ACIDIFICATION OF LAKES IN CANADA BY ACID PRECIPITATION AND THE RESULTING EFFECTS ON FISHES

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Abstract. In the Sudbury region of Ontario, Canada, fallout of sulfur oxides has been shown to be responsible for damage to vegetation, lakes and fishes.

The acidic fallout has been shown to effect a rate of acidification in many lakes that over several decades has resulted in the extinction of many species of fishes. Fish exhibit profound differences in acid tolerance but show some similarities in their physiological response to levels within the range of their individual susceptibilities. Prior to extinction most females of a particular species did not release their ova to be fertilized. The failure of females to spawn was coincident with an inability to maintain normal serum Ca levels. In some species growth was reduced despite an adequate supply of preferred food items. High concentrations of acid were considered to be the principal factor stressing the fish populations. Elevated concentrations of some heavy metals may add to the stress caused by high concentrations of acid.

1. Acid Precipitation in Canada

It is the intention of this paper to discuss the effects of acid precipitation on Canadian lakes and fishes. However it is only in the Sudbury, Ontario area that such effects have been well documented. The principal source of acid entering the Sudbury lakes comes from local Ni mining and smelting industries. In 1969 it was estimated that 2.6×10^6 metric t of sulfur oxide were released into the atmosphere from the Sudbury area (Beamish and Harvey, 1972). In 1970 the emissions were estimated to be equivalent to half of Canada's total emissions (EPS, 1973) or about 10% of the total United States of America emissions (Beamish, 1974a). In fact the Sudbury area may have the dubious distinction of being the largest single source of SO_2 in the world. The second largest point source (about 700 000 metric t) in Canada is at Noranda, Quebec about 138 km north of Sudbury (EPS, 1973) (Figure 1). Excluding the major cities of Toronto and Montreal and the important emission areas of Sudbury and Noranda there are only four or five other point sources ranging in annual emissions of 200 000 to 400 000 metric t that can be considered to be potential sources of acid precipitation to nearby lakes. In one of these areas, near Flin Flon, Manitoba a survey in 1973 of 27 lakes in the vicinity of the smelter revealed only one lake with a pH below 6.5 (Van Loon and Beamish, 1977). The one acid lake (pH 4.0–5.0) received acid effluent in the spring from a holding area. At present there is no other information that identifies other point sources of SO_2 in Canada as causing the acidification of lakes.

Similarly there is no published study at present that identifies long-range transportation of acid (from many point sources) as affecting Canadian lakes. Several studies have reported that fallout of acid has occurred and with hindsight long-range transport of acid may have been involved. On April 9, 1970 Barica and Armstrong (1971)

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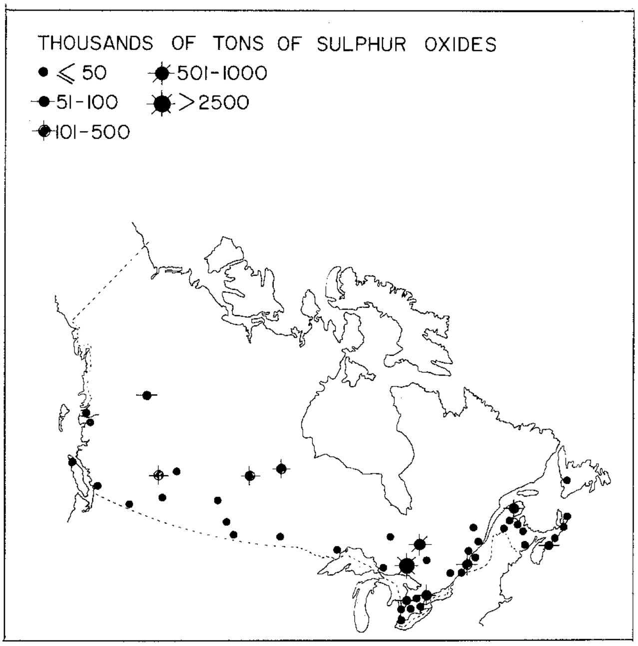

Fig. 1. Summary of principal sources of sulfur oxide emissions in Canada (from EPS, 1973).

recorded a snow at the Experimental Lakes Area (E.L.A.), in northwestern Ontario that contained excessive particulate material and sulfate concentrations 5 to 10 times greater than measured in previous samples. Since there are no major industrial areas in the vicinity of E.L.A. it appears that this fallout could have originated somewhere in the north central United States. Precipitation may also be the principal source of nutrients to the E.L.A. lakes (Schindler, 1971). In Halifax County, Nova Scotia acid lakes were found (Gorham, 1957) in which the acidity could not be completely accounted for by natural processes. Gorham felt that rain was a major source of SO_4 for some of these lake waters as 'suggested by recent analyses of Herman (unpublished), who found an average of 0.96 ppm total S, equivalent to 2.9 ppm SO_4, in rain collected over a 2 yr period at the Dominion Experimental Station, Kentville, Nova Scotia'. This is one of the earliest records of acid precipitation in Canada and it is possible that the source of this acid was either from the Halifax area or from combined areas on the east coast of North America.

2. Acid Precipitation in the Sudbury Area

The effects of acid fallout on plants and soils in the Sudbury area have been demonstrated in numerous studies over the past 30 yr (McCallum, 1944; Linzon, 1958, 1966, 1971; Gorham and Gordon, 1960a,b; McGovern and Basillie, 1972, 1973; Whitby and Hutchinson, 1974; Le Blanc *et al.*, 1972; Stokes *et al.*, 1973; and others). However the effects of Sudbury emissions on lakes have not been as extensively studied. Studies undertaken in the early 1960s did show a deterioration in water quality of lakes and ponds in the immediate Sudbury area (Gorham and Gordon, 1960a, 1963) and recently lakes located in the La Cloche Mountains some 65 km southwest of the smelters have been found to be extremely acidic (Beamish and Harvey, 1972).

There is good evidence to indicate that the Sudbury smelters are the principal source of acid entering the La Cloche Mountain lakes. As previously mentioned it is known that extremely large quantities of SO_2 are released annually into the atmosphere around Sudbury. A summary of the average percentage of wind hours as recorded at Sudbury, Ontario from 1961 to 1973 (Department of Transport, monthly record of meterological observations in Canada) indicates the prevailing wind directions are northeast and southwest (Figure 2a). By comparing the mean ground SO_2 concentrations from 1964 to 1968 (Figure 2b redrawn from Dreisinger and McGovern, 1970) it is apparent that SO_2 falls out in decreasing concentrations from the smelters in the direction of the prevailing winds. A similar fallout pattern occurs for Ni, Fe, and Cu (McGovern and Basillie, 1973; Kramer, 1973a). It is also known that the Sudbury smelters release large quantities of heavy metals into the atmosphere. Stack emission reports prepared by one of the companies indicate that approximately 14 500 t of Fe, 2000 t of Ni, and 1800 t of Cu have been released annually into the atmosphere over the last decade (Falkowski, 1973).

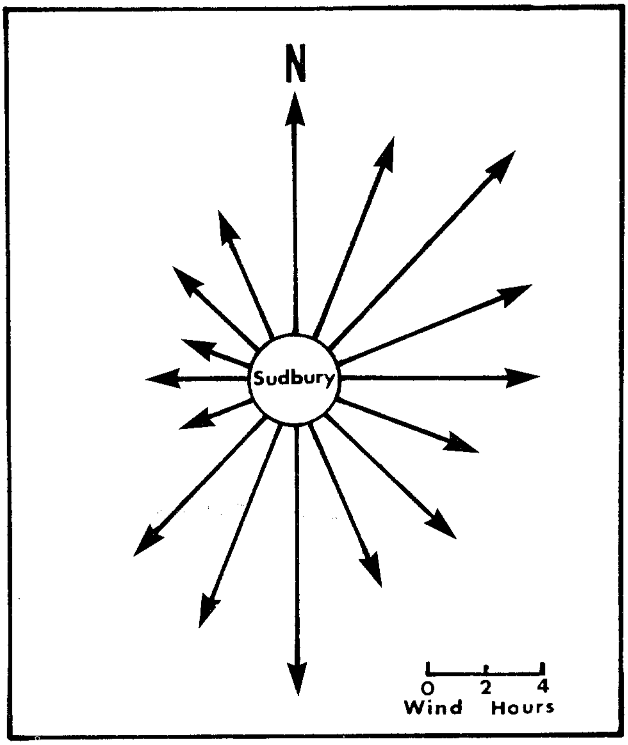

Fig. 2a. Average percentage of time wind blew in each of 16 compass directions. Length of arrows indicates the average percentage of wind-hours that were recorded for each direction from 1961 to 1972. Data obtained from Department of Transport, monthly meteorological observations in Canada.

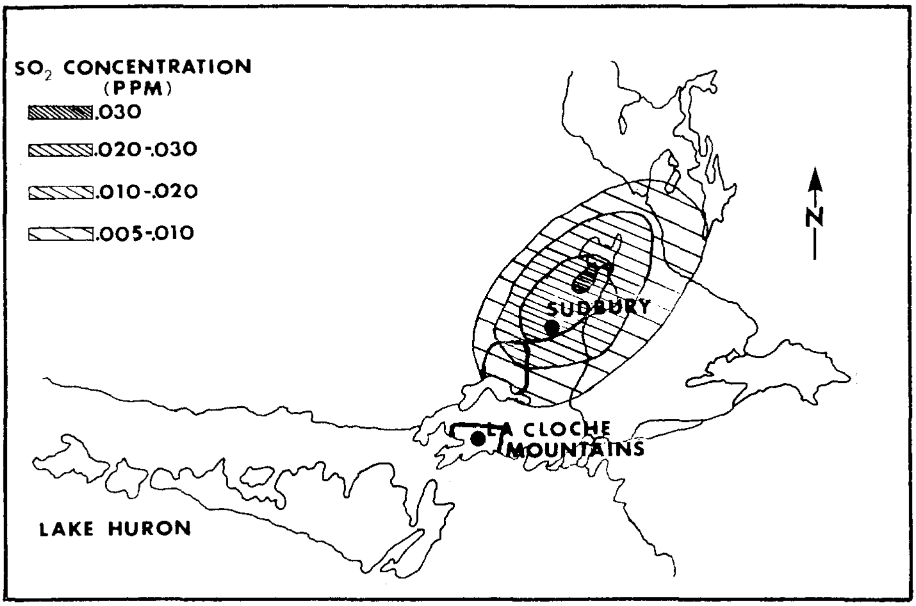

Fig. 2b. Average ground concentrations of SO_2 in the Sudbury area from 1964 to 1968. (Figure reproduced from Dreisinger and McGovern, 1970).

Plumes from the four main Sudbury smelters combined to form a plume approximately 25 km wide and contained SO_2 concentrations ranging from 0.3 to 0.02 ppm at a distance of 40 km from Sudbury (Whaley and Lee, 1971). Whaley and Lee (1974) used the plume dispersion study to show that high ground-level SO_2 concentrations measured at a site 36 km southwest of the Sudbury smelters during fumigation conditions could be attributed to Sudbury smelter emissions. These authors calculated ground-level SO_2 levels using the plume dispersion study and Sudbury smelter production figures, and were able to obtain a good correlation between observed and predicted ground-level SO_2 concentrations over the period 1961–1971.

In the immediate Sudbury area the pH of precipitation has been reported to average about 4.5 with an extreme low of 3.2 (Kramer, 1973a). In the La Cloche Mountains, the average pH of 18 precipitation events from 1972 to 1973 was 4.3 (Beamish and Van Loon, 1977). and the average pH of monthly precipitation collections for this period was 4.4. The lowest pH measured was 2.9 (Beamish and Harvey, 1972). As mentioned, precipitation in the Sudbury area also contains high concentrations of Ni and Cu (Beamish and Van Loon, 1975; Kramer, 1973b). Kramer (1973b) claimed that most of northern Ontario has been subjected to rates of fall of Ni that are 10 times the rate observed in the Continental United States. The consistent observation that substances or byproducts of substances known to be emitted from the smelters occur in precipitation; the evidence that concentrations decrease with distance from the smelters in the direction of the prevailing winds; the calculations showing that the plume disperses over great distances and ground-level concentrations can be related to concentrations of SO_2 in the plume; the effective 'labelling' of this plume by the high levels of Ni emitted by the industries and the anomalously high Ni concentrations in precipitation leave little doubt that fallout of substances from the plume is occurring in the Sudbury area.

It can be shown that this fallout has altered the water quality of lakes in the Sudbury area. Harvey (1975) has measured the sulfate concentration of over 100 lakes and found concentrations were highest close to the smelters and decreased with distance from the smelters. Sulfate ions were partially balanced to H ions indicating that part of the sulfate that was entering the lake from the atmosphere was in the form of H_2SO_4. A survey of 150 lakes in the La Cloche Mountain area indicated that some 33 lakes had a pH of 4.5 or less and one-half of the lakes had a pH of 5.5 or lower (Beamish and Harvey, 1972). From a study of the pH change in one lake over a period of 5 yr it was shown that the lake was acidifying at a rate of approximately 0.13 pH units per year (Beamish *et al.*, 1975a). This compares with an estimated average decrease of 0.16 pH units for 22 La Cloche Mountain lakes for which determinations measured in 1971 could be compared to readings taken 10 yr earlier (Beamish and Harvey, 1972).

A detailed examination of the precipitation loading of acid to a small lake in the La Cloche Mountains from 1972 to 1973 showed that this 21 ha lake received approximately 2100 kg of H_2SO_4 from precipitation in 1972, that would be capable of depressing the pH below its January 1972 value (Beamish and Van Loon, 1977) A titration curve, calculated using lake water obtained during an earlier period of higher pH, predicted that the addition of this much acid would reduce the pH of the lake from 5.2 to 4.8. The actual measured change was from 5.2 to 4.7. In 1973, 600 kg H_2SO_4 were added to the lake from precipitation that would be capable of depressing the pH below the January 1973 concentration. The titration curve for the lake predicted a pH change from 4.8 to 4.74. By January 1973, the lake pH had risen from 4.7 to 4.8 and there was no net change in pH throughout the year. Thus the pH of this lake during this 2 yr period was closely related to the acid content of the precipitation.

This study and others (Beamish, 1974a; Beamish *et al.*, 1975a,c) also indicated that lakes in the La Cloche Mountains contained high concentrations of Ni and Cu when compared to concentrations measured in lakes remote from major areas of industrialization. The remote area used for a comparison was part of the Canadian Shield as were the La Cloche Mountain lakes (Beamish *et al.*, 1975b).

It has been shown that the Sudbury plume was responsible for the deposition of SO_2, acid and Ni. It has also been shown that many La Cloche Mountain lakes were acid, contained elevated concentrations of Ni and probably responded to atmospheric loadings of acid as closely as the one lake studied. Therefore, there can be little doubt that industry in Sudbury has been a major contributor to the atmospheric pollution that has altered the water quality of these lakes.

3. Changes in Water Chemistry

Changes in water chemistry of Canadian lakes as a result of atmospheric inputs of acid have been described in only a few reports. Also it is difficult to examine changes in lake chemistry when the lake chemistry was not described before the change occurred. However, by comparing the chemistry of acidified lakes with the chemistry of unpolluted lakes from a similar geological area it is possible to gain some insight into the changes that have occurred.

As might be expected, sulfate concentrations have been shown to be high in many acidified lakes (Gorham and Gordon, 1960a; Harvey, 1975; Beamish and Van Loon, 1977). The high sulfate concentrations were found in association with low pH and by balancing anions and cations it was possible to demonstrate that part of the sulfate ion is balanced with H ion, indicating the pH results from the presence of H_2SO_4 (Beamish, 1974a). A comparison of the major ions in four of the acid lakes with unpolluted lakes (Table I) (see also Beamish, 1974a) indicated that the ionic composition was similar except for H and sulfate ions. Hydrogen ions were two to three orders of magnitude greater in the acidic lake than in the E.L.A. lakes and sulfate represented approximately 90% of the anions compared to an average of about 40% for the E.L.A. lakes.

Calcium concentrations were slightly higher in the acid La Cloche Mountain lakes (average 2.6 mg l^{-1}, Table II) than the average (2.0 mg l^{-1}) for the 102 E.L.A. lakes (Table I). Gorham and Gordon (1960) reported that Ca in ponds near Sudbury

TABLE I

Chemical composition of four acid lakes and non-polluted lakes in a remote area of N.W. Ontario. For details of water chemistry see references. Range in brackets

	O.S.A.[a]	Muriel[a]	George[b]	Lumsden[c]	102 lakes E.L.A. N.W. Ontario[d]
pH	4.5 (4.4–4.9)	4.7 (4.5–4.8)	5.0 (4.8–5.3)	4.8 (4.7–5.3)	6.5
Sulfate mgl^{-1}	15 (14–17)	15 (14–15)	14.3 (12–16)	10.7 (10.0–12.6)	3.8
Chloride mgl^{-1}	1(<1–1)	<1 (<1–1)	1.0 (0.6–1.6)	0.7 (0.5–1.2)	0.8
Na mgl^{-1}	0.6 (0.6–0.8)	0.6 (0.6–0.7)	0.8 (0.7–1.0)	0.4 (0.4–0.8)	0.9
Ca mgl^{-1}	3.2 (2.9–3.7)	3.4 (3.1–3.4)	3.2 (1.8–4.0)	2.2 (1.4–2.9)	2.0
Mg mgl^{-1}	0.9 (0.7–1.0)	0.9 (0.7–0.9)	1.0 (0.9–1.6)	0.7 (0.5–1.0)	0.6
K mgl^{-1}	0.4 (0.3–0.5)	0.3 (0.3–0.4)	0.5 (0.3–0.6)	0.3 (0.2–0.4)	0.3
Hardness (as $CaCO_3$) mgl^{-1}	11 (10–14)	11 (11–12)	12.3 (7.9–16.4)	8.4 (5.6–11.3)	7.5
Total dissolved solids mgl^{-1}	23 (7–59)	16 (15–16)	28 (10–49)	18 (10–25)	—
Total suspended solids mgl^{-1}	1 (0–2)	1 (0–1)	<1 (<1–4)	<1 (<1–4)	2
Bicarbonate alkalinity (as $CaCO_3$) mgl^{-1}	0.5	<0.5	<0.5	<0.5	10
Conductivity μmho cm^{-2}	48 (46–53)	32 (8–47)	40 (35–45)	32 (27–35)	19
Fe μg l^{-1}	23 (18–29)	40 (34–46)	27 (7–45)	35 (13–77)	143
Ni μg l^{-1}	11 (8–13)	12 (10–15)	10 (5–15)	8 (6–9)	<3
Cu μg l^{-1}	4 (2–6)	2 (2–4)	2 (1–8)	4 (2–16)	2
Zn μg l^{-1}	36 (30–48)	29 (25–31)	24 (8–45)	32 (17–35)	<1
Cd μg l^{-1}	<1	<1	<0.5 (<0.5)	0.4 (0.2–0.5)	<0.1
Pb μg l^{-1}	4 (2–6)	1 (0–3)	<2 (<2)	2 (1–3)	<1
Mn μg l^{-1}	—	—	220 (160–260)	258 (210–310)	3

[a] Beamish (1974a)
[b] Beamish *et al.* (1975a)
[c] Beamish and Van Loon (1977)
[d] Beamish *et al.* (1975b)

smelters appeared to decrease between pH 6 and pH 5 while below pH 5 Ca concentrations appeared to increase. There is some historic data of unknown analytical quality for the La Cloche lakes that suggests the Ca concentrations were at least double their present values. The historic data are to some extent corroborated by the observation that the less acidic Kakakise Lake (Table II) has a Ca concentration almost double the values of the nearby acid lakes. Since Ca appears to be very important to the survival of fish (Beamish *et al.*, 1975b) more information concerning the effect of acidification on the Ca content of lakes may be necessary for a thorough understanding of the response of fish to acidification.

TABLE II

Calcium concentrations (mg l^{-1}) for acidic lakes in the La Cloche Mountains

Lake	pH average	pH (range)	Ca average	Ca (range)	Lake	pH	Ca
George	5.0	(4.8–5.3)	3.2	(0.8–4.0)	1A[a]	4.4	2.2
Lumsden	4.8	(4.7–5.3)	2.2	(1.4–2.9)	2A	4.8	2.2
O.S.A.	4.5	(4.4–4.9)	3.2	(2.9–3.7)	3A	4.1	2.0
Muriel	4.7	(4.5–4.8)	3.4	(3.1–3.4)	4A	4.4	2.1
Kakakise	5.6		4.1		5A	4.5	1.1
A.Y. Jackson	4.4		2.9		6A	4.5	2.3

[a] Not named. See Beamish *et al.* (1974a) for locations.

It is apparent that bicarbonate alkalinity (as mg l^{-1} $CaCO_3$) will be greatly reduced in any lake of low pH. Alkalinity of the acidic La Cloche Mountain lakes was less than 0.5 mg l^{-1} which was at the limit of detection. By comparison alkalinity of the E.L.A. lake averaged 11.4 mg l^{-1} (Table I).

Heavy metal concentrations in the La Cloche lakes appeared to be greatly altered during the acidification process. As previously mentioned Ni and to a lesser extent Cu concentrations were higher in the acidic lakes than in the E.L.A. lakes. Nickel concentrations ranged from 8 to 12 $\mu g\ l^{-1}$, many times higher than found in most lakes (Table I; Beamish, 1974a). Copper concentrations averaged 2 to 5 $\mu g\ l^{-1}$ but were only slightly higher than found in the E.L.A. lakes. As previously discussed the higher concentrations of Ni (and Cu) appear to result from precipitation loadings (Beamish and Van Loon, 1977; Kramer, 1973a,b). Zinc concentrations (25 to 46 $\mu g\ l^{-1}$) were rather normal when compared to an average concentration of 49 $\mu g\ l^{-1}$ obtained for over 1500 samples from waters within the United States of America (Kopp and Kroner, 1969). They were, however, much higher than the average value for E.L.A. lakes. Zinc concentrations were similar in the acidic La Cloche Mountain lakes and lakes of similar pH in Sweden (Beamish and Van Loon, 1977; Hörnström *et al.*, 1973). Manganese concentrations were also high in both the La Cloche lakes and Swedish lakes. While the higher levels of Zn may be partly due to precipitation loading and increasing solubility at lower pH, the higher concentrations of Mn appear to be the result of increased solubility (Beamish and Van Loon, 1977).

4. Effects of Lake Acidification on Fishes

Extensive fishing operations have documented the absence of fish populations for several of the acidic La Cloche Mountain lakes (Beamish and Harvey, 1972; Beamish, 1974a; Beamish *et al.*, 1975a). Less intensive netting operations enabled a greater number of lakes to be examined and it was found that 28 of 67 lakes in the La Cloche Mountain region had lost the majority of their fishes.

In George Lake (Beamish *et al.*, 1975a) the condition of the ovaries of female fish was examined before, during and after the pH was reduced to levels that affected many of the resident species. Observations on the condition of the ovaries were also made on fishes from lakes in which the acid concentrations were high prior to the commencement of any study. It was found that most species ceased reproducing at pH values that varied among species, before major 'fish kills' occurred. Failure to reproduce was indicated by the failure of females to release ova. Ovaries were mature prior to the normal spawning period but few, if any, fish were found with spawned ovaries after the normal spawning period. Ova became flaccid and watery and fish appeared to resorb material from ovaries. Some old fish were found in this condition (Beamish, 1974a) suggesting that the development of ova but the failure to spawn may continue in some species for many years. It could not be determined if loss in production because of egg or fry mortalities occurred prior to the complete failure of females to release ova. Reduced recruitment appeared to occur for some species, however it was not determined if this reduction resulted from a reduced number of adults spawning; a reduced number of fertilized eggs deposited or an increased egg or fry mortality. Because recruitment into a population stopped after spawning ceased, the pH range at which spawning was inhibited was considered the critical value for the survival of the particular population. At concentrations greater than this value, the numbers in a population would decrease in response to the natural mortality rate which may be increased because of the added stress of the low pH.

Because different species responded to different levels of acidification and because reproduction appeared to be the most sensitive major physiological process that was critical to the survival of the species, it was necessary to determine the approximate pH at which species ceased reproduction. The term 'critically acidic' was adopted and defined to be the pH which was sufficient to inhibit reproduction of a particular species (Beamish, 1974a). A lake was then considered to be critically acidic at a pH which was sufficient to inhibit the reproduction of the most acid sensitive species in the lake. Fish populations from the acidic La Cloche Mountain lakes appeared to be affected in the pH range of 4.5 to perhaps as high as 6.0 (Beamish *et al.*, 1975a). The most sensitive species (Table III), smallmouth bass, walleye, lake trout, were also the most desired sportfish. Smallmouth bass appeared to be the most sensitive species in the area as they had disappeared from most lakes before this study commenced in 1966. Local residents reported this species to be abundant in several lakes prior to the late 1950s. It is possible that this species ceased reproduction at pH values above 6.0. Walleye is another important sportfish that appears to be very susceptible to additions of acid. This species disappeared by the mid 1960s from most lakes in the La Cloche

TABLE III

Approximate pH at which fish in the La Cloche Mountain lakes stopped reproduction

pH	Species	Family
6.0 + to 5.5	Smallmouth bass *Micropterus dolomieui*	Centrarchidae
	Walleye *Stizostedion vitreum*	Percidae
	Burbot *Lota lota*	Gadidae
5.5 to 5.2	Lake trout *Salvelinus namaycush*	Salmonidae
	Troutperch *Percopsis omiscomaycus*	Percopsidae
5.2 to 4.7	Brown bullhead *Ictalurus nebulosus*	Ictaluridae
	White sucker *Catostomus commersoni*	Catostomidae
	Rock bass *Ambloplites rupestris*	Centrarchidae
4.7 to 4.5	Lake herring *Coregonus artedii*	Salmonidae
	Yellow perch *Perca flavescens*	Percidae
	Lake chub *Couesius plumbeus*	Cyprinidae

Mountains. Lake trout were of intermediate tolerance, becoming extinct at pH values below 5.0 and ceasing reproduction at about 5.5. However, in one lake the occasional female lake trout was observed to have spawned when the lake pH was 5.2 to 5.0. The titration curve for several dilute lakes (Beamish and Van Loon, 1977) indicates that equal additions of acid in the range of pH from about 5.5 to 5.0 cause greater decreases in pH than at other pH values. Thus fish of intermediate susceptibility, lake trout, trout perch, brown bullhead, white sucker, and northern pike (Table III) may exhibit a shortened 'long-term' response to changes in lake chemistry. Cyprinids (minnows) were the most resistant species. The lake chub was observed to reproduce at pH of 4.5. Yellow perch, lake herring and rockbass also were tolerant of low pH values.

The minimum pH of 6.0 established for aquatic organisms by the National Technical Advisory Committee (1968) would probably be acceptable for most fishes. However, if smallmouth bass and walleye were desired species as they are in most areas then the acceptable pH may be at some value greater than 6.0. The pH range of 5 to 9 considered by the EIFAC Working Party on Water Quality (1968) not to be directly lethal for fish should be ignored as it has been shown that in the La Cloche lakes two to four important species were extinct before pH 5.0 was reached.

The extinction of fishes did *not* appear to be an indirect effect caused by an earlier loss of food items. Predators such as smallmouth bass, walleye lake trout, and northern pike all became extinct while major prey species such as lake herring and yellow perch and cyprinids remained abundant. White suckers in Lumsden Lake were observed to become extinct even though approximately 10 times the biomass of preferred benthic food items was present (Beamish, 1974b). A decrease in feeding intensity was observed for white suckers held for several months in sublethal concentrations of acid (Beamish, 1972) and it is possible white suckers and other species responded to acid stress in the natural environment in a similar manner by reducing feeding or food utilization or both. Changes in plankton composition of the La Cloche lakes have been reported (Sprules, 1975) but may not be important as the species most dependent upon plankton for food (lake herring) was one of the last species to become extinct (Beamish, 1974b).

Growth of some species did appear to be affected by the decreasing pH. Between 1966 and 1968 in Lumsden Lake the mean size of similar aged white suckers decreased as the population was becoming extinct (Beamish, 1974b). In 1972 and 1973 white suckers in George Lake were found to be significantly smaller than similar aged fish sampled earlier (Beamish *et al.*, 1975a). Many of the remaining lake trout and northern pike in George Lake in 1972 and 1973 were observed to be emaciated and generally in poor condition. The changes in growth of these species occurred during the period that the fish first stopped reproducing. During this same period, yellow perch increased in numbers then increased in mean size (Beamish *et al.*, 1975a). An increase in size as a lake became more acidic has also been reported for fish from acid lakes in other areas (Almer, 1972; Schofield, 1975). Since there is a wide range of tolerance to pH among fishes one might expect there is also a wide range of pH values in which growth of a species may be altered. Therefore it is important not only to identify changes in growth but to relate these changes to other physiological changes that may be occurring such as the failure to reproduce. If species are observed to increase in mean size at a specific age and the species have ceased to reproduce then such an observation would indicate that the response of white suckers and perhaps lake trout and northern pike in the La Cloche lakes may be characteristic only of the species or of the area.

It was found that female fish from the acid lakes had abnormally low serum Ca concentrations during the period of ovarian maturation (Beamish *et al.*, 1975a). The cause of this reduction in serum Ca of females was not determined but because changes occurred when pH was depressed to critical levels it did appear that the changes in normal Ca metabolism have resulted from the increased acid content of the lake and these changes caused or resulted from the reproductive failures. Another indication that normal Ca metabolism might be altered by the changes in water quality was found in the increased occurrence of deformed white suckers in George Lake (Beamish *et al.*, 1975a). The occurrence of deformities in fish during periods of sublethal acid stress has also been described in laboratory acid toxicity tests (Mount, 1973; Beamish, 1972). The similar response of white suckers in an acidifying acid lake and from a controlled laboratory experiment is accepted as corroboration that this species was responding to the stress of increased acidity.

5. Other Explanations for Observed Response of Fishes

It has been assumed that the cause of the reproductive failures and the ultimate extinction of the fish populations were a result of the increasing acid content of the lake. Another possibility would be that some unknown very toxic chemical was causing the observed responses. Such a possibility always is present in research and while there appears to be a more reasonable explanation for the observed responses, the presence of some unknown agent should not be completely discounted. A more probable alternative would be that the fish were responding to heavy metal toxicity, increased in effect because of the low pH. In the La Cloche lakes only Zn concentrations were sufficiently high (20 to 40 $\mu g\, l^{-1}$) to be potentially hazardous to fishes (Canadian Department of the Environment, 1972). The observed Zn concentrations were well below incipient LC50 values considered representative for most salmonid fishes in water of a hardness similar to the La Cloche lakes (Canadian Department of the Environment, 1972). The Zn concentrations were well within the range of 'safe' concentrations of 30 $\mu g\, l^{-1}$ which had no effect and 180 $\mu g\, l^{-1}$ which caused an 83% reduction in egg production of fathead minnows (*Pimephales promelas*) in hard water (Brungs, 1969). Zinc concentrations were also lower than concentrations considered to be 'safe' for *Daphnia magna* (Biesinger and Christensen, 1972). Manganese and Ni concentrations were high in all acid lakes, however, they were well below concentrations that caused a minimum of reproductive impairment to *Daphnia magna* (Biesinger and Christensen, 1972). Nickel concentrations were much lower than the 380 $\mu g\, l^{-1}$ considered 'safe' for fathead minnows in hard water (Pickering, 1974). Copper concentrations ranged from 2 to 4 $\mu g\, l^{-1}$, and were much lower than the value of 17 $\mu g\, l^{-1}$ that did not affect survival, growth or reproduction of adult brook trout (*Salvelinus fontinalis*) in soft water (McKim and Benoit, 1971). Cadmium ($<1\ \mu g\, l^{-1}$) was well below the range of 4.5 to 37 $\mu g\, l^{-1}$ that had no adverse effect on survival, growth or reproduction of fathead minnows in hard water (Pickering and Gast, 1972).

These tests of toxicity were performed at higher pH values and it is possible that the 'safe' levels are too high for the acidic La Cloche Mountain lakes. Conversely heavy metal concentrations probably increased gradually as the lakes acidified, allowing fish to acclimate to the increasing concentrations. Schofield (1965) found that only brook trout that were acclimated to higher Zn concentrations could be introduced into an acidic lake with high Zn concentrations. Also, if heavy metal concentrations increased as the lake acidified then the loss of the more sensitive species occurred at even lower concentrations than presently found.

In contrast to the lack of a good relationship between concentrations of heavy metals in the lakes and the concentrations observed to affect fishes in controlled laboratory experiments, there was a good correlation between pH and the observed responses of fishes. Mount (1973) showed that the survival of fathead minnows in hard water was not affected at pH 7.5 to 4.5 but at pH 5.9 and lower, egg production and hatchability were reduced. At pH 5.2 to 4.5 females did not spawn. It was in the range of pH 5.2 to 4.7 that five species in George Lake were first observed to stop reproducing (Beamish *et al.*, 1975a). The occurrence of decreased egg production and reduced hatchability was not studied in the acidic La Cloche Mountain lakes and may have influenced total fish production. Water quality standards allowing pH values lower than pH 6 were not considered acceptable for fathead minnows and Mount (1973) recommended that a minimum pH of 6.5 be maintained for fish populations.

In George Lake five species were observed to cease reproduction after pH dropped from 5.5 to 4.7 in the early spring of 1971, followed by a brief winter rise to 5.2, and a fall again to 4.8 in the summer of 1972 (Beamish *et al.*, 1975a). This is an increase from 0.003 to 0.020 mg l^{-1} of H ion in 1971 and a change from 0.006 to 0.016 mg l^{-1} in 1972. It also appears that small increases in Cu, Ni, and Mn may have occurred when the George Lake pH decreased from about 5.5 to 4.7 (Table IV). Zinc may have doubled in concentration from about 15 to 30 $\mu\text{g l}^{-1}$. Iron determinations were so variable that comparisons could not be made. There was no significant correlation ($p=0.05$) between pH and Cu, Ni, or Mn from February 1972 to November 1973 (Table IV). The decrease in Zn concentrations was significantly correlated ($p=0.05$) with increasing pH. A comparison of heavy metal concentrations in George Lake with concentrations from a nearby less acidic lake (Kakakise Lake, Table IV) indicates that heavy metal concentrations may have doubled in George Lake when the pH dropped from 5.5 to 4.7. However, the more than sixfold increase in H ion that lowered the pH into a range known to prevent fish from spawning (Mount, 1973) appeared to be a more important stress than the heavy metal increases that still were below concentrations considered to be safe for fishes. Thus there were small changes in heavy metal concentrations in relation to the very large increase in H ion concentration during the time many species in the lake first ceased spawning. Finally, there is substantial literature describing the levels of pH that are lethal to fishes (EIFAC, 1969; McKee and Wolf, 1963; Daudoroff and Katz, 1950; and others). While such literature in general does not consider the wide range of sensitivities exhibited by fishes and the effects of

TABLE IV

Heavy metal concentrations and 3 m pH values for George and Kakakise lakes[a]

Date	Cu	Ni	Cd	Zn	Pb	Fe	Mn	pH
George Lake								
February 1972	<2.5	—	<1	27	1.2	41	—	—
July	3	7	nd	20	1	19	260	5.0
August	3	11	—	31	3	20	260	4.9
September	4	8	nd	26	3	19	200	5.1
October	4	9	nd	27	nd	22	200	5.0
December	2	14	nd	20	nd	12	210	5.2
January 1973	3	9	0.3	32	1	7	—	4.8
February	2	10	<.2	24	nd	27	—	5.0
April	3	5	nd	21	nd	33	210	5.0
May	3	5	nd	21	nd	33	200	5.0
June	1	9	.5	11	<2	6	—	5.0
August	<1	9	<.5	25	3	32	220	5.1
November	1	9	.3	13	2	22	240	5.3
Kakakise Lake								
November 1972	<1	5	.2	10	<2	8	150	—
February 1973	2	6	<.2	12	nd	8	190	5.7

[a] See Beamish *et al.* (1975a) for methods of chemical analysis.
—indicates no measurement; nd indicates not detected.

prolonged sublethal concentrations of acid and resulting reproductive failures, it is unanimous in its agreement that pH values below 5.0 are harmful to fishes.

It is possible that synergistic effects of acid and heavy metals, or additive effects of heavy metals and acid may cause stress at a slightly higher pH than if heavy metals were not present. A fish may be responding to an acid stress modified by heavy metal toxicity but there does not appear to be any justification for considering that the failure of reproduction and ultimate extinction of fish populations have resulted primarily from the toxic effect of heavy metals. It is important to consider that the elevated concentrations of heavy metals such as Zn, Mn and perhaps other substances may occur because of increased weathering and solubility due to acidification of soils and lakes. If this is true then it is practical to think of fish populations as being stressed by an association of factors of which acid is the principal stressing agent as well as controlling the concentrations of the less important factors.

6. Court Action

In 1970 a court action was initiated by the Federal Department of Indian Affairs in cooperation with the Department of Justice. It was alleged that the major mining and smelting companies in Sudbury had caused damage to forests and lakes on a nearby Crown Indian Reserve as a result of their SO_2 and heavy metal emissions. For the purposes of the action, special investigations were conducted of the dispersion of the plume of SO_2 as it left the companies stacks; the correlation of quantities of SO_2 in the plume with measured ground-level concentrations, the effects of these emissions over the past few decades on forest in the Reserve; and the effects of emissions on lakes and fish populations. After discovery hearings, and subsequent trial postponements at the request of the companies, the action was settled out of court for an undisclosed sum without any liability being assessed. The settlement occurred in October 1974 just days before the trial was scheduled to commence.

Such a settlement while probably being beneficial to the Indian Reserve in that monies became available for the compensation of damages suffered, did not appear to be particularly helpful to those concerned with maintaining and improving the quality of the environment. However, because there was a settlement on the part of the companies, the action was important because it demonstrated that it is possible to provide evidence that at least can encourage major polluters to control the emissions of pollutants into the atmosphere.

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