace element known to ameliorate the toxicity of MeHg (Stoewsand et al. 1974), is reduced (Mushak 1985). An absence of selenium might exacerbate the toxicity of the higher-than-normal amounts of MeHg ingested with prey by piscivores on acidic lakes (Scheuhammer 1991).

The geographic extent or consequences of mercury intoxication in birds has not been assessed because of difficulties in establishing links between habitat acidity, dietary mercury, and piscivore health and reproduction in the wild. For example, although nesting eastern kingbirds (*Tyrannus tyrannus*) from an acid-stressed area near Sudbury, Ontario contained mercury in liver and feathers in amounts greater than in birds from buffered lakes (Glooschenko et al. 1986), other studies have shown that amounts of mercury in nonfledged common goldeneyes (*Bucephala clangula*) (Eriksson et al. 1989), other duck species (Scheuhammer 1991), and osprey eggs (Eriksson 1986*b*) were not substantially elevated near acidic lakes compared with non-acidic lakes. Clearly, more research is needed to assess the effects of mercury residues in prey of the appropriate types and sizes on reproductive success of birds and mammals that eat these prey in acid-stressed environments. A thorough analysis of amounts of mercury in prey sizes and types usually eaten by piscivores is required to fully evaluate risks to vulnerable species in North America.

Aluminum.--Aluminum is extremely susceptible to leaching from soil and to mobilization from lake sediments under acidic conditions. The chemistry of aluminum in acidified waters, however, is so complex that a straightforward relationship between acidity and the contamination of particular prey species is unlikely (Campbell and Stokes 1985). Elemental aluminum is not very toxic to birds, thus it is unlikely that amounts of dietary aluminum would be harmful to birds with normal nutrition (Scheuhammer 1991). Although aluminum is highly toxic to fish (Baker and Schofield 1982), it does not accumulate in the flesh of fish, mammals, or birds. This suggests that fish-eating birds probably are not at risk from increased exposure to aluminum at low pH (Scheuhammer 1991). Invertebrates can accumulate relatively high amounts of aluminum, but no evidence exists that there is a relation between amounts in various insects (e.g. chironomids, caddisflies, stoneflies, and mayflies) and the pH of water they inhabit (Sadler and Lynam 1985, Ormerod et al. 1988), despite much higher aqueous aluminum concentrations in acidic lakes and streams.

Insectivorous birds that feed in aquatic environments may be exposed to dietary aluminum at levels known to cause significant biological effects. It was implicated as a cause of reproductive impairment in birds breeding beside acidic lakes in Sweden. Nyholm and Myhrberg (1977) reported reduced eggshell quality and hatching success, lower clutch size, and increased female mortality in pied flycatchers and other flycatchers (Tyrannidae) nesting near a remote acid-stressed lake. Aluminum obtained from aquatic insect prey was implicated (Nyholm 1981) even though levels of essential elements, such as calcium and phosphorous, were not measured in insects emerging from the lake. The gross abnormalities reported by Nyholm (1981) have not been observed in similar studies elsewhere (Glooschenko et al. 1986, Blancher and McNicol 1988, Ormerod et al. 1988). Several researchers (Carriere et al. 1986, Glooschenko et al. 1986, Blancher and McAuley 1987, Longcore et al. 1987, Scheuhammer 1987*b*, Ormerod et al. 1988) have suggested that a scarcity of essential calcium in acidified environments may produce eggshell deformations and cause reduced hatchling growth, as a consequence of disruptions in normal calcium availability and metabolism, rather than the secondary effect of increased aluminum accumulation suggested by Nyholm (1981). A reduced intake of essential minerals, such as calcium, combined with exposure to nonessential metals (aluminum, cadmium, lead) can enhance the absorption and toxicity of metals (Washko and Cousins 1977, Carlson and Nielsen 1985). Interference with dietary absorption and normal metabolism of calcium and phosphorus by aluminum, which leads to bone abnormalities and impaired growth, has been observed in animals (Street 1942, Storer and Nelson 1968). However, almost all toxicological studies that have investigated the physiological and reproductive effects of nonessential dietary metals in birds have employed diets with super-adequate amounts of calcium and phosphorus. It is probable that significant effects of nonessential metals have been masked in previous studies that employed high-calcium feeds as the basal diet. Controlled experiments with breeding birds have documented that dietary aluminum can affect reproduction in birds when amounts approach concentrations of calcium and phosphorus in the diet (Carriere et al. 1986, Sparling 1990). Breeding birds, especially females that require calcium for egg-laying, accumulate certain metals from their diet more efficiently when calcium in the diet is low (Scheuhammer 1991). Recently, Sparling (1990) investigated the role of dietary levels of aluminum, calcium, and phosphorus on growth and survival of captive black duck and mallard ducklings. Both species had stunted growth and high rates of mortality, along with signs of aluminum toxicosis (Al > 50% dietary P levels), even when calcium and phosphorus levels approximated recommended amounts in the diet. Black ducks were more sensitive to these treatment diets than mallards were. Empirical data relating dietary levels of aluminum, cadmium, and lead to substantial impairment of reproduction in birds when calcium or phosphorus are low, are needed.

Other Metals (Cadmium and Lead).--Studies of chronic, low-level dietary toxicity of cadmium and lead in birds are few (Scheuhammer 1991). Although fairly low amounts of these elements in foods can be disruptive to normal physiology of birds and produce significant reproductive dysfunction, Scheuhammer (1991) concluded that exposure to cadmium and lead from acidification is sufficiently low that harm to avian health and reproduction is unlikely.

Ecological Effects

The principal risk of airborne pollutants to birds is probably from the long-term deterioration of habitat and disruption of food webs, rather than from direct toxic or even chronic effects of acids or metals mobilized by acidification. Increasing evidence indicates that the most significant effects of acidification on birds is through indirect effects on quality and quantity of food organisms, particularly during breeding. Indirect effects are defined as changes in a population not related to direct toxicity to 1 or more life stages of a species (e.g. the selective mortality of acid-sensitive species in the prey community may or may not be accompanied by an increase in acid-tolerant species). In the following sections, we review the evidence for ecological effects of acidification on aquatic birds related to the disruption of food webs, and further discuss the risk of similar indirect effects of acidification on forest birds.

Modification of Food Webs of Aquatic Birds.--Although increasing evidence that indirect effects, such as changes in food-web structure within lakes, can occur rapidly during both acidification and recovery of lakes (Eriksson et al. 1980, Schindler et al. 1985, Mills et al. 1987, Stenson and Eriksson 1989), most documented changes in aquatic biota during acidification have been linked to direct acid toxicity (low pH or exposure to metals) to 1 or more life stages of individual species. Most early records of biological damage arose from large-scale synoptic surveys conducted in the few heavily acidified areas of North America and Scandinavia, and focused primarily on water chemistry and damage to adult sport fish at pH values below 5.5 (Harvey and Lee 1982). Laboratory bioassays and whole lake acidification experiments have been conducted in the United States (i.e. Little Rock Lake in Wisconsin; Brezonik et al. 1986, Watras and Frost 1989), in the United Kingdom (a stream in Wales, McCahon and Pascoe 1989), and in Canada (i.e. 3 lakes in Ontario; Schindler 1988) and clearly link acidification with acute toxicity to fish population declines. Further evidence from bioassays, field surveys, and whole ecosystem experiments have shown that many of the forage fishes (e.g. several members of the the minnow family, Cyprinidae) and many organisms lower in the aquatic food web (algal, zooplankton, and benthic communities) have been shown to be sensitive to pH (NAPAP 1991). Impaired reproduction and reduced numbers of fish, amphibians, and some groups of invertebrates, including some aquatic insects (primarily mayflies, caddisflies, and stoneflies), amphipods, crayfish, snails, clams, and leeches, have been documented in acid-stressed systems in eastern North America and elsewhere (Eilers et al. 1984, Raddum and Fjellheim 1984, Schindler et al. 1985, Mills and Schindler 1986, Okland and Okland 1986, Freda 1991). Loss of organisms begins when the pH of lakes falls below 6.0. Because relatively higher numbers of invertebrate taxa are sensitive to acidification, detrimental effects on food chains may occur well before direct toxicity to adult fish is evident (Schindler et al. 1989).

Current evidence indicates that the number of aquatic taxa in an ecosystem usually declines with increasing acidity (Eilers et al. 1984, Mills and Schindler 1986, Stephenson and Mackie 1986). Often the ecological niche of the taxa is lost as a result of acidity (e.g. *Hyalella azteca*, France and LaZerte 1987) but the loss is compensated by an increase in numbers of acid-tolerant species, resulting in little or no depletion of overall biomass (Eriksson et al. 1980, Dixit and Smol 1989). Nonetheless, the impoverishment of a biotic community may destablize it (Schindler et al. 1989), and can have detrimental effects on food webs supporting predatory fish and aquatic birds. Many waterbirds use high-protein, mineral-rich foods, particularly small fish and aquatic invertebrates for egg production (Swanson and Meyer 1973) and for rapid growth of young (Reinecke and Owen 1980), and are consequently subjected to large changes in the makeup of aquatic prey communities during acidification. New species assemblages may not be suitable replacements for the original food web and, in extreme instances, entirely new food webs appear in acidified lakes with top positions occupied by predatory insects, rather than fish (Henrikson et al. 1980).

The importance of fish as a key group influencing the trophic structure of fresh waters has received increased attention as a result of the acid-precipitation phenomenon (Eriksson et al. 1980, Nilssen et al. 1984). Many of the current ideas concerning the effects of acidification on waterbirds are based on our knowledge of the interactions among fish, invertebrates, and the abiotic envrionment. Research on the effects of predation by fish on the structure of invertebrate communities has shown that some members of the fish community compete with birds for the same species of invertebrate prey. Birds (waterfowl, shorebirds, and many passerines) feeding on aquatic invertebrates and those (flycatchers, swallows, goatsuckers, blackbirds, warblers, and waxwings) feeding on flying insects that have aquatic larval stages are competing to some extent with fish (Blancher and McAuley 1987). Conversely, a healthy, diverse, and abundant supply of fish is an important source of food for the young of many fish-eating species (e.g. loons, mergansers, herons, bitterns, terns, ospreys, eagles, kingfishers).

Although the effects of acidification on avian predators of fish and invertebrates are still poorly understood (Stenson and Eriksson 1989), increasing evidence suggests that changes in food-web structure can occur during acidification and may have pronounced effects on waterbirds. Changes in the composition, abundance, and nutritional value of aquatic prey communities can affect the choice of habitat for feeding and nesting by birds, and can have a negative effect on avian breeding success (Eriksson 1984, DesGranges and Rodrigue 1986, Ormerod and Tyler 1987, Alvo et al. 1988, Blancher and McNicol 1988, McAuley and Longcore 1988*a*, McNicol et al. 1990). The ultimate effect of decreasing pH on avian predators may vary with the severity of acidification and with foraging habits of the species.

Modifications to aquatic food chains that affect wetland birds fall more or less into 3 catgories: decreases (or increases) in the abundance of prey, decreased diversity of prey, and decreased quality of prey.

Birds that specialize on acid-sensitive prey (e.g. certain fish, molluscs, mayflies, some caddisflies, dragonflies, leeches, and crustaceans) find diminished prey at low pH. Because of their reliance on a healthy and abundant supply of fish as food for their young, many fish-eating birds are threatened by the effects of acidification on fish populations (Haines 1981, Longcore et al. 1987, Wiener 1987). The effect of reduced fish populations on fish-eating birds that use acidifying waterbodies seems to depend on the birds' foraging behavior and ability to use alternate, acid-tolerant prey.

Eriksson (1985, 1986*a*, 1987) argued that increased abundance of aquatic insects, coupled with increased water clarity under acid conditions, would initially compensate for reduced densities of fish. Pursuit divers (e.g. Arctic loons (*Gavia arctica*) and mergansers (*Mergus* spp.) might benefit from clear water wherein they could search a larger volume of water per unit of time spent foraging. In Sweden, adult Arctic loons eat almost entirely fish that they pursue underwater, but they initially feed insects to their young and can successfully raise chicks on fishless lakes (Bergman and Derksen 1977). In contrast, those species that catch fish near the surface of the water, such as ospreys (*Pandion haliaetus*), kingfishers (*Ceryle alcyon*), and common terns (*Sterna hirundo*), do not benefit from increased water clarity and must spend proportionately more time foraging to catch fewer available fish (Eriksson 1987). In parts of Sweden, fishing success of ospreys has declined, which has led to an increased risk of nestling mortality from lower rates of food delivery to the nest (Eriksson 1986*b*).

In North America, acid-rain studies of piscivorous birds have concentrated largely on pursuit divers, including the common loon (*Gavia immer*) and common merganser (*Mergus merganser*). Small, forage fish, including minnows, are preferred prey of these birds (Barr 1973, McNicol et al. 1987*c*), and are reduced in abundance or absent in acidic lakes (Mills and Schindler 1986, McNicol et al. 1987*a*, Parker 1988). Both Parker (1985) in the Adirondack Mountain region of New York state and McNicol et al. (1987*b*) in northern Ontario examined the fish prey base for piscivores breeding over a range of pHs and reported reduced species richness, reduced density and biomass of fish, and a greater proportion of acid-tolerant species (e.g. non-cyprinids, such as yellow perch) in acidic lakes. In Ontario, common merganser ducklings fed primarily on cyprinids, and were raised successfully only on those lakes where fish were present and where the pH was greater than 6.0 (McNicol et al. 1990). These results suggest that merganser chicks were not able to sustain normal growth and development on acidic lakes (pH <6.0) even by switching to nonfish prey, including acid-tolerant invertebrates.

Common loons require large numbers of fish to feed their young during the 2-3 months that the chicks remain on their natal lake (Barr 1973, Kerekes 1990). A reduced supply of fish in acidic lakes has been implicated in causing reduced foraging efficiency of adult loons observed by Alvo (1985) and Parker (1985), and may have contributed to difficulties of adults in raising young to fledging in eastern Canada (Alvo et al. 1988, Kerekes 1990, Wayland and McNicol 1990). In certain situations, adult loons may compensate for the diminishing fish resource at pH 6.0-5.0 by increasing their foraging effort (including transporting fish from nearby lakes), or switching to less palatable fish prey or nonfish prey (newts, tadpoles, or aquatic invertebrates). Unlike Arctic loons breeding in Scandinavia, common loons that continue to nest on highly acidic (pH <5.0), fishless lakes of the Precambrian Shield of North America are unlikely to raise chicks to fledging solely on the acid-tolerant invertebrates available there (Wayland and McNicol 1990).

A decrease in total biomass or numerical abundance of prey available to wetland birds is not a universal consequence of increased acidity (RMCC 1990). For example, riparian birds that eat insects emerging from wetlands may not be exposed to a reduction in total biomass of insect prey at low pH (Glooschenko et al. 1986, St. Louis et al. 1990, Blancher and McNicol 1991). The loss of acid-sensitive prey generally results in an increased abundance of more acid-tolerant species that benefit from the lack of competition or predation under acidic conditions. Invertebrate food webs of acid lakes often are less diverse and, if fish are absent, are dominated by certain benthic (some odonates) and nektonic (notonectids, corixids, and dytiscids) invertebrates (Eriksson et al. 1980, Bendell and McNicol 1987). In certain situations (e.g. acidic, fishless waters), these insects replace fish as top predators of the food web, and thereby partly compensate for the loss of acid-sensitive invertebrates. Several studies have examined competition between fish and breeding waterfowl for invertebrate foods (Eriksson 1979, 1983, Eadie and Keast 1982, Pehrsson 1974, 1984, Hunter et al. 1986*b*). For some insect-eating birds, feeding conditions can improve when fish disappear as wetlands acidify (generally below pH 5.0). Several species, the common goldeneye in particular, exploit insect prey that proliferate in acidic, fishless wetlands (Eriksson 1984, Hunter et al. 1986*b*, McNicol et al. 1987*c*). Yet, some diving ducks and most dabbling ducks are poorly adapted to exploit the increased availability of highly-mobile insects because of their bill form and feeding habits (Eriksson 1987, McNicol et al. 1987*b*, McAuley and Longcore 1988*b*).

A more general result of acidification is a reduction in species richness of aquatic organisms (Ford 1988). Several invertebrate taxa--notably molluscs (Gastropoda), crustaceans (Amphipoda), leeches (Hirudinea), mayflies (Ephemeroptera), and some species of water striders (Gerridae), caddisflies (Trichoptera) and damselflies and dragonflies (Odonata), and Cladocerans--are sensitive to acidification and become scarce or disappear between pH 6.0 and 5.0 (Havas and Hutchinson 1982, Eilers et al. 1984, Raddum and Fjellheim 1984, Ormerod and Tyler 1986, Bendell 1988, Bendell and McNicol 1991). Birds that specialize on acid-sensitive prey are particularly vulnerable. For example, the Eurasian dipper (*Cinclus cinclus*), an exclusively riverine species, feeds heavily on acid-sensitive mayfly nymphs and caddisfly larvae from streams where the dippers breed (Ormerod 1985, Ormerod et al. 1987*a*). In acid streams, where fewer of these prey are available, dipper nestlings are fed less often than nestlings on non-acid streams, resulting in slower growth and poor survival (Ormerod and Tyler 1987, Omerod et al. 1987*b*).

For many waterbirds that breed on or near acidifying wetlands, invertebrate foods may be particularly scarce between pH 6.0 and 5.0 after many acid-sensitive invertebrates have been lost, but when fish still inhabit the lakes. Until the acidity reduces or eliminates fish, they will continue to compete with ducks and other waterbirds for the remaining invertebrates (DesGranges and Rodrigue 1986). Insectivorous waterfowl, for example, may find low amounts of food at these moderate pH levels because they must compete with the remnant fish populations for the same depleted prey resource and are nutritionally dependent on a few acid-tolerant taxa (DesGranges and Hunter 1987, McNicol et al. 1987*a*). In Ontario, waterfowl that ate acid-sensitive prey at high pHs encountered a diminshed prey resource at low pH (B. E. Bendell and D. K. McNicol, unpubl. ms.). An acidity-related reduction in the types of prey eaten also has been observed for young ring-necked ducks (*Aythya collaris*) in Maine (McAuley and Longcore 1988*b*), and tree swallows (*Tachycineta bicolor*) nesting near acid wetlands in Ontario (Blancher and McNicol 1991). A reduced diversity in the diet of birds feeding on or near acid lakes can cause reproductive effects if the likelihood of prey shortage is increased at any time, or if the remaining prey are of relatively poor nutritional quality (Blancher 1991).

Some evidence suggests that ducklings that rely on insects are adversely affected at pH's that still support fish competitors. Experimental studies using imprinted young black ducks revealed that competition from fish can slow growth of ducklings and decrease foraging efficiency (DesGranges and Rodrigue 1986, Hunter et al. 1986*a*), particularly under acidic conditions (DesGranges and Hunter 1987, Haramis and Chu 1987). Suppressed phytoplankton and algal growth, and reduced invertebrate biomass were reported on artificially acidified wetlands where duckling growth, physiological condition, and survival were affected (Rattner et al. 1987).

Irrespective of their abundance and diversity, the nutritional quality of available prey may be adversely affected when an essential dietary element becomes limited as a result of acidification. For example, the caloric content of invertebrates may be reduced at low pH (Raddum and Steigen 1981). As lakes acidify, the reduced availability of essential minerals, particularly calcium and phosphorous, may adversely affect avian reproduction or growth of young.

An adequate supply of dietary calcium is crucial during reproduction in birds for proper formation of eggshells and skeletal growth of hatchlings (Greely 1962, Chambers et al. 1966, Dean et al. 1967). Fish-eating birds can obtain calcium from the bones of fish (when available), but other birds must supplement their diet with high-calcium foods. Wild birds actively select high-calcium grit and foods before and during egg-laying (MacLean 1974, Jones 1976, Ankney and Scott 1980). Mineral-rich foods, especially those with a highly calcified shell or exoskeleton (e.g. snails, clams, crayfish, and amphipods), are particularly sensitive to acidification, and are often among the first taxa to disappear (Eilers et al. 1984; Mills and Schindler 1986; Okland and Okland 1986; Scheuhammer 1991; B. E. Bendell and D. K. McNicol, unpubl. ms.). Those prey that remain may contain lower amounts of calcium than the same species found at higher pH's (Havas and Hutchinson 1983, Sadler and Lynam 1985, Yan et al. 1989). In the U.K., calcium levels in 2 insect orders (stonefly nymphs [Plecoptera] and caddisfly larvae [Trichoptera]) increased significantly with pH (Ormerod et al. 1988), a result also measured in whirlygig beetles (Gyrinidae) taken from Ontario lakes (Scheuhammer 1991).

Calcium requirements of growing young and egg-laying birds (0.5% Ca, dry wt.) are in excess of values typically found in invertebrates from acid wetlands (0.1-0.5%) (Scheuhammer 1991), thereby forcing birds to obtain these prey elsewhere or do without. Tree swallows nesting near circumneutral wetlands in Ontario often brought to their nestlings calcium-rich foods and grit, including fish bones, crayfish exoskeleton, and clam and snail shells. But they rarely brought these items to nests near acid wetlands, where proportionately more dipterans and terrestrial insects were used (Blancher and McNicol 1991, St. Louis and Breebaart 1991). Limits to the amount of dietary calcium available in prey from acidic environments may contribute to reduced clutches and decreased growth of birds near acidic waterbodies (Glooschenko et al. 1986, Vickery 1989, Ormerod et al. 1991, Blancher and McNicol 1991). Again, studies of the Eurasian dipper show reduced levels of serum calcium in adults and nestlings, thinner eggshells, and reduced clutch size and nestling growth where the dippers nested along acidic streams (Ormerod and Tyler 1987; Ormerod et al. 1988, 1991). Sparling (1990) observed that pen-reared black duck and mallard ducklings were adversely affected when raised on treatment diets low in calcium and phosphorus or low in calcium and high in phosphorus, and noted further that elevated aluminum levels, interacting with low calcium and phosphorus, increased mortality and further retarded growth among black ducks. The toxicological importance of increased amounts of nonessential metals in prey eaten by birds at low pH, as a function of the reduced intake of dietary calcium, was discussed in the **Toxicological Effects** section of this paper.

Habitat Selection by Waterbirds.--Many variables influence the distribution and density of breeding birds, including the quality of nesting habitat and fidelity to natal breeding lakes. Lake acidity is important in determining the quality of nesting and brood-rearing habitat for many waterbird species (Ormerod and Tyler 1987, DesGranges and Houde 1989). Acidification of forest ponds, streams, and lakes affects availability of food organisms, but also may alter aquatic plant communities used as food, cover, or nesting sites for a variety of birds (Haines and Hunter 1982, Hansen 1987). With the exception of the study of DesGranges and Houde (1989), acid rain studies have ignored the importance of aquatic plant communities in the selection of breeding habitats by birds in acidic environments. Many lakes and wetlands that are important breeding areas for waterbirds are also vulnerable to acidification. Longcore et al. (1987) evaluated the potential effects of acidification and its severity on several migratory bird species common in eastern North America. A sizeable portion (17%) of the breeding range of those species coincided with areas sensitive to acidification. In Ontario, nearly 1/2 of the estimated 373,000 pairs of ducks and loons on the Precambrian Shield (6 species only) nest in areas exposed to acid deposition (McNicol et al. 1990).

The distribution in summer of many birds often reflects the quality of breeding habitat, as measured by the availability of preferred prey. Birds whose prey (principally fish and certain acid-sensitive invertebrates) are reduced by acidification, breed at lower densities around acidic waterbodies. For example, local declines in dipper populations have been recorded in parts of Britain and West Germany (Kaiser 1985, Ormerod and Tyler 1987). The abundance of breeding dippers along streams in Wales is strongly correlated with pH, a result of selection for streams with a high abundance of acid-sensitive invertebrates (Ormerod et al. 1985, 1986). An historical decline in dippers along the River Irfon was associated with a decline of 1.7 pH units between the late 1960s and 1984.

Some fish-eating birds also breed in lower densities in acid-stressed areas (Table 2). Fewer ospreys now breed in areas of Sweden with many acid lakes (Eriksson 1986*b*), whereas fewer kingfishers have been reported on acid streams than on non-acid streams in upland Wales (Goriup 1989). Loss of fish from acid lakes also may be responsible for the decline in numbers of loons and mergansers observed in Sweden (Almer et al. 1974, 1978). In southern Quebec, common loons avoid acidic lakes (DesGranges and Darveau 1985, DesGranges and Houde 1989), whereas in Ontario, fewer loon and merganser broods were produced relative to the number of nesting pairs in an acid-stressed area than in an unaffected area (McNicol et al. 1987*a*). In Wisconsin, Blair (1990) reported that loons occupied large, clear, deep lakes of low productivity, similar to those observed in Ontario (McNicol et al. 1987*a*, Alvo et al. 1988, Wayland and McNicol 1990), in Quebec (Desgranges and Houde 1989), and in New York (Parker 1988). Blair argued that his study lakes were often strikingly similar (i.e. clear water) to lakes that were acidified and he suggested that loons may be mistakenly identifying acidified lakes as preferred lakes on the basis of physical characteristics (depth and water clarity). Loons have attempted to nest and raise young on acidified lakes (Alvo et al. 1988, Parker 1988, Wayland and McNicol 1990), although food may be limited.

Conversely, comparative studies of acid and non-acid waterbodies (Pehrsson 1974, Hunter et al. 1986*b*) have shown that the increased insect abundance in the absence of fish might attract certain waterfowl. The inverse relationship between the presence of fish and the use of waterbodies by oldsquaw (*Clangula hyemalis*) (Pehrsson 1974) and common goldeneyes (Eriksson 1979, 1983; Eadie and Keast 1982; McNicol et al. 1987*a*) might explain the increased density of breeding goldeneye observed on acid, fishless lakes in Canada (DesGranges and Darveau 1985, McNicol et al. 1987*c*, 1990).

The distribution of most bird species in riparian areas of lacustrine communities during the breeding season did not seem to be affected by the degree of soil mineralization and acidity (DesGranges and Houde 1989). The pH of wetlands was usually acidic (<5.0) because of organic acids, but most riparian species did not seem affected. Instead, distribution of major families (Charadriidae, Scolopacidae, Tyrannidae, and Emberizidae) were related to habitat physiognomy (i.e. vegetational structure). The authors cautioned that further acidification of riparian habitats in southern Quebec might influence breeding distribution of species that prefer habitats with neutral soils, e.g. common yellowthroat (*Geothlypis trichas*).

Reproductive Performance of Waterbirds.--Few detailed studies of the effects of wetland acidity on avian reproduction have been undertaken. Blancher and McAuley (1987) noted that reproductive success of birds with a variety of feeding habits and niches, including divers, surface feeders, aerial flycatchers, piscivores, and insectivores was adversely affected by wetland acidity (Table 2). For those birds that do breed on or along acidified lakes and streams, reproductive consequences are commonly associated with reduced food abundance, availability, or quality (Blancher and McAuley 1987). Decreased clutch size, thinner eggshells, later breeding, fewer second clutches, smaller young with poorer growth and lower survival, decreased foraging efficiency, and poorer overall reproductive success are among the costs noted for various species (Table 2). Relation between acidity and avian reproductive parameters, however, is often obscured by other variables, such as competition with fish, predation, and species variability. Such inherent variability, coupled with poor experimental designs and inadequate sample sizes, has contributed to the apparent contradictory results among different studies.

For example, loon reproduction may be either unaffected (Arctic loons, Eriksson 1987; common loons, Parker 1988) or lowered (McNicol et al. 1987*a*, Alvo et al. 1988, Wayland and McNicol 1990) on acid-stressed lakes. The effect of reduced fish populations in acidic lakes on some fish-eating birds (especially diving species) depends on whether increased water clarity (which can enhance capture of fish by birds) and decreased fish predation on chicks and on invertebrate prey of small chicks, can compensate for the decreased density of fish prey (Eriksson 1987). For common loon pairs, the ability to successfully fledge 2 chicks on acid-sensitive lakes may be severely compromised by an inadequate supply of suitable fish prey as lakes acidify (McNicol et al. 1987*b*, Kerekes 1990, Wayland and McNicol 1990). Others (Barr 1973, 1986) have linked poor reproduction by loons to elevated levels of mercury in fish prey (see earlier section). The reality of mercury contamination in fish may have serious consequences for those loons that continue to breed in acid-sensitive areas of eastern North America (Alexander 1987, McIntyre 1989). Other piscivores also suffer when fish stocks are reduced or disappear. In Ontario, nearly fledged common mergansers were found only on lakes containing fish and where the pH was greater than 6.0. In Sweden, ospreys (a surface-plunging species) breeding in areas with many acidic lakes had reduced productivity (Eriksson et al. 1983).

Among insect-eating birds, dippers have shown impaired breeding performance along acid streams in Wales and Scotland, probably as a result of impoverished food supplies (Ormerod and Tyler 1987, Ormerod et al. 1988, Vickery 1989). In Ontario, a negative influence of wetland acidity was observed on several aspects of tree swallow reproduction, including investment in eggs by laying females, size and growth

Table 2. Studies[a] that either did (Yes) or did not (No) yield evidence that acidic deposition affected certain species of birds.

Species	Diet/ Foraging		Breeding Distribution		Reproductive Measures		Reference[a]
	Yes	No	Yes	No	Yes	No	
Common loon	x		x	x	x	x	1-3, 22-24
Arctic loon						x	4
Common merganser			x		x		5, 22
Belted kingfisher			x				6
Osprey	x		x		x		7, 8
Black duck	x		x		x[b]		9-12
Common goldeneye			x[b]				5, 10
Ring-necked duck	x				x		13, 14
Eurasian dipper	x		x		x		15-17
Eastern kingbird				x	x		18
Tree swallow	x			x	x		19-21

[a] 1 = Alvo et al. 1988; 2 = Parker 1988; 3 = Wayland and McNicol 1989; 4 = Eriksson 1987; 5 = McNicol et al. 1987*b*; 6 = Goriup 1989; 7 = Eriksson et al. 1983; 8 = Eriksson 1986*b*; 9 = Hunter et al. 1986*a*; 10 = DesGranges and Darveau 1985; 11 = Rattner et al. 1987; 12 = Haramis and Chu 1987; 13,14 = McAuley and Longcore 1988*a,b*; 15,16 = Ormerod et al. 1985, 1986; 17 = Ormerod and Tyler 1987; 18 = Glooschenko et al. 1986; 19,20 = Blancher and McNicol 1988, 1991; 21 = St. Louis et al. 1990; 22 = Blancher et al. 1991; 23 = DesGranges and Houde 1989; 24 = Blair 1990.

[b] The effect was beneficial.

of nestlings, and number of fledglings produced (Blancher and McNicol 1988). Both the foraging behavior of adult tree swallows and the diet of nestlings varied markedly in relation to the acidity of the lake near where the birds nested (St. Louis et al. 1990, Blancher and McNicol 1991). The inadequacy of emerging and other available insect prey over and around acidic wetlands was implicated in the reduced breeding success.

Insectivorous waterfowl may have higher or lower reproductive success at acid sites, depending on whether the wetlands retain fish populations. Black duck (*Anas rubripes*) reproductive success has been reported as equal to or better on acid, fishless wetlands compared to higher pH wetlands with fish (DesGranges and Rodrigue 1986, Hunter et al. 1986*b*), presumably because reductions in acid-sensitive prey are partly offset by an increase in other prey when competing fish populations are reduced or eliminated. In studies where fish status among lakes did not differ or was experimentally controlled, lake acidity had a negative effect on waterfowl reproduction (DesGranges and Rodrigue 1986, Haramis and Chu 1987, Rattner et al. 1987, McAuley and Longcore 1988*a*). These studies showed that the growth, feeding behavior and survival of ducklings of several species, including black ducks, goldeneyes, and ring-necked ducks, was markedly altered on acidified wetlands compared to controlled sites or wetlands with higher pHs. In Ontario, the common goldeneye, a species that prefers fishless lakes, fledged fewer young per breeding pair on acid, fishless lakes (pH <5.0) compared with naturally-fishless lakes (pH >6.3) (McNicol et al. 1990). An attempt to model effects of acidification on waterfowl is presented in Blancher et al. (1992).

Although competition with fish has been a complicating factor in many studies, it does not nullify the overall negative relationship often observed between acidity and duckling growth and survival (DesGranges and Hunter 1987). Unfortunately, present data do not permit clearly distinguishing the relative importance of lake productivity (nutrient levels), acidity, and competition with fish to waterbird reproductive success. Yet, it is clear that a significant reproductive cost may be associated with raising young on or near systems (rivers, streams, wetlands, and lakes) whose food web has become increasingly simplified and nutritionally diminished as a combined result of the loss of acid-sensitive invertebrates, and the proliferation of a few, acid-tolerant taxa in the absence of fish. The worst situation for insect-eating birds would undoubtedly arise at pHs just high enough to support fish (DesGranges and Hunter 1987, McNicol et al. 1987*b,c*). Such wetlands are likely to be more numerous throughout the acid-sensitive terrain of eastern North America than those that have been acidified to the point of losing all fish populations.

Changes in Soil pH and Invertebrates. --The effects of acid precipitation on wildlife that inhabits terrestrial environments is poorly documented compared to effects on organisms in aquatic habitats. Various invertebrate taxa (e.g. beetles, earthworms, millipeds, lepidopteran larvae), however, are less abundant in declining forests (DesGranges et al. 1987, Schreiber and Newman 1988) or in acidic soils (Read et al. 1987). Although research and debate continue, it is evident that many diverse terrestrial habitats, including forests in eastern North America, have been affected by acid deposition with associated adverse effects on avian communities. Loss of habitat or change in habitat structure especially affects specialist species (i.e. species with narrow diet or habitat requirement), which are ill-prepared to adapt to altered environments (Table 1) (Schreiber and Newman 1988). Certain amphibians (e.g. red-backed salamander [*Plethodon cinereus*]) are adversely affected by reduced soil pH (Wyman and Hawksley-Lescault 1987), whereas other species may be restricted in terrestrial habitats because of effects of low pH on larvae in aquatic habitats (Freda 1986). Changes in abundance of prey might affect predator numbers and thus modify invertebrate communities, especially decomposer food webs, similar to those observed in aquatic habitats (Eriksson et al. 1980).

One avian species that might be especially affected through the food chain in the terrestrial environment is the American woodcock (*Scolopax minor*), which feed mostly on earthworms (Lumbricidae) (Mendall and Aldous 1943, Sheldon 1971, Miller and Causey 1985). In the northern part of their range (Reynolds, 1977*a*), woodcock eat primarily 3 species of earthworms: *Aporrectodea tuberculata* (= *A. caliginosa*; Easton 1983), *Dedrobaena octaedra*, and *Lumbricus rubellus* (Reynolds 1977*a*). In the southern part of the range the assemblages of earthworms important to woodcock are unknown (MacDonald 1983). Further, woodcock eat about 150 g per day of food, which equals or exceeds the body weight of a male woodcock (Mendall and Aldous 1943, Sheldon 1971). Many earthworm species prefer a soil pH of 7.0 and are sensitive to hydrogen-ion concentration (Bodenheimer 1935). Thus, pH of soil can limit distribution, numbers, and species in any particular soil (Reynolds 1971, 1977*b*; Edwards and Lofty 1972, Hagvar 1980, Kuperman 1990, Ma et al. 1990, Esher et al. 1992, Esher et al. in press). Although some species tolerate low pH, including *Dedrobaena octaedra* (Borenbusch 1930, Satchell 1955), others, such as *A. tuberculata*, which must be considered the most important contributor to the woodcock energy budget, are acid-intolerant (Satchell 1955). Earthworms are extremely important in decomposition of plant organic matter and in soil formation, yet they also are repeatedly exposed in many ways to toxic chemicals from forestry and agricultural uses (Edwards and Bohlen 1992). Any additional effects of acidic deposition that lowers soil pH and reduces earthworm abundance might affect woodcock and a multitude of amphibians, reptiles, mammals, and birds (MacDonald 1983), which eat substantial numbers of earthworms.

EFFECTS ON AMPHIBIANS AND REPTILES

Many species of amphibians are known to be sensitive to increased acidity and the toxic metals associated with acidified environments (Tome and Pough 1982, Clark and Hall 1985, Freda 1986, 1991). As for other aquatic organisms, reproductive failure is the major effect of acidic water on amphibians. Most species require water for oviposition and larval development, although adults are either aquatic, semi-aquatic, or terrestrial. Early investigations of toxic properties of acidic waters considered only pH, e.g. Pough (1976) reported that survival of spotted salamanders (*Ambystoma maculatum*) in meltwater ponds was reduced when pH was below 6.0. Additional field surveys (chemical and biological) of breeding habitats of amphibians, coupled with laboratory bioassays, have shown that acidic pond water can affect reproduction of amphibians by causing mortality of embryos and larvae (Pierce 1985, Freda 1986). Critical pH for egg and larval survival for most amphibian populations is below

5.0, making them less sensitive to acidity than many species of fish and aquatic invertebrates (Blancher 1991).

While ontogenetic variation in acid tolerance is large, amphibian embryos are generally more susceptible to low pH than are larvae. Mortality occurs primarily because of inhibition of hatching; critical pH levels for embryos vary among species, but usually are below 5.0 (Freda and Dunson 1985, Clark and LaZerte 1985). This sensitivity is particularly important for species that breed in early spring because embryos will probably be exposed to the most extreme pH then (Freda and Dunson 1985). Direct mortality of larvae has been observed following severe pH depressions associated with episodic rainfall or snowmelt (Gascon and Bider 1985). After hatching, however, tolerance to acidity increases throughout larval development (Pierce et al. 1984, Clark and Hall 1985, Freda and Dunson 1985), although chronic exposure to water of sub-lethal pH can lead to reduced rates of larval growth (Freda and Dunson 1985, 1986). Newly-hatched tadpoles are more sensitive than embryos to aluminum (Clark and Lazerte 1985, Freda and McDonald 1990), although toxicity of aluminum to amphibians is highly dependent on pH of water (Freda 1991). The combination of low pH and high levels of aluminum may have a synergistic, negative effect (Andren et al. 1988). Adults seem to be the most acid-tolerant life stage, presumably because they are predominantly terrestrial except during the breeding season, thus, are not exposed to continous contact with an acidic environment. Acidity, however, does influence the selection of habitats by some species; adult salamanders can detect gradients of substrate acidity and select neutral substrates instead of acidic ones (Mushinsky and Brodie 1975).

A variety of habitats are used by amphibians for breeding, including temporary and permanent ponds, ombrotrophic bogs, lakes, rivers, small streams, and even forest soils, which are occupied by terrestrial salamanders. Most amphibian breeding sites are small ponds that are low in buffering capacity and humic in nature, which confounds the contribution made by natural (organic) versus anthropogenic sources of acidity. Pough and Wilson (1977) estimated that 1/2 the species of frogs and toads in the United States, and 1/3 the aquatic salamanders breed in temporary ponds. In Canada, among 16 of 17 amphibian species more than 50% of each of their ranges overlap with areas affected by acid precipitation (Clark 1992); more than 1/2 of these species breed in temporary ponds. These habitats are formed largely from acidic water during spring snowmelt and from run-off during rainstorms (Clark and Euler 1982), which results in pH levels below those in nearby lakes and permanent ponds (Pough and Wilson 1977, Dale et al. 1985, Freda and Dunson 1985). Whereas data on the chemistry of temporary or permanent ponds is limited, Freda (1986) reported that 5 to 81% of ponds surveyed in several studies had a pH under 5.0, within the critical pH range of many species. Further episodic declines in pH in these ponds following snowmelt or rainfall may have dramatic effects on amphibian reproduction.

The reduction in recruitment associated with acidification of ponds affects both the local distribution and abundance of amphibians. With some exceptions, regional surveys of amphibians typically show an avoidance of the most acidic habitats for breeding (Freda 1986). In the United States and Europe, several studies have documented reduced amphibian populations in acidic habitats (Gosner and Black 1957, Mushinsky and Brodie 1975, Cooke and Fraser 1976, Saber and Dunson 1978, Strijbosch 1979, Freda and Dunson 1986, Leuven et al. 1986). Gosner and Black (1957) were the first to report an association between a species' tolerance to low pH and its abundance in naturally acidic ponds in the New Jersey Pine Barrens. Later, Pough (1976) reported that anthropogenically caused declines in pH of ponds were adversely affecting *Ambystoma* salamanders in New York. Albers and Prouty (1987) in Maryland stated that neither the number of egg masses nor the survival of embryos of spotted salamanders (*Ambystoma maculatum*) was correlated with the pH of temporary woodland ponds. In Colorado and Wyoming, Corn et al. (1989) have reported that northern leopard frogs (*Rana pipiens*) and American toads (*Bufo boreus*) have declined substantially, but losses were not linked to acidic depositions.

In Canada, amphibian surveys have been conducted in Ontario, Quebec, and Nova Scotia. In Ontario, Glooschenko et al. (1992) observed that spotted salamanders (*A. maculatum*) and leopard frogs (*R. pipiens*) were conspicuously absent in areas adjacent to Sudbury where low pH and high levels of aluminum were recorded in breeding ponds. Clark (1986*a,b*) found that absence of several species of amphibians was related to increased acidity. In Quebec, acidity and total organic carbon were correlated with the density of egg masses of wood frogs (*Rana sylvatica*) (Gascon and Planas 1986). In Nova Scotia, presence of amphibian species and chemistry of breeding sites were not correlated (Dale et al. 1985).

The partly contradictory findings from studies that depict enormous intraspecific variation in acid tolerance may result from; (a) different methods used by investigators, (b) geographic variation in acid tolerance of the same species, particularly when compared to laboratory tests (e.g. Pierce and Harvey 1987), or (c) possible evolutionary adaptations to acidic conditions (Andren et al. 1989). However, virtually all studies have focused on amphibians that breed in temporary ponds. Little information is available for species at risk in other habitats such as mountain headwater springs and seeps (Freda 1986).

Synoptic surveys have revealed that amphibian populations may be reduced in ponds where pH is not low enough to be directly toxic to embryos or larvae (Clark 1986*a,b*; Gascon and Planas 1986). Indirect effects of acidification, particularly changes in food webs of temporary ponds, may be influencing amphibian distribution, abundance, and recruitment. Benthic invertebrates and zooplankton on which larval salamanders feed and phytoplankton on which tadpoles are dependent can be dramatically affected by acidification (Haines 1981). Sublethal exposure to acidity or aluminum inhibits rate of growth of tadpoles and salamanders (Freda and Dunson 1985, 1986; Cummins 1986), which ultimately may affect the outcome of competitive and predatory interactions that are strongly influenced by body size (Wilbur 1984). Whereas fish are capable of reducing amphibian populations in non-acidified waters (Macan 1966), the new top predators in acidified waters without fish (i.e. Odonate larvae, Dytiscidae, Notonectidae, Corixidae, and newts) may consume large numbers of the vulnerable life stages of certain species, depending on palatability (Henrikson 1990).

Few data are available on effects of soil acidity on the distribution of terrestrial amphibians (Vernberg 1955, Mushinsky and Brodie 1975), especially data on tolerance of adult or terrestrial juvenile life stages to acidic conditions. A study in New York revealed that eastern red-backed salamanders (*Plethodon cinereus*) avoid soils with a pH below 3.7 (Wyman and Hawksley-Lescault 1987), a finding that was consistent with laboratory trials that depicted chronic effects of pH between 4.0 and 3.0 on growth of juveniles. *P. cinereus* was excluded from 27% of available forest habitat surveyed because of low pH. Wyman and Hawksley-Lescault (1987) concluded that the influence of soil pH on salamander distribution might fundamentally change the forest floor decomposer food web of which *P. cinereus* is an upper-level consumer. This finding might be especially critical if acidic deposition accelerates acidification of soils in forests of the northeastern United States and southeastern Canada where this species occurs.

Reductions in amphibian populations linked to habitat acidification could have severe consequences for aquatic and terrestrial ecosystems. Many species have aquatic larval and terrestrial adult life stages, and thereby form an important link in the flow of energy between these 2 ecosystems. In aquatic habitats larval amphibians are important predators of algae and invertebrates (Seale 1980), whereas adults and larvae are prey for invertebrates, fish, birds, and small mammals. In terrestrial ecosystems, adult amphibians are an important source of energy for many tertiary consumers, i.e. birds and mammals (Burton and Likens 1975*a,b*), as well as a top predator at most levels of the detrital food web. Changes in composition, distribution, and abundance of amphibian species because of habitat acidification could alter the structure and function of aquatic and terrestrial food webs and disrupt the flow of energy between these ecosystems.

Reduced numbers of amphibians and earthworms also can affect reptilians that prey on them. Catling and Freedman (1980) reported that Butler's garter snakes (*Thamnophis butleri*) feed nearly exclusively on earthworms, whereas the sympatric eastern garter snake (*T. sirtalis*) eats a mixed diet of earthworms and anuran amphibia. For Vancouver Island, Gregory (1978) stated that the northwestern garter snakes (*T. ordinoides*) specialized on earthworms and slugs, whereas *T. sirtalis* ate amphibians and earthworms. In Kansas, western worm snakes (*Carphophis amoenus vermis*) eat *Allolobophora* spp. earthworms (Clark 1970). In Ontario, Reynolds (1977*b*) identified several species of earthworms from the stomachs of Butler's garter snakes, including the acid-intolerant species, *Aporrectodea tuberculata*. Logier (1958) lists 5 other American snakes that prey on earthworms.

CONCLUSIONS

The effects of acidic depositions on vertebrate wildlife are complex and difficult to evaluate, especially for those species that have high mortality from being hunted. Further, biogeochemical interactions of natural organic acids with anthropogenic compounds create difficulty in separating the effects of each.

Documented, direct effects of acidic depositions on wildlife in terrestrial habitats is scanty. This result is largely because of the lack of gross effects on terrestrial vegetation, except in unique geographical or altitudinal situations (e.g. Camels Hump, Vt.). Localized, even regional indirect effects have been recorded for certain wildlife prey species. Acidification of soil, for example, changes invertebrate populations, especially earthworms, that are primary prey of numerous small mammals, amphibians, reptiles, and birds, particularly American woodcock. Vegetation used as forage by wildlife can contain elevated amounts of toxic metals (especially mercury and cadmium), which are enhanced through acidic depositions and the acidification process.

A broad spectrum of evidence documents the complex effects of acidification in the aquatic environment through comparisons of wetlands of different acidities and experimental acidification of individual lakes and small watersheds. Because effects of acidification on wildlife are mostly indirect, severity of effects vary geographically and with each wildlife species and are related to what a species eats and how it reproduces. The acidification of wetland habitats that change abundance or diversity of invertebrate taxa importantly affect aquatic waterbirds, particularly insect- and fish-eating birds. These effects are through losses of primary prey species, losses in species high in calcium, or increases in numbers of organisms that contain toxic metals, especially methylmercury.

Although severe effects may occur in localized areas in the U.S. and Canada (e.g. Sudbury, Ontario) general effects are found mostly throughout the northeastern U.S. and Canada. Because the acidification process is governed by the acid-neutralizating capacity (ability to buffer by calcium carbonates) of underlying bedrock and soils, the amount and rate of airborne pollutants (e.g. SO_4^{2-}, NO_3^-) that an area receives is critical. Moreover, evidence from locations where point-source emmissions have been curtailed, has revealed that the acidification process is reversible and that wetland ecosystems can recover, although the process is gradual. This fact underscores the urgency to fully implement and comply with provisions of the United States/Canada Air Quality Agreement through enforcement of the 1990 Clean Air Act, as amended, to reduce as rapidly as possible industrial and vehicular emissions that contribute substantially to acidic deposition. The mutual goals of the United States/Canada Air Quality Agreement must be attained for reducing emissions, long-term monitoring of atmospheric pollutants, and monitoring the health of aquatic and terrestrial ecosystems. Furthermore, to achieve a better understanding of the natural variability within physical and biological systems we must determine threshold amounts (kg/ha/yr) of SO_2 and NO_x that affect biological systems to predict ecological response to these pollutants as emissions are curtailed. Research should continue to evaluate current effects of acidified habitats on wildlife and to determine how wildlife and their habitats respond to reduced emissions of these airborne contaminants.

LITERATURE CITED

Abrahamsen, G. 1980. Impact of atmospheric sulfur deposition on forest ecosystems. Pages 397-415 *in* D. S. Shriner, C. R. Richmond, and S. E. Lindberg, eds. Atmospheric sulfur deposition-environmental impact and health effects. Proc. *2nd* Life Sci., Symp. Ann Arbor Sci. Publishers Inc./The Butterworth Group, Ann Arbor, Mich.

Albers, P. H., and R. M. Prouty. 1987. Survival of spotted salamander eggs in temporary woodland ponds of coastal Maryland. Environ. Pollut. 46:45-61.

Alexander, L. L. 1987. Patterns of mortality in wintering common loons. Page 77 *in* P. I. V. Strong, ed. Papers From The 1987 Conference on Loon Research and Management. North Am. Loon Fund. Meredith, N.H.

Alexander, M. 1980. Effects of acid precipitation on biochemical activities in soil. Pages 47-52 *in* D. Drablos and A. Tollan, eds. Ecological impact of acid precipitation. Proc. Int. Conf., Sandefjord, Norway, SNSF Project, Oslo.

Allen, A. W. 1986. Habitat Suitability Index Model: Mink. National Ecology Center, Division of Wildlife and Contaminant Research, U.S. Fish and Wildl. Serv., U.S. Dep. Inter. Wash. Biol. Rep. 82(10.127), Nov. 1986, Revised.

Almer, B., W. Dickson, C. Ekstrom, E. Hornstrom, and V. Miller. 1974. Effects of acidification on Swedish lakes. Ambio 3:30-36.

___, W. Dickson, C. Ekstrom, and E. Hornstrom. 1978. Sulfur pollution and the aquatic ecosystem. Pages 271-311 *in* J. O. Nriagu, ed. Sulfur in the environment. Part II. Ecological impacts. John Wiley and Sons, N.Y.

Altshuller, A. P., and R. A. Linthurst, eds. 1984. The acidic deposition phenomena [*sic*] and its effects: Critical Assessment Review Papers, Vol. II, Effects Sciences. N.C. State Univ. Acid Precipitation Program, Raleigh, North Carolina. U.S. Environ. Prot. Agency, EPA-600/8-83-0168BF. Wash. D.C.

Alvo, R. 1985. The breeding success of common loons (*Gavia immer*) in relation to lake alkalinity. M.Sc. Thesis, Trent Univ., Peterborough, Ont. 122pp.

___, R., D. J. T. Hussell, and M. Berrill. 1988. The breeding success of common loons (*Gavia immer*) in relation to alkalinity and other lake characteristics in Ontario. Can. J. Zool. 66:746-752.

Amthor, J. S. 1984. Does acid rain directly influence plant growth? Some comments and observations. Environ. Pollut. (Ser. A) 3:1-6.

Andersson, M. 1988. Toxicity and tolerance of aluminum in vascular plants. Water, Air, and Soil Pollut. 39:439-462.

Andren, C., L. Henrikson, M. Olsson, and G. Nilson. 1988. Effects of pH and aluminium on embryonic and early larval stages of Swedish brown frogs *Rana arvalis, R. temporaria* and *R. dalmatina*. Holarct. Ecol. 11:127-135.

___, M. Marden, and G. Nilson. 1989. Tolerance to low pH in a population of moor frogs, *Rana arvalis*, from an acid and a neutral environment: a possible case of rapid evolutionary response to acidification. Oikos 56:215-223.

Andrews, J. D., and A. D. Hasler. 1943. Fluctuations in the animal populations of the littoral zone in Lake Mendota. Trans. Wis. Acad. Sci., Arts, and Letters 35:175-185.

Ankney, C. D., and D. M. Scott. 1980. Changes in nutrient reserves and diet of breeding brown-headed cowbirds. Auk 97:684-696.

Annau, Z., and C. U. Eccles. 1987. Sensory deficits caused by exposure to methyl mercury. Pages 104-113 *in* C. U. Eccles and Z. Annau, eds. The toxicity of methyl mercury. Johns Hopkins Univ. Press, Baltimore, Md.

Anon. 1987. White paper on the forest effects of air pollution. Am. For. Assoc., Wash. 17pp.

Anon. 1988. Acid rain: a national sensitivity assessment. Inland Waters and Lands Directorate, Environment Canada, Environ. Fact Sheet 88-1, 6pp.

Arbib, R. 1980. The blue list for 1980. Am. Birds 33:830.

Arts, G. H. P., J. G. M. Roelofs, and M. J. H. De Lyon. 1990. Differential tolerances among soft-water macrophyte species to acidification. Can. J. Bot. 68:2127-2134.

Baker, J. P., and C. L. Schofield. 1982. Aluminum toxicity to fish in acidic waters. Water, Air, and Soil Pollut. 18:289-309.

Banfield, A. W. F. 1974. The Mammals of Canada. Natl. Museum of Nat. Sci., Natl. Mus. of Canada., Univ. Toronto Press, Toronto. 438pp.

Barnard, J. E., A. A. Lucier, R. T. Brooks., A. H. Johnson, P. H. Dunn, and D. F. Karnosky. 1990. Changes in forest health and productivity in the United States and Canada. Natl. Acid Precipitation Assess. Prog., Acidic Deposition: State of Science and Technology. Vol. 3, Rep. 16. Office of the Director, Wash. D.C. 186pp.

Barr, J. F. 1973. Feeding biology of the common loon (*Gavia immer*) in oligotrophic lakes of the Canadian Shield. Ph.D. Thesis. Univ. Guelph, Guelph, Ont. 204pp.

___. 1986. Population dynamics of the Common Loon (*Gavia immer*) associated with mercury-contaminated waters in northwestern Ontario. Can. Wildl. Serv. Occas. Pap. Ser. No. 56, 25pp.

Battarbee, R. W., and D. F. Charles. 1986. Diatom-based pH reconstruction studies of acid lakes in Europe and North America: a synthesis. Water, Air, and Soil Pollut. 30:347-354.

Beamish, R. J., and H. H. Harvey. 1972. Acidification of the La Cloche Mountain lakes, Ontario, and resulting fish mortalities. J. Fish. Res. Bd. Can. 29:1131-1143.

Bell, H. L. 1971. Effects of low pH on the survival and emergence of aquatic insects. Water Res. 5:313-319.

Bendell, B. E. 1988. Lake acidity and the distribution and abundance of water striders (Hemiptera: Gerridae) near Sudbury, Ontario. Can. J. Zool. 66:2209-2211.

___, and D. K. McNicol. 1987. Fish predation, lake acidity and the composition of aquatic insect assemblages. Hydrobiologia 150:193-202.

___, and ___. 1991. An assessment of leeches (Hirudinea) as indicators of lake acidification. Can. J. Zool. 69:130-133.

Bergman, R. D., and D. V. Derksen. 1977. Observations on Arctic and red-throated loons at Storkensen Point, Alaska. Arctic 30:41-51.

Bevanger, K., and O. Albu. 1986. Decrease in a Norwegian feral mink *Mustela vison* population -- a response to acid precipitation? Biol. Conserv. 38: 75-78.

Bjorklund, I., H. Borg, and K. Johansson. 1984. Mercury in Swedish lakes -- Its regional distribution and causes. Ambio 13:118-121.

Blair, R. B. 1990. Water quality and the summer distribution of common loons in Wisconsin. Passenger Pigeon 52:119-126.

Blancher, P. J. 1991. Acidification: implications for wildlife. Trans. North Am. Wildl. Nat. Resour. Conf. 56:195-204.

___, and D. G. McAuley. 1987. Influence of wetland acidity on avian breeding success. Trans. North Am. Wildl. Nat. Resour. Conf. 52:628-635.

___, and D. K. McNicol. 1988. Breeding biology of tree swallows in relation to wetland acidity. Can. J. Zool. 66:842-849.

___, and ___. 1991. Tree swallow diet in relation to wetland acidity. Can. J. Zool. 69:2629-2637.

___, ___, R. K. Ross, C. H. R. Wedeles, and P. Morrison. 1992. Towards a model of acidification effects on waterfowl in eastern Canada. Pages 57-63 *in* B. Morrison, J. P. Dempster and W. J. Manning, eds. Special Issue, Effects of Acidic Pollutants on Freshwater Plants and Animals. Environ. Pollut. 78.

Bloomfield, J. A., S. O. Quinn, R. J. Scrudato, D. Long, A. Richards, and F. Ryan. 1980. Atmospheric and watershed inputs of mercury to Cranberry Lake, St. Lawrence County, New York. Pages 175-210 *in* T. Y. Toribara, M. W. Miller and P. E. Morrow, eds. Polluted Rain. Plenum Press, N.Y.

Blus, L. J., C. J. Henny, and B. M. Mulhern. 1987. Concentrations of metals in mink and other mammals from Washington and Idaho. Environ. Pollut. 44:307-318.

Bodenheimer, F. S. 1935. Soil conditions which limit earthworm distribution. Zoogeographica 2:572-578.

Bornebusch, C. H. 1930. The fauna of the forest soil. Forstl. Forsogsvaes. Dan. 11:1-224.

Bourbonniere, R. A. 1987. Organic geochemistry of bog drainage waters. Pages 139-145 *in* C. D. A. Rubec and R. P. Overend, eds. Symposium '87 Wetlands/Peatlands. Edmonton, Alberta. Ottawa, Ont.

Braune, B. M. 1987. Comparison of total mercury levels in relation to diet and molt for nine species of marine birds. Arch. Environ. Contam. Toxicol. 16:217-224.

Brazil, J., and S. Ferguson. 1989. Cadmium concentrations in Newfoundland moose. Alces 24:52-57.

Brezonik, P. L., L. A. Baker, J. R. Eaton, T. M. Frost, P. Garrison, T. K. Kratk, J. J. Magnuson, W. J. Rose, B. K. Shephard, W. A. Swenson, C. J. Watras, and K. E. Webster. 1986. Experimental acidification of Little Rock Lake, Wisconsin. Water, Air, and Soil Pollut. 31:115-121.

Brown, L. 1967. Ecological distribution of six species of shrews and comparison of sampling methods in the central Rocky Mountains. J. Mammal. 48:617-623.

Burton, T. M., and G. E. Likens. 1975*a*. Energy flow and nutrient cycling in salamander populations in the Hubbard Brook Experimental Forest, New Hampshire. Ecology 56:1068-1080.

___, and ___. 1975*b*. Salamander populations and biomass in the Hubbard Brook Experimental Forest, New Hampshire. Copeia 75:541-546.

Campbell, P. G. C., and P. M. Stokes. 1985. Acidification and toxicity of metals to aquatic biota. Can. J. Fish. Aquat. Sci. 42:2034-2049.

Cappon, C. J., and J. C. Smith. 1981. Mercury and selenium content and chemical form in fish muscle. Arch. Environ. Contam. Toxicol. 10:305-319.

Carlson, B. L., and S. W. Nielsen. 1985. Influence of dietary calcium on lead poisoning in mallard ducks (*Anas platyrhynchos*). Amer. J. Vet. Res. 46:276-282.

Carriere, D., K. L. Fisher, D. B. Peakall, and P. Anghern. 1986. Effects of dietary aluminum sulphate on reproductive success and growth of Ringed Turtle-Doves (*Streptopelia risoria*). Can. J. Zool. 64:1500-1505.

Catling, P. M. and B. Freedman. 1980. Food and feeding behavior of sympatric snakes at Amherstburg, Ontario. Can. Field. Nat. 94:28-33.

Chambers, G. D., K. C. Sadler, and R. P. Breitenbach. 1966. Effects of dietary calcium levels on egg production and bone structure of pheasants. J. Wildl. Manage. 30:65-73.

Clark, D. R., Jr. 1970. Ecological study of the worm snake *Carphophis vermis* (Kennicott). Univ. of Kan. Publ., Mus. Nat. Hist. 19:85-194.

Clark, K. L. 1986*a*. Distributions of anuran populations in central Ontario relative to habitat acidity. Water, Air and Soil Pollut. 30:727-734.

___. 1986*b*. Responses of spotted salamander, *Ambystoma maculatum*, populations in central Ontario to habitat acidity. Can. Field-Nat. 100:463-469.

___. 1992. Monitoring the effects of acidic deposition on amphibian populations in Canada. Pages 63-66 *in* C. A. Bishop and K. E. Pettit, eds. Declines in Canadian amphibian populations: designing a national monitoring strategy. Occas. Pap. 76, Can. Wildl. Serv., Ottawa.

___, and D. Euler. 1982. The importance of pH and habitat disturbance in amphibian distributions in central Ontario. Tech. Rep. of the Wildlife Component, Lakeshore Capacity Study, Ont. Minist. Nat. Resour., Toronto.

___, and R. J. Hall. 1985. Effects of elevated hydrogen ion and aluminum concentration on the survival of amphibian embryos and larvae. Can. J. Zool. 63:116-123.

___, and B. D. LaZerte. 1985. A laboratory study of the effects of aluminum and pH on amphibian eggs and tadpoles. Can. J. Fish. Aquat. Sci. 42:1544-1551.

Clark, T., K. Clark, S. Paterson, K. Mackay, and R. J. Norstrom. 1988. Wildlife monitoring, modeling, and fugacity---they are indicators of chemical contamination. Environ. Sci. Technol. 22:120-127.

Cogbill, C. V. 1976. The history and character of acid precipitation in eastern North America. Water, Air, and Soil Pollut. 6:407-413.

___, and G. E. Likens. 1974. Acid precipitation in the northeastern United States. Water Resour. Res. 10:1133-1137.

___, G. E. Likens, and T. A. Butler. 1984. Uncertainties in historical aspects of acid precipitation: getting it straight. Atmos. Environ. 18:2261-2270.

Conaway, C. H. 1952. Life history of the water shrew (*Sorex palustris navigator*). Am. Midl. Nat. 48:219-248.

___, and D. W. Pfitzer. 1952. *Sorex palustris* and *Sorex dispar* from the Great Smoky Mountains National Park. J. Mammal. 33:106-108.

Conroy, N., K. Hawley, W. Keller, and C. Lafrance. 1976. Influences of the atmosphere on lakes in the Sudbury area. Pages 146-165 *in* D. H. Matheson and F. C. Elder, eds. Atmospheric contribution to the chemistry of lake waters. J. Great Lakes Res., Int. Assoc. Great Lakes Res. (Suppl. 1 to Vol. 2).

Cooke, A. S., and J. F. D. Frazer. 1976. Characteristics of newt breeding sites. J. Zool., Lond. 178:223-236.

Cope, W. G., J. G. Wiener, and R. G. Rada. 1990. Mercury accumulation in yellow perch in Wisconsin seepage lakes: relation to lake characteristics. Environ. Toxicol. Chem. 9:931-940.

Corn, P. S., W. Stolzenburg, and R. B. Bury. 1989. Acid precipitation studies in Colorado and Wyoming: interim report of surveys of montane amphibians and water chemistry. U.S. Fish and Wildl. Serv. Biol. Rep. 80(40.26). 56pp.

Cowling, E. B. 1982. Acid precipitation in historical perspective. Environ. Sci. Technol. 16:110A-123A.

____. 1983. The North American acid rain situation. Pages 53-73 *in* Ecological effects of acid deposition. Natl. Swedish Environ. Prot. Bd. Rep. PM 1636.

Crete, M., F. Potvin, P. Walsh, J.-L. Benedetti, M. A. Lefebvre, J.-P. Weber, G. Paillard, and J. Gagnon. 1987. Pattern of cadmium contamination in the liver and kidneys of moose and white-tailed deer in Quebec. Sci. Total Environ. 66:45-53.

____, R. Nault, P. Walsh, J.-L. Benedetti, M. A. Lefebvre, J.-P. Weber, and J. Gagnon. 1989. Variation in cadmium content of caribou tissues from northern Quebec. Sci. Total Environ. 80:103-112.

Cronan, C. S., and C. E. Schofield. 1979. Aluminum leaching in response to acid precipitation: effects on high-elevation watersheds in the Northeast. Science 204:304-306.

Crowder, A. 1991. Acidification, metals and macrophytes. Environ. Pollut. 71:171-203.

Cummins, C. P. 1986. Effects of aluminum and low pH on growth and development in *Rana temporaria* tadpoles. Oecologia 69:248-252.

Dale, J. M., B. Freedman, and J. Kerekes. 1985. Acidity and associated water chemistry of amphibian habitats in Nova Scotia. Can. J. Zool. 63:97-105.

Darveau, M., J.-L DesGranges, and G. Gauthier. 1992. Habitat use by three breeding insectivorous birds in declining maple forests. Condor 94:72-82

Dean, W. F., M. L. Scott, R. J. Young, and W. J. Ash. 1967. Calcium requirements of ducklings. Poult. Sci. 46:1496-1499.

Demayo, A., M. C. Taylor, K. W. Taylor, and P. V. Hodson. 1982. Toxic effects of lead and lead compounds on human health, aquatic life, wildlife plants, and livestock. CRC Crit. Rev. Environ. Control 12:257-305.

DesGranges, J.-L. 1987. Forest birds as biological indicators of the progression of maple dieback in Quebec. Pages 249-257 *in* A. W. Diamond and F. C. Fillion, eds. The value of birds. ICBP Tech. Publ. No. 6.

____, and M. Darveau. 1985. Effect of lake acidity and morphometry on the distribution of aquatic birds in southern Quebec. Holarctic Ecol. 8:181-190.

____, and J. Rodrigue. 1986. Influence of acidity and competition with fish on the development of ducklings in Quebec. Water, Air, and Soil Pollut. 30:743-750.

____, and M. L. Hunter, Jr. 1987. Duckling response to lake acidification. Trans. North Am. Wildl. Nat. Resour. Conf. 52:636-644.

____, and B. Houde. 1989. Effects of acidity and other environmental parameters on the distribution of lacustrine birds in Quebec. Pages 7-41 *in* J.-L. DesGranges, ed. Studies of the effects of acidification on aquatic wildlife in Canada: lacustrine birds and their habitats in Quebec. Occas. Pap. Ser.No. 67., Can. Wildl. Serv., Ottawa.

____, J.-L., Y. Maufette, and G. Gagnon. 1987. Sugar maple forest decline and implications for forest insects and birds. Trans. North Am. Wildl. Nat. Resour. Conf. 52:677-689.

Diamond, A. W. 1989. Impacts of acid rain on aquatic birds. Environ. Monit. and Assess. 12:245-254.

Dickson, W. 1980. Properties of acidified water. Pages 75-83 *in* D. Drablos and A. Tollan, eds. Ecological impact of acid precipitation. Proc., Int. Conf., Sandefjord, Norway. SNSF Proj., Oslo.

Dietz, F. 1973. The enrichment of heavy metals in submerged plants. Pages 53-62 *in* S. H. Jenkins, ed. Advances in water pollution research. Proc. 6*th* Int. Conf., Pergamon Press, Oxford.

Dillon, P. J., H. E. Evans, and P. J. Scholer. 1988. The effects of acidification on metal budgets of lakes and catchments. Biogeochemistry 5:201-220.

Dixit, S. S., A. S. Dixit, and R. D. Evans. 1987. Paleolimnological evidence of recent lake acidification in two Sudbury (Canada) lakes. Sci. Total Environ. 67:53-67.

___, and J. P. Smol. 1989. Algal assemblages in acid-stressed lakes with particular emphasis on diatoms and chrysophytes. Pages 91-114 *in* S. S. Rao, ed. Acid stress and aquatic microbial interactions. CRC Press, Inc., Boca Raton, Fl.

Doi, R., H. Ohno, and M. Harada. 1984. Mercury in feathers of wild birds from the mercury-polluted area along the shore of the Shiranui Sea, Japan. Sci. Total Environ. 40:155-167.

Doyle, J. J. 1977. Effects of low levels of dietary cadmium in animals--A review. J. Environ. Qual. 6:111-116.

Drent, P. J., and J. W. Woldendorp. 1989. Acid rain and eggshells. Nature 339:431.

Driscoll, C. T., G. E. Likens, L. O. Hedin, J. S. Eaton, and F. H. Bormann. 1989. Changes in the chemistry of surface waters: 25-year results at the Hubbard Brook Experimental Forest, NH. Environ. Sci. Technol. 23:137-143.

Eadie, J. M., and A. Keast. 1982. Do goldeneye and perch compete for food? Oecologia 55:225-230.

Easton, E. G. 1983. A guide to the valid names of Lumbricidae (Oligochaeta). Pages 475-486 *in* J. E. Satchell, ed. Earthworm ecology, from Darwin to vermicultural. Chapman and Hall, N.Y.

Edwards, C. A. and J. R. Lofty. 1972. Biology of earthworms. Chapman and Hall. Ltd., Lond. 283pp.

___, and P. J. Bohlen. 1992. The effects of toxic chemicals on earthworms. Pages 23-99 *in* G. W. Ware, ed. Reviews of Environ. Contam. Toxicol. Vol. 125. Springer-Verlag, N.Y.

Eilers, J. M., G. J. Lien, and R. G. Berg. 1984. Aquatic organisms in acidic environments: A literature review. Wis. Dep. Nat. Resour., Tech. Bull. 150. 18pp.

Eisler, R. 1985*a*. Selenium hazards to fish, wildlife, and invertebrates: A synoptic review. U. S. Fish and Wildl. Serv. Biol. Rep. 85(1.5). 57pp.

___. 1985*b*. Cadmium hazards to fish, wildlife, and invertebrates: a synoptic review. U.S. Fish and Wildl. Serv. Biol. Rep. 85(1.2). 46pp.

___. 1987. Mercury hazards to fish, wildlife, and invertebrates: a synoptic review. U.S. Fish and Wildl. Serv. Biol. Rep. 85(1.10). 90pp.

___. 1988. Lead hazards to fish, wildlife, and invertebrates: a synoptic review. U.S. Fish and Wildl. Serv. Biol. Rep. 85(1.14). 134pp.

Eriksson, M. O. G. 1979. Competition between freshwater fish and goldeneyes *Bucephala clangula* (L.) for common prey. Oecologia 41:99-107.

___. 1983. The role of fish in the selection of lakes by non-piscivorous ducks: mallard, teal and goldeneye. Wildfowl 34:27-32.

___. 1984. Acidification of lakes: effects on waterbirds in Sweden. Ambio 13:260-262.

___. 1985. Prey detectability for fish-eating birds in relation to fish density and water transparency. Ornis Scand. 16:1-7.

___. 1986*a*. Reproduction of black-throated diver (*Gavia arctica*) in relation to fish density in oligotrophic lakes in southwestern Sweden. Ornis Scand. 17:245-248.

___. 1986*b*. Fish delivery, production of young, and nest density of Osprey (*Pandion haliaetus*) in southwest Sweden. Can. J. Zool. 64:1961-1965.

___. 1987. Some effects of freshwater acidification on birds in Sweden. ICBP Tech. Publ. 6:183-190.

___, L. Henrikson, B. I. Nilsson, G. Nyman, H. G. Oscarson, A. and E. Stenson. 1980. Predator-prey relations important for the biotic changes in acidified lakes. Ambio 9:248-249.

___, ___, and H. G. Oscarson. 1983. Acid rain - a future danger for the osprey, *Pandion haliaetus*. Var Fagelvarld 42:293-300 (in Swedish, English summary).

___, ___, and ___. 1989. Metal contents in liver tissues of non-fledged goldeneye, *Bucephala clangula* ducklings: A comparison between samples from acidic, circumneutral, and limed lakes in south Sweden. Arch. Environ. Contam. Toxicol. 18:255-260.

Esher, R. J., D. H. Marx, S. J. Ursic, R. L. Baker, L. R. Brown, and D. C. Coleman. 1992. Simulated acid rain effects on fine roots, ectomycorrhizae, microorganisms, and invertebrates in pine forests of the southern United States. Water, Air, and Soil Pollut. 61:269-278.

___, R. L. Baker, S. J. Ursic, and L. C. Miller. 1993. Responses of invertebrates to experimental acidification of forest floor under southern pine. Pages 74-82 *in* J. R. Longcore and G. F. Sepik, eds. Proc. Eighth American Woodcock Symposium, U.S. Fish and Wildl. Serv., Biol. Rep. 16. (in press).

Evans, L. S. 1982. Biological effects of acidity in precipitation on vegetation: a review. Environ. and Exp. Bot. 22:155-169.

___. 1984. Botanical aspects of acidic precipitation. Bot. Rev. 50:449-490.

Federer, C. A., J. W. Hornbeck, L. M. Tritton, C. W. Martin, R. S. Pierce, and C. T. Smith. 1989. Long-term depletion of calcium and other nutrients in eastern US [*sic*] forests. Environ. Manage. 13:593-601.

Fimreite, N. 1971. Effects of dietary methylmercury on ring-necked pheasants: with special reference to reproduction. Can. Wildl. Serv., Occas. Pap. Ser. No. 9. 37pp.

Ford, J. 1988. The effects of chemical stress on aquatic species composition and community structure. Pages 99-144 *in* S. A. Levin, M. A. Harwell, J. R. Kelly, and K. D. Kimball, eds. Ecotoxicology: problems and approaches. Springer-Verlag, N.Y.

France, R. L., and B. D. LaZerte. 1987. Empirical hypothesis to explain the restricted distribution of *Hyalella azteca* (Amphipoda) in anthropogenically acidified lakes. Can. J. Fish. Aquat. Sci. 44:1112-1121.

Francis, A. J., D. Olson, and R. Bernatsky. 1980. Effect of acidity on microbial processes in a forest soil. Pages 166-167 *in* D. Drablos and A. Tollan, eds. Ecological impact of acid deposition. Proc. Int. Conf., Sandefjord, Norway, SNSF Project, Oslo.

Frank, A., L. Peterson, and T. Morner. 1981. Lead and cadmium in tissues from elk (*Alces alces*), roe deer (*Capreolus capreolus*) and hares (*Lepus europaus, L. timidus*). Svensk Veterinartidn. 33:151-156.

Freda, J. 1986. The influence of acidic pond water on amphibians: a review. Water, Air, and Soil Pollut. 30:439-450.

___. 1991. The effects of aluminum and other metals on amphibians. Environ. Pollut. 71:305-328.

___**, and W. A. Dunson.** 1985. Field and laboratory studies of ion balance and growth rates of ranid tadpoles chronically exposed to low pH. Copeia 1985(2):415-423.

___**, and** ___. 1986. Effects of low pH and other chemical variables on the local distribution of amphibians. Copeia 1986:454-466.

___**, and D. G. McDonald.** 1990. Effects of aluminum on the leopard frog, *Rana pipiens*: life stage comparisons and aluminum uptake. Can. J. Fish. Aquat. Sci. 47:210-216.

Fritz-Sheridan, R. P. 1985. Impact of simulated acid rains on nitrogenase activity in *Peltigera aphthosa* and *P. polydactyla*. Lichenologist 17:27-31.

Froslie, A., A. Haugen, G. Holt, and G. Horheim. 1986. Levels of cadimum in liver and kidneys from Norwegian cervides. Bull. Environ. Contam. Toxicol. 37:453-460.

Galloway, J. N., and E. B. Cowling. 1978. The effects of precipitation on aquatic and terrestrial ecosystems: a proposed precipitation chemistry network. J. Air Pollut. Control Assoc. 28:229-235.

___**, E. B. Cowling, E. Gorham, and W. W. FcFee.** 1978. A national program for assessing the problem of atmospheric deposition (acid rain). Nat. Resour. Ecol. Lab., Colo. State Univ., Fort Collins. 97pp.

Gambell, A. W., and D. W. Fisher. 1966. Chemical composition of rainfall in eastern North Carolina and southeastern Virginia. U.S. Geol. Surv. Water-Supply Pap. 1535-K:K1-K41. Gov. Print. Off., Wash., D.C.

Gardner, W. S., D. R. Kendall, R. R. Odom, H. L. Windom, and J. A. Stephens. 1978. The distribution of methyl mercury in a contaminated salt marsh ecosystem. Environ. Pollut. 15:243-251.

Gascon, C., and J. R. Bider. 1985. The effect of pH on bullfrog, *Rana catesbeiana*, and green frog, *Rana clamitans melanota*, tadpoles. Can. Field-Nat. 99:259-261.

___**, and D. Planas.** 1986. Spring pond water chemistry and the reproduction of the wood frog, *Rana sylvatica*. Can. J. Zool. 64:543-550.

Gerell, R. 1967. Food selection in relation to habitat in mink (*Mustela vison* Schreber) in Sweden. Oikos 18:233-246.

Gibson, J. H. 1984. Evaluation of wet chemical deposition in North America. Pages 1-13 *in* B. B. Hicks, ed. Deposition both wet and dry. Acid Precipitation Series, Vol, 4, J. I. Teasley, Series, ed. Butterworth Publishers. Stoneham, Mass.

Gilbert, F. F., and E. G. Nancerkivell. 1982. Food habits of mink (*Mustela vison*) and otter (*Lutra canadensis*) in northeastern Alberta. Can. J. Zool. 60:1282-1288.

Gilbert, O. L. 1986. Field evidence for an acid rain effect on lichens. Environ. Pollut. (Series A) 40:227-231.

Gilmour, C. C., and E. A. Henry. 1991. Mercury methylation in aquatic systems affected by acid deposition. Environ. Pollut. 71:131-169.

Glass, G. E., and O. L. Loucks. 1980. Impacts of airborne pollutants on wilderness areas along the Minnesota-Ontario border. Rep. EPA-600/3-80-044., U.S. Environ. Prot. Agency, Environ. Res. Lab., Duluth, Minn. 187pp.

Glooschenko, V., P. Blancher, J. Herskowitz, R. Fulthorpe, and S. Rang. 1986. Association of wetland acidity with reproductive parameters and insect prey of the eastern kingbird (*Tyrannus tyrannus*) near Sudbury, Ontario. Water, Air, and Soil Pollut. 30:553-567.

___, C. Downes, R. Frank, H. E. Braun, E. M. Addison, and J. Hickie. 1988. Cadimum levels in Ontario moose and deer in relation to soil sensitivity to acid precipitation. Sci. Total Environ. 71:173-186.

___, W. F. Weller, P. G. R. Smith, R. Alvo, and J. H. G. Archbold. 1992. Amphibian distribution with respect to pond water chemistry near Sudbury, Ontario. Can. J. Fish Aquat. Sci. 49(Suppl. 1):114-121.

Gordon, G. E. 1987. A decade of acid rain research. Pages 2-9 *in* R. W. Johnson, G. E. Gordon, eds., W. Calkins, and A. Z. Elzerman, Assoc. eds. The chemistry of acid rain--sources and atmoshperic processes. ACS Synposium Series 349. Am. Chem. Soc., Wash., D.C.

Gorham, E. 1955. On the acidity and salinity of rain. Geochim. Cosmochim. Acta 7:231-239.

___. 1957. The chemical composition of rain from Rosscahill in county Galway. Ir. Nat. J. 12:122-126.

___. 1958. The influence and importance of daily weather conditions in the supply of chloride, sulphate and other ions to fresh waters from atmopsheric precipitation. Philos. Trans. Royal Soc. Lond., (Ser. B) 247:147-178.

___. 1961. Factors influencing supply of major ions to inland waters, with special reference to the atmosphere. Geol. Soc. Am. Bull. 72:795-840.

___. 1981. Scientific understanding of atmospheric-biosphere interactions: a historical overview. Atmosphere-biosphere interactions: toward a better understanding of the ecological consequences of fossil fuel combustion. Natl. Acad. Press, Wash., D.C.

___, and A. G. Gordon. 1963. Some effects of smelter pollution upon aquatic vegetation near Sudbury, Ontario. Can. J. Bot. 41:371-378.

Goriup, P. D. 1989. Acidic air pollution and birds in Europe. Oryx 23:82-86.

Gosner, K. L., and I. H. Black. 1957. The effects of acidity on the development and hatching of New Jersey frogs. Ecology 38:256-262.

Grahn, O. 1977. Macrophyte succession in Swedish lakes caused by deposition of airborne acid substances. Water, Air, and Soil Pollut. 7:295-306.

___. 1986. Vegetation structure and primary production in acidified lakes in southwestern Sweden. Experientia 42:465-470.

___, H. Hultberg, and L. Landner. 1974. Oligotrophication ---a self-accelerating process in lakes subjected to excessive supply of acid substances. Ambio 3:93-94.

Granat, L. 1972. On the relation between pH and the chemical composition in atmospheric precipitation. Tellus 24:550-560.

Greely, F. 1962. Effects of calcium deficiency on laying hen pheasants. J. Wildl. Manage. 26:186-193.

Greer, K. R. 1955. Yearly food habits of the river otter in the Thompson Lakes Region, northwestern Montana, as indicated by scat analysis. Am. Midl. Nat. 54:299-313.

Gregory, P. T. 1978. Feeding habits and diet overlap of three species of garter snakes (*Thamnophis*) on Vancouver Island. Can. J. Zool. 56:1967-1974.

Gunn, J. M., and W. Keller. 1990. Biological recovery of an acid lake following reductions in industrial emissions of sulphur. Nature (Lond.) 345:431-433.

Hagvar, S. 1980. Effects of acid precipitation on soil and forest. 7. Soil animals. Pages 202-203 *in* D. Drablos and A. Tollan, eds. Ecological impact of acid precipitation. Proc. Int. Conf., Sandefjord, Norway, SNSF Project, Oslo.

Haines, T. A. 1981. Acidic precipitation and its consequences for aquatic ecosystems: a review. Trans. Am. Fish. Soc. 110:669-707.

___, and M. L. Hunter, Jr. 1982. Waterfowl and their habitat: threatened by acid rain? Int. Waterfowl Symp., Ducks Unlimited 4:177-188.

___, and J. Akielaszek. 1983. A regional survey of chemistry of headwater lakes and streams in New England: Vulnerability to acidification. U.S. Fish and Wildl. Serv., FWS/OBS-80/40.15. 141pp.

___, and ___. 1984. Effects of acidic precipitation on Atlantic salmon rivers in New England. U.S. Fish and Wildl. Serv., FWS/OBS-80/40.18. 108pp.

Hakanson, L. 1980. The quantitative impact of pH, bioproduction and Hg-contamination on the Hg-content of fish (pike). Environ. Pollut. (Ser. B) 1:285-304.

Hall, R. J., and K. R. Kelson. 1975. The Mammals of North America. Ronald Press Co., N.Y. Vol 1,2. 1083pp.

___, and G. E. Likens. 1980. Ecological effects of experimental acidification on a stream ecosystem. Pages 375-376 *in* D. Drablos and A. Tollan, eds. Ecological impact of acid precipitation. Proc. Int. Conf., Sandefjord, Norway, SNSF Project, Oslo.

___, ___, S. B. Fiance, and G. R. Hendrey. 1980. Experimental acidification of a stream in the Hubbard Brook Experimental Forest, New Hampshire. Ecology 61:976-989.

Hamilton, S. J., and T. A. Haines. 1989. Bone characteristics and metal concentrations in white suckers (*Catostomus commersoni*) from one neutral and three acidified lakes in Maine. Can. J. Fish. Aquat. Sci. 46:440-446.

Hamilton, W. J., Jr. 1936. Food habits of the mink in New York. J. Mammal. 17:169.

Hansen, D. A., and G. M. Hidy. 1982. Review of questions regarding rain acidity data. Atmos. Environ. 16:2107-2126.

Hansen, P. W. 1987. Acid rain and waterfowl: the case for concern in North America. Izaak Walton League of America. Arlington, Va. 39pp.

Haramis, G. M., and D. S. Chu. 1987. Acid rain effects on waterfowl: use of black duck broods to assess food resources of experimentally acidified wetlands. Pages 173-181 *in* A. W. Diamond and F. L. Filion, eds. The value of birds. Int. Council for Bird Preservation, Tech. Publ. No. 6, Cambridge, U.K.

Harvey, H. H., and C. Lee. 1982. Historical fisheries changes related to surface water pH changes in Canada. Pages 45-55 *in* T. A. Haines and R. E. Johnson, eds. Acid Rain/ Fisheries: Proceedings of an International Symposium on Acidic Precipitation and Fishery Impacts in Northeastern North America. Am. Fish. Soc., North. Div., Bethesda, Md.

Havas, M. 1983. Effect of low pH on the chemical composition of aquatic invertebrates from tundra ponds at the Smoking Hills, N.W.T., Canada. Can. J. Zool. 61:241-249.

___, and T. C. Hutchinson. 1982. Aquatic invertebrates from the Smoking Hills, N.W.T.: effect of pH and metals on mortality. Can. J. Zool. 39:980-903.

Hedin, L. O., G. E. Likens, and F. H. Bormann. 1987. Decrease in precipitation acidity resulting from decreased SO_4^{2-} concentration. Nature 325:244-246.

Heinz, G. 1974. Effects of low dietary levels of methyl mercury on mallard reproduction. Bull. Environ. Contam. Toxicol. 11:386-392.

___. 1976. Methylmercury: Second-year feeding effects on mallard reproduction and duckling behaviour. J. Wildl. Manage. 40:82-90.

Hendrey, G. R., and F. A. Vertucci. 1980. Benthic plant communities in acidic Lake Colden, New York: sphagnum and the algal mat. Pages 314-315 *in* D. Drablos and A. Tollan, eds. Ecological impact of acid precipitation. Proc. Int. Conf., Sandefjord, Norway, SNSF Project, Oslo.

___, J. N. Galloway, S. A. Norton, C. L. Schofield, P. W. Shaffer, and D. A. Burns. 1980*a*. Geological and hydrochemical sensitivity of the eastern United States to acid precipitation. U.S. Environ. Prot. Agency, Corvallis Environ. Res. Lab. Rep. EPA-600/3-80-024, Corvallis, Or. 99pp.

___, ___, ___, ___, ___, and ___. 1980*b*. Sensitivity of eastern United States to acid precipitation impacts on surface waters. Pages 216-217 *in* D. Drablos and A. Tollan, eds. Ecological impact of acid precipitation. Proc. Int. Conf., Sandefjord, Norway, SNSF Project, Oslo.

Henrikson, B.-I. 1990. Predation on amphibian eggs and tadpoles by common predators in acidified lakes. Holarctic Ecol. 13:201-206.

Henrikson, L., H. G. Oscarson, and J. A. E. Stenson. 1980. Does the change of predator system contribute to the biotic development in acidified lakes? Page 316 *in* D. Drablos and A. Tollan, eds. Ecological Impact of Acid Precipitation. Proc. Int. Conf., Sandefjord, Norway, SNSF Project, Oslo.

Herman, F. A., and E. Gorham. 1957. Total mineral material, acidity, sulfur and nitrogen in rain and snow at Kentville, Nova Scotia. Tellus 9:180-183.

Hesse, L. W., R. L. Brown, and J. F. Heisinger. 1975. Mercury contamination of birds from a polluted watershed. J. Wildl. Manage. 39:299-304.

Hidy, G. M. 1987. Subcontinental air pollution phenomena. Pages 10-27 *in* R. W. Johnson, and G. E. Gordon, eds. The chemistry of acid rain--sources and atmospheric processes. ACS Symposium Series 349. Am. Chem. Soc., Wash., D.C.

Hildebrand, S. G., R. H. Strand, and J. W. Huckabee. 1980. Mercury accumulation in fish and invertebrates of the North Fork Holston River, Virginia and Tennessee. J Environ. Qual. 9:393-400.

Hooper, E. T. 1942. The water shrew (*Sorex palustris*) of the southern Allegheny Mountains. Mus. Zool., Univ. Michigan, Ann Arbor. Occas. Pap. 463:1-4.

Hultberg, H., and O. Grahn. 1976. Effects of acid precipitation on macrophytes in oligotrophic Swedish lakes. Pages 208-217 *in* D. H. Matheson and F. C. Edler, eds. Atmospheric contribution to the chemistry of lake waters. Int. Assoc. of Great Lakes Res., J. Great Lakes Res. (Suppl. 1 to Vol. 2).

Hunter, M. L., Jr., J. J. Jones, K. E. Gibbs, and J. R. Moring. 1986*a*. Duckling responses to lake acidification: do black ducks and fish compete? Oikos 47:26-32.

___, ___, J. W. Whitham, and T. M. Mingo. 1986*b*. Biomass and species richness of aquatic macrophytes in four Maine (U.S.A.) lakes of different acidity. Aquat. Bot. 24:91-95.

Hutchinson, T. C. 1978. Conclusions and recommendations. Pages 617-627 *in* T. C. Hutchinson and M. Havas, eds. NATO Conf. on: Effects of acid precipitation on terrestrial ecosystems. Plenum Press, N.Y.

Irving, P. M. 1983. Acidic precipitation effects on crops: a review and analysis of research. J. Environ. Qual. 12:442-453.

Jacknow, J., J. L. Ludke, and N. C. Coon. 1986. Monitoring fish and wildlife for environmental contanminants: the National Contaminant Biomonitoring Program. U. S. Fish and Wildl. Serv., Leafl. 4. 15pp.

Jackson, M. L. 1963. Interlayering of expansible layer silicates in soils by chemical weathering. Pages 29-64 *in* W. F. Bradley, ed. Proceedings of the Eleventh National Conference on Clays and Clay Minerals. Clay Mineral Soc., Ottawa.

Jenkins, D. W. 1980. Biological monitoring of toxic metals: Vol. 1. Biological Monitoring and Surveillance. Environmental Monitoring Systems Laboratory. Off. Res. and Dev., U.S. Environ. Prot. Agency. Las Vegas, Nevada. EPA-600/3-80-089. 215pp.

Johnson, A. H., T. G. Siccama, R. S. Turner, and D. G. Lord. 1984. Assessing the possibility of a link between acid precipitation and decreased growth rates of trees in the northeastern United States. Pages 81-95 *in* R. A. Linthurst, ed. Direct and indirect effects of acidic deposition on vegetation. Acid Precipitation Ser., Vol 5. Butterworth Publishers, Ann Arbor Sci. Book, Ann Arbor, Mich.

Johnson, D. H. 1951. The water shrews of the Labrador Peninsula. Proc. Biol. Soc. Wash. 64:109-116.

Johnson, M. G. 1987. Trace element loadings to sediments of fourteen Ontario lakes and correlation with concentrations in fish. Can. J. Fish. Aquat. Sci. 44:3-13.

Jones, H. G., M. Ouellet, and D. F. Brakke. 1980. The evolution of acidity in surface waters of Laurentides Park (Quebec, Canada) over a period of 40 years. Pages 226-227 *in* D. Drablos and A. Tollan, eds. Ecological impact of acid precipitation. Proc. Int. Conf., Sandefjord, Norway, SNSF Project, Oslo.

Jones, P. J. 1976. The utilization of calcareous grit by laying *Quelea quelea*. Ibis 118:575-576.

Kahl, J. S., S. A. Norton, R. K. MacRae, T. A. Haines, and R. B. Davis. 1989. The influence of organic acidity on the acid-base chemistry of surface waters in Maine, USA. Water, Air, and Soil Pollut. 46:221-233.

Kaiser, A. 1985. Zur Verbreitung und Bestandssituation der Wasseramsel (*Cinclus c. aquaticus*) in Rheinhessen, Rheingau und ostlichem Hunsruck. Okol. Vogel (Ecol. Birds) 7:185-196.

Kaminski, R. M., and H. H. Prince. 1981. Dabbling duck activity and foraging responses to aquatic macroinvertebrates. Auk 98:115-126.

Kaufmann, P. R., A. T. Herlihy, J. W. Elwood, M. E. Mitch, W. S. Overton, M. J. Sale, J. J. Messer, K. A. Cougan, D. V. Peck, K. H. Recknow, A. J. Kinney, S. J. Christie, D. D. Brown, C. A. Hagley, and H. I. Jager. 1988. Chemical characteristics of streams in the mid-Atlantic and southeastern United States. Volume I: Population descriptions and physico-chemical relationships. EPA/600/3-88/021b. U.S. Environ. Prot. Agency, Wash., D.C.

Keller, W., J. R. Pitblado, and J. Carbone. 1992. Chemical responses of acidic lakes in the Sudbury, Ontario, area to reduced smelter emissions., 1981-89. Can. J. Fish Aquat. Sci. 49 (Suppl. 1):25-32.

Kelso, J. R. M., and J. M. Gunn. 1984. Responses of fish communities to acidic waters in Ontario. Pages 105-115 *in* G. R. Hendrey, ed. Early biotic responses to advancing lake acidification. Butterworth Publ., Toronto.

___, C. K. Minns, J. E. Gray, and M. L. Jones. 1986. Acidification of surface waters in eastern Canada and its relationship to aquatic biota. Can. Spec. Publ. Fish. and Aquat. Sci. 87. 42pp.

Kerekes, J. 1990. Possible correlation of summer loon population with the trophic state of a water body. Int. Verein. Limnol. Verh. 24:349-353.

___, and B. Freedman. 1989. Characteristics of three acidic lakes in Kejimkujik National Park, Nova Scotia, Canada. Arch. Environ. Contam. Toxicol. 18:183-200.

___, ___, G. Howell, and P. Clifford. 1984. Comparison of the characteristics of an acidic eutrophic, and an acidic oligotrophic lake near Halifax, Nova Scotia. Water, Pollut. Res. J. Can. 19:1-10.

Knudsen, G. J., and J. B. Hale. 1968. Food habits of otters in the Great Lakes Region. J. Wildl. Manage. 32:89-93.

Korschgen, L. J. 1958. December food habits of mink in Missouri. J. Mammal. 39:521-527.

Kramer, J. R. 1976. Geochemical and lithological factors in acid precipitation. Pages 611-618 *in* Proc. 1*st* Int. Symp. on Acid Precipitation and the Forest Ecosystem. U.S. Dep. Agric., For. Serv., Gen. Tech. Rep. NE-23.

Krause, G. H. M., U. Arndt, C. J. Brandt, J. Bucher, G. Kenk, and E. Matzner. 1986. Forest decline in Europe: development and possible causes. Water, Air, and Soil Pollut. 31:647-668.

Krecker, F. H. 1939. A comparative study of the animal populations of certain submerged aquatic plants. Ecology 20:553-562.

Krueger, G. L., T. K. Morris, R. R. Suskind, and E. M. Widner. 1985. The health effects of aluminum compounds in mammals. CRC Crit. Rev. in Toxicol. 13:1-24.

Krug, E. C., and C. R. Frink. 1983. Effects of acid rain on soil and water. Conn. Agric. Exp. Stn., Bull. 811. New Haven, Conn. 45pp.

Krull, J. N. 1970. Aquatic plant macroinvertebrate associations and waterfowl. J. Wildl. Manage. 34:707-718.

Kucera, E. 1983. Mink and otter as indicators of mercury in Manitoba waters. Can. J. Zool. 61:2250-2256.

Kunz, T. H. 1982. Roosting Ecology. Pages 1-55 *in* T. H. Kunz, ed. Ecology of Bats. Plenum Press, N.Y.

Kuperman, R. G. 1990. Acidic deposition, soil invertebrates, decomposition and nutrient dynamics in oak-hickory forests of the Ohio corridor pollution gradient. Pages 296-304 *in* O. L. Loucks, editor. Air pollutants and forest response: The Ohio corridor study. Holcomb Research Institute, Working Paper 134. Butler University and Miami University.

Landers, D. H., J. M. Eilers, D. F. Brakke, W. S. Overton, P. E. Kellar, M. E. Silverstein, R. D. Schonbrod, R. E. Crowe, R. A. Linthurst, J. M. Omernik, S. A. Teague, and E. P. Meier. 1987. Characteristics of lakes in the western United States. Vol. 1. Population descriptions and physico-chemical relationships. U.S. Environ. Prot. Agency, EPA-600/3-86-054a. Wash., D.C. 176pp.

___, W. S. Overton, R. A. Linthurst, and D. F. Brakke. 1988. Eastern lake survey--regional estimates of lake chemistry. Environ. Sci. Technol. 22:128-135.

LaZerte, B. 1986. Metals and acidification: an overview. Water, Air, and Soil Pollut. 31:569-576.

___, and P. J. Dillon. 1984. Relative importance of anthropogenic versus natural sources of acidity in lakes and streams of central Ontario. Can. J. Fish. Aquat. Sci. 41:1664-1674.

Lehtonen, J. 1989. Effects of acidification on the metal levels in aquatic macrophytes in Espoo, S. Finland. Ann. Bot. Fenn. 26:39-50.

Lerman, A. (ed.) 1978, Lakes: chemistry, geology, physics. Springer-Verlag, N.Y. 363pp.

Leuven, R. S. E. W., C. den Hartog, M. M. C. Christiaans, and W. H. C. Heijligers. 1986. Effects of water acidification on the distribution pattern and the reproductive success of amphibians. Experientia 42:495-503.

Likens, G. E., F. H. Bormann, and N. M. Johnson. 1972. Acid rain. Environment 14:33-40.

___, R. F. Wright, J. N. Galloway, and T. J. Butler. 1979. Acid rain. Sci. Am. 241:43-51.

___, and T. J. Butler. 1981. Recent acidification of precipitation in North America. Atmos. Environ. 15:1103-1109.

Liljestrand, H. M., and J. J. Morgan. 1979. Error analysis applied to indirect methods for precipitation acidity. Tellus 31:421-431.

Lillie, R. A., and J. W. Mason. 1980. pH and alkalinity of Wisconsin lakes--a report to the acid deposition task force. Wis. Dep. Nat. Resour., Madison. 23pp.

Lindberg, P., and T. Odsjo. 1983. Mercury levels in feathers of peregrine falcon *Falco peregrinus* compared with total mercury content in some of its prey species in Sweden. Environ. Pollut (Ser. B) 5:297-318.

Linscombe, G., N. Kinler, and R. J. Aulerich. 1982. Mink. Pages 629-643 *in* J. A. Chapman and G. A. Feldhamer, eds. Wild Mammals of North America, Biology, Management, and Economics. The Johns Hopkins University Press, Baltimore and London.

Linzon, S. N. 1985. Forest damage and acidic precipitation. The E.B. Eddy Distinguished Lecture Series. Presented at the Faculty of Forestry, Univ. of Toronto. 30pp.

____. 1986. Effects of gaseous pollutants on forests in eastern North America. Water, Air, and Soil Pollut. 31:537-550.

Logier, E. B. S. 1958. The snakes of Ontario. Univ. of Toronto Press. 94pp.

Lohm, U. 1980. Effects of experimental acidification on soil organism populations and decomposition. Pages 178-179 *in* D. Drablos and A. Tollan, eds. Ecological impact of acid precipitation. Proc. Int. Conf., Sandefjord, Norway, SNSF Project, Oslo.

Longcore, J. R., R. K. Ross, and K. L. Fischer. 1987. Wildlife resources at risk through the acidification of wetlands. Trans. North Am. Wildl. Nat. Resour. Conf. 52:608-618.

Ma, W.-C., L. Brussaard, and J. A. DeRidder. 1990. Long-term effects of nitrogenous fertilizers on grassland earthworms (Oligochaeta: Lumbricidae): their relation to soil acidification. Agric., Ecosystems and Environ. 30:71-80.

Macan, T. T. 1966. The influence of predation on the bottom fauna of a moorland fish pond. Arch. Hydrobiol. 61:432-452.

MacDonald, D. W. 1983. Predation on earthworms by terrestrial vertebrates. Pages 393-414 *in* J. E. Satchell, ed. Earthworm ecology--from Darwin to vermicultural. Chapman and Hall, N.Y.

MacIntire, W. H., and J. B. Young. 1923. Sulfur, calcium, magnesium and potassium content and reaction of rainfall at different points in Tennessee. Soil. Sci. 15:205-227.

MacLean, S. F. 1974. Lemming bones as a source of calcium for arctic sandpipers (*Calidris* spp.). Ibis 116:552-557.

Malcolm, R. L. 1985. Geochemistry of stream fulvic and humic substances. Pages 181-209 *in* G. R. Aiken, D. M. McKnight, R. L. Wershaw, and P. MacCarthy, eds. Humic substances in soil, sediment, and water: geochemistry, isolation, and characterization. A Wiley-Interscience Publication, John Wiley and Sons, Inc. N.Y.

Manion, P. D. 1987. Decline as a phenomenon in forests: pathological and ecological considerations. Pages 267-275 *in* T. C. Hutchinson and K. M. Meema, eds. Effects of atmospheric pollutants on forests, wetlands, and agricultural ecosystems. Springer-Verlag, Berlin and Heidelberg.

Mattsson, P., L. Albanus, and A. Frank. 1981. Cadmium and some other elements in liver and kidney from moose (*Alces alces*). Var Foda 33(8-9):335-345.

____, and T. H. Kunz. 1982. Roosting Ecology. Pages 1-55 *in* T. H. Kunz, ed., Ecology of Bats. Plenum Press, N.Y.

McAuley, D. G., and J. R. Longcore. 1988*a*. Survival of juvenile ring-necked ducks on wetlands of different pH. J. Wildl. Manage. 52:169-176.

____, D. G., and J. R. Longcore. 1988*b*. Foods of juvenile ring-necked ducks: relationship to wetland pH. J. Wildl. Manage. 52:177-185.

McCahon, C. P., and D. Pascoe. 1989. Short-term experimental acidification of a Welsh stream: toxicity of different forms of aluminum at low pH to fish and invertebrates. Arch. Environ. Contam. Toxicol. 18:233-242.

McFee, W. W., J. M. Kelly, and R. H. Beck. 1977. Acid precipitation effects on soil pH and base saturation of exchange sites. Water, Air, and Soil Pollut. 7:401-408.

McGaha, Y. J. 1952. The limnological relations of insects to certain aquatic flowering plants. Trans. Am. Microscop. Soc. 71:355-381.

McIntyre, J. W. 1989. The Common Loon cries for help. Natl. Geogr. 175:510-524.

McMurtry, M. J., D. L. Wales, W. A. Scheider, G. L. Beggs, and P. E. Dimond. 1989. Relationship of mercury concentrations in lake trout (*Salvelinus namaycush*) and smallmouth bass (*Micropterus dolomieui*) to the physical and chemical characteristics of Ontario lakes. Can. J. Fish. Aquat. Sci. 46:426-434.

McNicol, D. K., B. E. Bendell, and R. K. Ross. 1987*a*. Studies of the effects of acidification on aquatic wildlife in Canada: waterfowl and trophic relationships in small lakes in northern Ontario. Can. Wildl. Serv. Occas. Pap. Ser. 62. Ottawa. 76pp.

___, **B. E. Bendell, and D. G. McAuley.** 1987*b*. Avian trophic relationships and wetland acidity. Trans. North Am. Wildl. Nat. Resour. Conf. 52:619-627.

___, **P. J. Blancher, and B. E. Bendell.** 1987*c*. Waterfowl as indicators of wetland acidification in Ontario. Pages 149-166 *in* A. W. Diamond and F. L. Filion, eds. The value of birds. Int. Counc. for Bird Preserv., Tech. Publ. 6. Cambridge, U.K.

___, **R. K. Ross, and P. J. Blancher.** 1990. Waterfowl as indicators of acidification in Ontario. Can. Intl. Union Game Biol. 19:251-258.

Mendall, H. L., and C. M. Aldous. 1943. The ecology and management of the American woodcock. Maine Coop. Wildl. Res. Unit, Orono, Maine. 201pp.

Miller, D. L., and M. K. Causey. 1985. Food preferences of American woodcock wintering in Alabama. J. Wildl. Manage. 49:492-496.

Miller, D. R., and H. Akagi. 1979. pH affects mercury distribution, not methylation. Ecotoxicol. Environ. Safety 3:36-38.

Miller, G. E., I. Wile, and G. G. Hitchin. 1983. Patterns of accumulation of selected metals in members of the soft-water macrophyte flora of Central Ontario Lakes. Aquat. Bot. 15:53-64.

Mills, K. H., and D. W. Schindler. 1986. Biological indicators of lake acidification. Water, Air, and Soil Pollut. 30:779-789.

___, **S. M. Chalanchuk, L. C. Mohr, and I. J. Davies.** 1987. Responses of fish populations in Lake 223 to 8 years of experimental acidification. Can. J. Fish. Aquat. Sci. Suppl. 1. 44:114-125.

Mineau, P., G. A. Fox, R. J. Norstrom, D. V. Weseloh, D. J. Hallett, and J. A. Ellenton. 1984. Using the herring gull to monitor levels and effects of organochlorine contamination in the Canadian Great Lakes. Pages 425-452 *in* J. O. Nriagu and M. S. Simmons, eds. Toxic contaminants in the Great Lakes. Advances in Environ. Sci. Tech., Vol. 14. A. Wiley-Interscience Publ. John Wiley and Sons, Inc. N.Y.

Mitchell, B. A. 1989. Acid rain and birds: how much proof is needed? Am. Birds 43:234-241.

Moloney, K. A., L. J. Stratton, and R. M. Klein. 1983. Effects of simulated acidic, metal-containing precipitation on coniferous litter decomposition. Can. J. Bot. 61:3337-3342.

Moyle, J. B. 1961. Aquatic invertebrates as related to larger water plants and waterfowl. Minn. Dep. Conser., Invest. Rep. 233. 24pp (mimeo).

Mushak, P. 1985. Potential impact of acid precipitation on arsenic and selenium. Environ. Health Perspect. 63:105-113.

Mushinsky, H. R., and E. D. Brodie. 1975. Selection of substrate pH by salamanders. Am. Midl. Nat. 93:440-443.

NAPAP. 1990. Annual Report, 1989 and Findings Update. Sec. 2, Aquatic effects, Pages F-3 to F-16. NAPAP, Wash., D.C.

___. 1991. National Acid Precipitation Assessment Program--1990. Intergrated Assessment Report. The NAPAP Office of the Director, Wash., D.C. 520pp.

Newman, J. R., and R. K. Schreiber. 1984. Animals as indicators of ecosystem responses to air emissions. Environ. Manage. 8:309-324.

Nilssen, J. P., T. Ostdahl, and W. T. W. Potts. 1984. Species replacements in acidified lakes: physiology, predation or competition? Rep. to Inst. Freshwater. Res. 61:148-153.

Norton, S. A. 1980. Geological factors controlling the sensitivity of aquatic ecosystems to acidic precipitation. Pages 521-531 *in* D. S. Shriner, C. R. Richmond, and S. E. Lindberg, eds. Atmospheric sulfur deposition: environmental impact and health effects. Ann Arbor Sci. Publ. Inc., Ann Arbor, Mich.

___, **J. J. Akielaszek, T. A. Haines, K. L. Stromborg, and J. R. Longcore.** 1982. Bedrock geologic control of sensitivity of aquatic ecosystems in the United States to acidic deposition. Explanatory text for: National Atmospheric Deposition Program (1982), Distribution of surface waters sensitive to acidic precipitation: A state-level atlas. Univ. of Maine, Geological Sciences, Orono, Maine. 66pp.

Nriagu, J. O., and J. M. Pacyna. 1988. Quantitative assessment of worldwide contamination of air, water and soils by trace metals. Nature 333:134-139.

Nussbaum, R. A., and C. Maser. 1969. Observations of *Sorex palustris* preying on *Dicamptodon ensatus*. The Murrelet 50:23-24.

Nyholm, N. E. I. 1981. Evidence of involvement of aluminum in causation of defective formation of eggshells and of impaired breeding in wild passerine birds. Environ. Res. 26:363-371.

___, **and H. E. Myhrberg.** 1977. Severe eggshell defects and impaired reproductive capacity in small passerines in Swedish Lapland. Oikos 29:336-341.

Oden, S. 1968. The acidification of air and precipitation and its consequences on the natural environment. Ecology Committee Bull. 1. Swed. Natl. Acad. Sci. Res. Counc., Stockholm, Sweden. 117pp. [translated by Translation Consultants, Ltd.]

___. 1976. The acidity problem--an outline of concepts. Water, Air, and Soil Pollut. 6:137-166.

Okland, J., and K. A. Okland. 1980. pH level and food organism for fish: Studies of 1,000 lakes in Norway. Pages 326-327 *in* D. Drablos and A. Tollan, eds., Ecological impact of acid precipitation. Proc. Int. Conf., Sandefjord, Norway, SNSF Project, Oslo.

___, **and** ___. 1986. The effects of acid deposition on benthic animals in lakes and streams. Experientia (Basel) 42:471-486.

Omernik, J. M., and C. F. Powers. 1982. Total alkalinity of surface waters--a national map. Environ. Prot. Agency, Environ. Res. Lab., Corvallis, Oreg. EPA-600/D-82-333. 7pp.

___, **and A. J. Kinney.** 1984. Total alkalinity of surface waters: a map of the New England and New York region. Environ. Prot. Agency, Environ. Res. Lab., Corvallis, Oreg. EPA-600/D-84-216. 11pp.

___, **and G. E. Griffith.** 1985 Total alkalinity of surface waters: a map of the Upper Midwest region. Environ. Prot. Agency, Environ. Res. Lab., Corvallis, Oreg. EPA-600/D-85-043. 19pp.

Ormerod, S. J. 1985. The diet of breeding dippers *Cinclus cinclus* and their nestlings in the catchment of the River Wye, mid-Wales: a preliminary study by faecal analysis. Ibis 127:316-331.

___, **and S. J. Tyler.** 1986. The diet of dippers *Cinclus cinclus* wintering in the catchment of the River Wye, Wales. Bird Study 33:36-45.

___, **and** ___. 1987. Dippers (*Cinclus cinclus*) and grey wagtails (*Motacilla cinerea*) as indicators of stream acidity in upland Wales. Pages 191-208 *in* A. W. Diamond and F. L. Filion, eds. Int. Counc. for Bird Preserv. Tech. Publ. 6. Cambridge, U.K.

___, ___, **and J. M. S. Lewis.** 1985. Is the breeding distribution of dippers influenced by stream acidity? Bird Study 32:32-39.

___, **N. Allinson, D. Hudson, and S. J. Tyler.** 1986. The distribution of breeding dippers (*Cinclus cinclus* [L.]; Aves) in relation to stream acidity in upland Wales. Freshwater Biol. 16:501-507.

___, **S. Efteland, and L. E. Gabrielsen.** 1987*a*. The diet of breeding dippers *Cinclus cinclus cinclus* and their nestlings in southwestern Norway. Holarctic Ecol. 10:201-205.

___, **K. R. Wade, and A. S. Gee.** 1987*b*. Macrofloral assemblages in upland Welsh streams in relation to adidity, and their importance to invertebrates. Freshwater Biol. 18:545-557.

___, **K. R. Bull, C. P. Cummins, S. J. Tyler, and J. A. Vickery.** 1988. Egg mass and shell thickness in dippers *Cinclus cinclus* in relation to stream acidity in Wales and Scotland. Environ. Pollut. 55:107-121.

___, **J. O'Halloran, S. D. Gribbin, and S. J. Tyler.** 1991. The ecology of dippers *Cinclus cinclus* in relation to stream acidity in upland Wales: breeding performance, calcium physiology, and nestling growth. J. Appl. Ecol. 28:419-433.

O'Connor, D. G,, and S. W. Nielsen. 1981. Environmental survey of methylmercury levels in wild mink (*Mustela vison*) and otter (*Lutra canadensis*) from the northeastern United States and experimental pathology of methylmercurialism in the otter. Pages 1728-1745 *in* J. A. Chapman and D. Pursely, eds. Worldwide Furbearer Conference Proceedings, Vol. 3, Worldwide Furbearer Conference, Inc. Frostburg, Md.

O'Shea, T. J., and J. L. Ludke. 1979. Monitoring fish and wildlife for environmental pollutants. U. S. Fish and Wildl. Serv., U.S. Gov. Print. Off., Wash., D.C. 12pp.

Paces, T. 1985. Acidification in central Europe and Scandinavia: a competition between anthropogenic, geochemical and biochemical processes. Ambio 14:354-356.

___. 1986. Weathering rates of gneiss and depletion of exchangeable cations in soils under environmental acidification. J. Geol. Soc. Lond. 143:673-677.

Parker, K. E. 1985. Foraging and reproduction of the common loon (*Gavia immer*) on acidified lakes in the Adirondack Park, New York. M.Sc. Thesis, State Univ. of New York, Syracuse, N.Y. 145pp.

____. 1988. Common loon reproduction and chick feeding on acidified lakes in the Adirondack Park, New York. Can. J. Zool. 66:804-810.

Pearse, P. H., F. Bertrand, and J. W. MacLaren. 1985. Currents of change. Final Report. Inquiry on federal water policy. Ottawa. 222pp.

Pehrsson, O. 1974. Nutrition of small ducklings regulating breeding area and reproductive output in the long-tailed duck, *Clangula hyemalis*. Natl. Swed. Environ. Prot. Board., Trans. Intl. Congr. Game Biol. 11:259-264.

____. 1984. Relationships of food to spatial and temporal breeding strategies of mallards in Sweden. J. Wildl. Manage. 48:322-339.

Pfeiffer, M. H., and P. J. Festa. 1980. Acidity status of lakes in the Adirondack region of New York in relation to fish resources. N.Y. Dep. Environ. Conserv., Rep. FW-P168 (10/80). 36pp. (plus appendices I, II, III).

Pierce, B. A. 1985. Acid tolerance in amphibians. Bioscience 35:239-243.

____**, and J. M. Harvey.** 1987. Geographic variation of acid tolerance in Connecticut wood frogs. Copeia 1987:94-103.

____**, J. B. Hoskins, and E. Epstein.** 1984. Acid tolerance of Connecticut wood frogs (*Rana sylvatica*). J. Herpetol. 18:159-167.

Postel, S. 1984. Air pollution, acid rain, and the future of forests. Worldwatch Institute. Worldwatch Paper 58. 54pp.

Pough, F. H. 1976. Acid precipitation and embryonic mortality of spotted salamanders, *Ambystoma maculatum*. Science 192.:68-70.

____**, and R. E. Wilson.** 1977. Acid precipitaton and reproductive success of *Ambystoma* salamanders. Water, Air, and Soil Pollut. 7:307-316.

Raddum, G. G., and A. L. Steigen. 1981. Reduced survival and calorific content of stoneflies and caddisflies in acid water. Pages 97-101 *in* R. Singer, ed. Effects of acidic precipitation on benthos. North Am. Benthol. Soc., Springfield, Ill.

____**, and A. Fjellheim.** 1984. Acidification and early warning organisms in freshwater in western Norway. Verh. Int. Verein. Limnol. 22:1973-1980.

Rattner, B. A., G. M. Haramis, D. S. Chu, C. M. Bunck, and C. G. Scanes. 1987. Growth and physiological condition of black ducks reared on acidified wetlands. Can. J. Zool. 65:2953-2958.

Read, H. J., C. P. Wheater, and M. H. Martin. 1987. Aspects of the ecology of Carabidae (Coleoptera) from woodlands polluted by heavy metals. Environ. Pollut 48:61-76.

Reinecke, K. J., and R. B. Owen, Jr. 1980. Food use and nutrition of black ducks nesting in Maine. J. Wildl. Manage. 44:549-558.

Reuss, J. O., and D. W. Johnson. 1985. Effect of soil processes on the acidification of water by acid deposition. J. Environ. Qual. 14:26-31.

Reynolds, J. W. 1971. The effects of altitude, soil moisture, and soil acidity on earthworms (Oligochaeta: Acanthodrilidae and Lumbricidae) density, biomass, and species diversification in *Liriodendron tulipifera* L. stands in two areas of east Tennessee. Assoc. Southeast. Biol. Bull. 18:52.

____. 1977*a*. Earthworms utilized by the American woodcock. Pages 161-169 *in* D. M. Keppie and R. B. Owen, Jr., eds. Proc. Sixth Woodcock Symposium. Fredericton, N.B.

____. 1977*b*. The earthworms (Lumbricidae and Sparganophilidae) of Ontario. Royal Ontario Museum. 144pp.

Richardson, D. H. S., and C. M. Young. 1977. Lichens and vertebrates. Pages 121-144 *in* M. R. D. Seaward, ed. Lichen Ecology. Academic Press Inc., N.Y.

RMCC. 1990. The 1990 Canadian long range transport of air pollutants and acid deposition report. Part 4: Aquatic effects. Federal/Provincial Research and Monitoring Coordination Committee (RMCC). Environment Canada, Downsview, Ontario. 151pp.

Roberts, D. A., R. Singer, and C. W. Boylen. 1985. The submersed macrophyte communities of Adirondack lakes (New York, U.S.A.) of varying degrees of acidity. Aquat. Bot. 21:219-235.

Rosenqvist, I. Th. 1978. Alternative sources for acidification of river water in Norway. Sci. Total Environ. 10:39-49.

Rosine, W. N. 1955. The distribution of invertebrates on submerged aquatic plant surfaces in Muskee Lake, Colorado. Ecology 36:308-314.

Saber, P. S., and W. A. Dunson. 1978. Toxicity of bog water to embryonic and larval anuran amphibians. J. Exp. Zool. 204:33-42.

Sadleir, R. M. F. S. 1969. The ecology of reproduction in wild and domestic mammals. Methuen and Co. Ltd., Lond. 321pp.

Sadler, K., and S. S. Lynam. 1985. The mineral content of some freshwater invertebrates in relation to stream pH and calcium concentration. Central Electricity Generating Board. Leatherhead, U.K., Rep. TPRD/L/2781/N84.

Satchell, J. E. 1955. Some aspects of earthworm ecology. Pages 180-201 *in* D. K. Mc E. Kevan,. editor. Soil Zoology. Butterworths, Lond.

Sawhney, B. L. 1968. Aluminum interlayers in layer-silicates -- effect of OH/Al ratio of Al solution, time of reaction and type of structure. Clays and Clay Minerals 16:157-163.

Scanlon, P. F., K. I. Morris, A. G. Clark, N. Fimreite, and S. Lierhagen. 1986. Cadmium in moose tissues: comparison of data from Maine, U.S.A. and from Telemark, Norway. Alces 22:303-312.

Scheider, W. A., D. S. Jeffries, and P. J. Dillon. 1979*a*. Effects of acidic precipitation on Precambrian freshwaters in southern Ontario. Int. Assoc. Great Lakes Res., J. Great Lakes Res. 5:45-51.

___, **W. R. Snyder, and B. Clark.** 1979*b*. Deposition of nutrients and major ions by precipitation in south-central Ontario. Water, Air, and Soil Pollut. 12:171-185.

Schell, V. A., and J. J. Kerekes. 1989. Distribution and abundance of benthic macroinvertebrates relative to pH and nutrients in eight lakes of Nova Scotia, Canada. Water, Air, and Soil Pollut. 46:359-374.

Scheuhammer, A. M. 1987*a*. The chronic toxicity of aluminum, cadmium, mercury, and lead in birds: a review. Environ. Pollut. 46:263-295.

___. 1987*b*. Reproductive effects of chronic low-level dietary metal exposure in birds. Trans. North Am. Wildl. Nat. Resour. Conf. 52:658-664.

___. 1988. Chronic dietary toxicity of methylmercury in the zebra finch (*Poephila guttata*). Bull. Environ. Contam. Toxicol. 40:123-130.

___. 1991. Effects of acidification on the availability of toxic metals and calcium to wild birds and mammals. Environ. Pollut. 71:329-375.

Schindler, D. W. 1988. Effects of acid rain on freshwater ecosystems. Science 239:149-157.

___, **and M. A. Turner.** 1982. Biological, chemical and physical responses of lakes to experimental acidification. Water, Air, and Soil Pollut. 18:259-271.

___, **K. H. Mills, D. F. Malley, D. L. Findlay, J. A. Shearer, I. J. Davies, M. A. Turner, G. A. Linsey, and D. R. Cruikshank.** 1985. Long-term ecosystem stress: the effects of years of experimental acidification on a small lake. Science 228:1395-1401.

___, **S. E. M. Kasian, and R. H. Hesslein.** 1989. Biological impoverishment in lakes of the midwestern and northeastern United States from acid rain. Environ. Sci. Technol. 23:573-580.

Schofield, C. 1978. Toxicity of metals. Pages 31-35 *in* G. Hendrey, ed., Limnological aspects of acid precipitation. Brookhaven National Laboratory, Upton, N.Y.

Schreiber, R. K., and J. R. Newman. 1988. Acid precipitation effects on forest habitats: implications for wildlife. Conserv. Biol. 2:249-259.

Schroeder, L. D. 1973. A literature review on the role of invertebrates in waterfowl management. Colo. Div. Wildl., Spec. Rep. 29, 13pp.

Schroeder, W. H., M. Dobson, D. M. Kane, and N. D. Johnson. 1987. Toxic trace elements associated with airborne particulate matter: a review. J. Air Pollut. Contr. Assoc. 37:1267-1285.

Schwarz, I. O. (Chair) 1983 (1987). Saurehaltige Niederschlage-Entstehung und Wirkungen auf terrestrische "Oko systme." [Acidic Precipitation - Formation and impact on terrestrial ecosystems]. VDI Commission for Air Pollution Prevention. Translated by C. Jeffrey Brandt (1986), Wash., D.C.

Scott, M. G., and T. C. Hutchinson. 1987. Effects of a simulated acid rain episode on photosynthesis and recovery in the caribou-forage lichens, *Cladina stellaris* (OPIZ.) Brodo and *Cladina rangiferina* (L.) Wigg. New Phytol. 107:567-575.

Sealander, J. A. 1943. Winter food habits of mink in southern Michigan. J. Wildl. Manage. 7:411-417.

Seale, D. B. 1980. Influence of amphibian larvae on primary production, nutrient flux, and competition in a pond ecosystem. Ecology 61:1531-1550.

Shaw, G. G. 1983. Acid rain SO_4 and food quality for wild herbivores. Interim Rep., Can. Wildl. Serv., Ottawa. 18pp.

___, **and L. Cocks.** 1982. The effect of SO_2 on food quality for wild herbivores. Pages 571-587 *in* Symposium/Workshop Proceedings: Acid Forming Emissions in Alberta and Their Ecological Effects. Alberta Dep. Environ., Can. Petroleum Assoc. Oil Sands Environ. Study Group, 9-12 Mar. 1982. Edmonton, Alberta.

Sheldon, W. G. 1971. The book of the American woodcock. Univ. of Mass. Press, Amherst. 227pp.

___, **and W. G. Toll.** 1964. Feeding habits of the river otter in a reservoir in central Massachusetts. J. Mammal. 45:449-455.

Siccama, T. G., M. Bliss, and H. W. Vogelmann. 1982. Decline of red spruce in the Green Mountains of Vermont. Bull. Torrey Bot. Club 109:162-168.

Sigal, L. L., and J. W. Johnston, Jr. 1986*a*. Effects of acidic rain and ozone on nitrogen fixation and photosynthesis in the lichen *Lobaria pulmonaria* (L.) Hoffm. Environ. and Exp. Bot. 26:59-64.

___, **and** ___. 1986*b*. Effects of simulated acidic rain on one species each of *Pseudoparmelia, Usnea*, and *Umbilicaria*. Water, Air, and Soil Pollut. 27:315-322.

Sileo, L., and W. N. Beyer. 1985. Heavy metals in white-tailed deer living near a zinc smelter in Pennsylvania. J. Wildl. Dis. 21:289-296.

Singer, R., and K. L. Fischer. 1984. Other related biota. Pages 5-129 - 5-139 *in* A. P. Altshuller and R. A. Linthurst, eds. The acidic deposition phenomena [*sic*] and its effects: Critical Assessment Review Papers, Vol. II, Effects Sciences. N.C. State Univ. Acid Precipitation Program, Raleigh, N.C. U.S. Environ. Prot. Agency, Off. Res. and Dev., EPA-600/8-83-0168BF. Wash., D.C.

Sloan, R., and C. L. Schofield. 1983. Mercury levels in brook trout (*Salvelinus fontinalis*) from selected acid and limed Adirondack lakes. Northeast. Environ. Sci. 2:165-170.

Smith, R. A. 1852. On the air and rain of Manchester. Mem. Manchester Lit. and Philos. Soc., Ser. 1, 10:207-217.

___. 1872. Air and Rain-- the beginnings of a chemical climatology. Longmans, Green, and Co., Lond. 600pp.

Sorenson, M. W. 1962. Some aspects of water shrew behavior. Am. Midl. Nat. 68:445-462.

Sparling, D. W. 1990. Acid precipitation and food quality: Inhibition of growth and survival in black ducks and mallards by dietary aluminum, calcium and phosphorus. Arch. Environ. Contam. Toxicol. 19:457-463.

Spry, D. J., and J. G. Wiener. 1991. Metal bioavailability and toxicity to fish in low-alkalinity waters: a critical review. Environ. Pollut. 71:243-304.

Steinnes, E. 1989. Cadmium in the terrestrial environment: Impact of long-range atmospheric transport. Tox. Environ. Chem. 19:139-145.

Stensland, G. J. 1979. Calculating precipitation pH with application to the Junge data. Pages 79-108 *in* R. G. Semonin, J. Bartlett, D. F. Gatz, M. E. Peden, L. M. Skowron, and G. J. Stensland, eds. Study of atmospheric pollution scavenging. 17*th* Prog. Rep., Contract No. EY-76-S-02-1199. Atmos. Sci. Sec., Ill. State Water Survey, Urbana.

___, **and R. G. Semonin.** 1982. Another interpretation of the pH trend in the United States. Bull. Am. Meteorol. Soc. 63:1277-1284.

Stenson, J. A. E., and M. O. G. Eriksson. 1989. Ecological mechanisms important for the biotic changes in acidified lakes in Scandinavia. Arch. Environ. Contam. Toxicol. 18:201-206.

Stephenson, M., and G. L. Mackie. 1986. Lake acidification as a limiting factor in the distribution of the freshwater amphipod *Hyalella azteca*. Can. J. Fish. Aquatic. Sci. 43:288-292.

St. Louis, V. L., and L. Breebaart. 1991. Calcium supplements in the diet of tree swallows nesting near acid sensitive lakes. Condor 93:286-294.

___, ___, **and J. C. Barlow.** 1990. Foraging behaviour of tree swallows over acidified and nonacidic lakes. Can. J. Zool. 68:2385-2392.

Stoewsand, G. S., C. A. Bache, and D. J. Lisk. 1974. Dietary selenium protection of methylmercury intoxication of Japanese quail. Bull. Environ. Contam. Toxicol. 11:152-156.

Storer, N. L., and T. S. Nelson. 1968. The effect of various aluminum compounds on chick performance. Poult. Sci. 47:244-247.

Street, H. R. 1942. The influence of aluminum sulfate and aluminum hydroxide upon the absorption of dietary phosphorus by the rat. J. Nutr. 24:111-119.

Strijbosch, H. 1979. Habitat selection of amphibians during their aquatic phase. Oikos 33:363-372.

Suns, K., C. Curry, and D. Russell. 1980. The effects of water quality and morphometric parameters on mercury uptake by yearling yellow perch. Ont. Minist. Environ., Tech. Rep. LTS 80-1, Rexdale, Ont.

Swanson, G. A., and M. I. Meyer. 1973. The role of invertebrates in the feeding ecology of Anatidae during the breeding season. Pages 143-185 *in* The Waterfowl Habitat Management Symposium at Moncton, New Brunswick, Canada. Atlantic Waterfowl Council.

Thompson, D. C., and K. H. McCourt. 1981. Seasonal diets of the Porcupine Caribou Herd. Am. Midl. Nat. 105: 70-76.

Tome, M. A., and F. H. Pough. 1982. Responses of amphibians to acid precipitation. Pages 245-254 *in* T. A. Haines and R. E. Johnson, eds. Acid Rain/Fisheries: Proceedings of an International Symposium on Acidic Precipitation and Fishery Impacts in Northeastern North America. Am. Fish. Soc., North. Div. Bethesda, Md.

Ulrich, B. 1982. An ecosystem oriented hypothesis on the effect of air pollution on forest ecosystems. Background paper for expert meeting on effects of acid deposition, Stockholm, June, 1982. 17pp.

____. 1983. Soil acidity and its relation to acid deposition. Pages 127-146 *in* B. Ulrich and J. Pankrath, eds. Effects of Accumulation of Air Pollutants in Forest Ecosystems. D. Reidel Publ. Co. Dodrecht and Boston.

____, R. Mayer, and P. K. Khanna. 1980. Chemical changes due to acid precipitation in a loess-derived soil in central Europe. Soil Sci. 130:193-199.

Vernberg, J. F. 1955. Correlation of physiology and behavior indexes of activity in the study of *Plethodon cinereus* (Green) and *Plethodon glutinosus* (Green). Am. Midl. Nat. 54:382-393.

Vickery, J. A. 1989. The effects of surface water acidification on riparian birds - with particular reference to the dipper. Ph. D. Thesis, Oxford Univ.

Voigts, D. K. 1976. Aquatic invertebrate abundance in relation to changing marsh vegetation. Am. Mid. Nat. 95:313-322.

Washko, P. W., and R. J. Cousins. 1977. Role of dietary calcium and calcium binding protein in cadmium toxicity in rats. J. Nutr. 107:920-928.

Watras, C. J., and T. M. Frost. 1989. Little Rock Lake (Wisconsin): perspectives on an experimental ecosystem approach to seepage lake acidification. Arch. Environ. Contam. Toxicol. 18:157-165.

Watt, W. D., D. Scott, and S. Roy. 1979. Acidification and other chemical changes in Halifax County lakes after 21 years. Limnol. Oceanogr. 24:1154-1161.

Wayland, M., and D. K. McNicol. 1990. Status report on the effects of acid precipitation on common loon reproduction in Ontario: the Ontario Lakes Loon Survey. Can. Wildl. Serv. Tech. Rep. Ser. 92, Can. Wildl. Serv., Ottawa. 26pp.

Wiener, J. G. 1987. Metal contamination of fish in low-pH lakes and potential implications for piscivorous wildlife. Trans. North Am. Wildl. Nat. Resour. Conf. 52:645-657.

____, and P. M. Stokes. 1990. Enhanced bio-accumulation of mercury, cadimum, and lead in low-alkalinity waters: an emerging regional environmental problem. Environ. Toxicol. Chem. 9:821-823.

____, W. R. Fitzgerald, C. J. Watras, and R. G. Rada. 1990. Partitioning and bioavailability of mercury in an experimentally acidified Wisconsin lake. Environ. Toxicol. Chem. 9:909-918.

Wilbur, H. M. 1984. Complex life cycles and community organization in amphibians. Pages 195-224 *in* P. W. Price, C. N. Slobodchikoff, and W. S. Gaud, eds. A new ecology: novel approaches to interactive systems. Wiley-Interscience Publ., N.Y.

Wile, I, and G. Miller. 1983. The macrophyte flora of 46 acidified and acid-sensitive soft water lakes in Ontario. Ontario Ministry of the Environment. 35pp.

____, G. E. Miller, G. G. Hitchin, and N. D. Yan. 1985. Species composition and biomass of the macrophyte vegetation of one acidified and two acid-sensitive lakes in Ontario. Can. Field-Nat. 99:308-312.

Winfrey, M., and J. Rudd. 1990. Environmental factors affecting the formation of methymercury in low-pH lakes. Environ. Toxicol. Chem. 9:853-869.

Wisniewski, J, and E. L. Keitz. 1983. Acid rain deposition patterns in the continental United States. Water, Air, and Soil Pollut. 19:1-13.

Wren, C. D. 1984. Distribution of metals in tissues of beaver, raccoon and otter from Ontario, Canada. Sci. Total Environ. 34:177-184.

____. 1986*a*. A review of metal accumulation and toxicity in wild mammals. I. Mercury. Environ. Res. 40:210-244.

____. 1986*b*. Mammals as biological monitors of environmental metal levels. Environ. Monit. and Asses. 6:127-144.

____, **P. M. Stokes, and K. L. Fisher.** 1986. Mercury levels in Ontario mink and otter relative to food levels and environmental acidification. Can. J. Zool. 64:2854-2859.

____, **and H. R. MacCrimmon.** 1983. Mercury levels in sunfish (*Lepomis gibbosus*) relative to pH and other environmental variables of Precambrian Shield lakes. Can. J. Fish. Aquat. Sci. 40:1737-1744.

____, **and G. L. Stephenson.** 1991. The effect of acidification on the accumulation and toxicity of metals to freshwater invertebrates. Environ. Pollut. 71:205-241.

____, **and P. M. Stokes.** 1988. Depressed mercury levels in biota from acid and metal stressed lakes near Sudbury, Ontario. Ambio 17:28-30.

____, **H. MacCrimmon, R. Frank and P. Suda.** 1980. Total and methyl mercury levels in wild mammals from the Precambrian Shield area of south central Ontario, Canada. Bull. Environ. Contam. Toxicol. 25:100-105.

____, **H. R. MacCrimmon, and B. R. Loescher.** 1983. Examination of bioaccumulation and biomagnification of metals in a Precambrian Shield lake. Water, Air, and Soil Pollut. 19:277-291.

Wrigley, R. E. 1969. Ecological notes on the mammals of southern Quebec. Can. Field-Nat. 83:201-211.

Wyman, R. L., and D. S. Hawksley-Lescault. 1987. Soil acidity affects distribution, behavior, and physiology of the salamander, *Plethodon cinereus*. Ecology 68:1819-1827.

Yan, N. D., and P. J. Dillon. 1984. Experimental neutralization of lakes near Sudbury, Ontario. Pages 417-456 *in* J. Nriagu, ed. Environmetal impacts of smelters. John Wiley and Sons, Inc. N.Y.

____, **G. L. Mackie, and D. Boomer.** 1989. Chemical and biological correlates of metal levels of crustacean zooplankton of Canadian shield lakes: a multivariate analysis. Sci. Total Environ. 87/88:418-438.

Xun, L., N. Campbell, and J. Rudd. 1987. Measurements of specific rates of net methyl mercury production in the water column and surface sediments of acidified and circumneutral lakes. Can. J. Fish. and Aquatic Sci. 44:750-757.

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