THERMALLY STRATIFIED ACID WATER IN LATE WINTER - A KEY FACTOR INDUCING SELF-ACCELERATING PROCESSES WHICH INCREASE ACIDIFICATION

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ABSTRACT

Ion separation of acid air pollutants out of snow causes sudden, deep pH-drops in lakes and running waters at an early stage of snowmelting. These pH-drops have drastic effects on fish populations and are suggested to be the main cause of *Sphagnum* invasion and changes in the microflora already at an early stage of acidification, i.e. when summer pH-values are about 6. These effects in turn reduce the nutrient recycling and accelerate the acidification process.

INTRODUCTION

During the last ten to fifteen years, fish and crayfish populations in thousands of lakes and running waters in Sweden and Norway have suffered from increasing water acidity (Hultberg and Stenson 1970, Anon 1971, Jensen and Snekvik 1972, Almer et al. 1974, Svärdson 1974).

Odén and Ahl (1970) and Snekvik (1972) have shown that sharp pH-drops occur at snowmelting in rivers and lakes in Sweden and Norway.

In southern Norway polluted snow was found to have considerable influence on the quality of the water in lakes and brooks in winter and spring. Great quantities of e.g. $SO_4^{=}$, NO_3^{-}, Zn and Pb were found together with high acidity in the upper strata of lakes. A poor bottom fauna consisting mainly of *Sialis* sp., *Chironomidae* and *Oligochaetes* were found in shallow areas (1 m depth) while the number of species and biomass increased at greater depths (Haugen and Langeland 1973).

Oligotrophic Lakes and brooks with low buffer capacity would be especially susceptible to pH-drops. Grahn and Hultberg (1974) observed acidification effects in a lake with summer pH-values just below 6. *Sphagnum* sp. had invaded lake Örvattnet in the province of Värmland in 1967 when summer pH-values were about 5.8.

Effects such as fish kill, reduced fish reproduction, death among groups of invertebrates, *Sphagnum* invasion, and changes in the microflora already at an early stage of acidification cause feed-back mechanisms which delay nutrient recycling and accelerate the acidification process (Grahn et al. 1974). Sharp pH-drops at the time of snowmelting are suggested to be a main factor inducing these biological perturbations in aquatic ecosystems.

INVESTIGATED AREAS AND METHODS

The annual variations in pH have been studies in lakes in two areas in south-western Sweden: ten in the province of Bohuslän since late 1969, and three in the province of Värmland since 1973 (Figure 1). Since the discovery of drastic pH-drops in Bohuslän in April 1970, effects on fish populations in running waters have been studied by means of electrofishing at three stations, fish mortality tests (fish in net-cages at ten stations), and by studying the occurrence of false annuli in seatrout otoliths. Also, fishing with survey nets and rotenone treatment has been used at three stations to study fish populations in the lakes (Figure 2). In addition, skindiving has been used to study macrophytes and the microflora in both areas.

RESULTS AND DISCUSSION

Among the investigated lakes in Bohuslän, the yearly pH-variation is greatest at 1 m depth in lakes with summer pH-values around 5.2 - 5.5. In the very acid lakes, the variations are small. In <u>all</u> the lakes, a sharp drop in pH occurred in the spring of 1970. No such drop has been observed during any of the following winters. As an example, the yearly variation in pH in Lake Härsevatten and Lake Timmervatten is shown in Figure 3.

Figure 4 gives a more detailed example of the drastic pH-drop from 5 to 4.2 in April 1970. The winter 1969-70 had unusually much snow, with an average snow depth of around 0.7 m. The temperature was low from mid November and no snowmelting occurred until mid April. pH was 4.4 - 4.5 in snow profiles in the area, but the pH-drop at the start of snowmelting at 1 m depth in Lake Timmervatten and other lakes in the

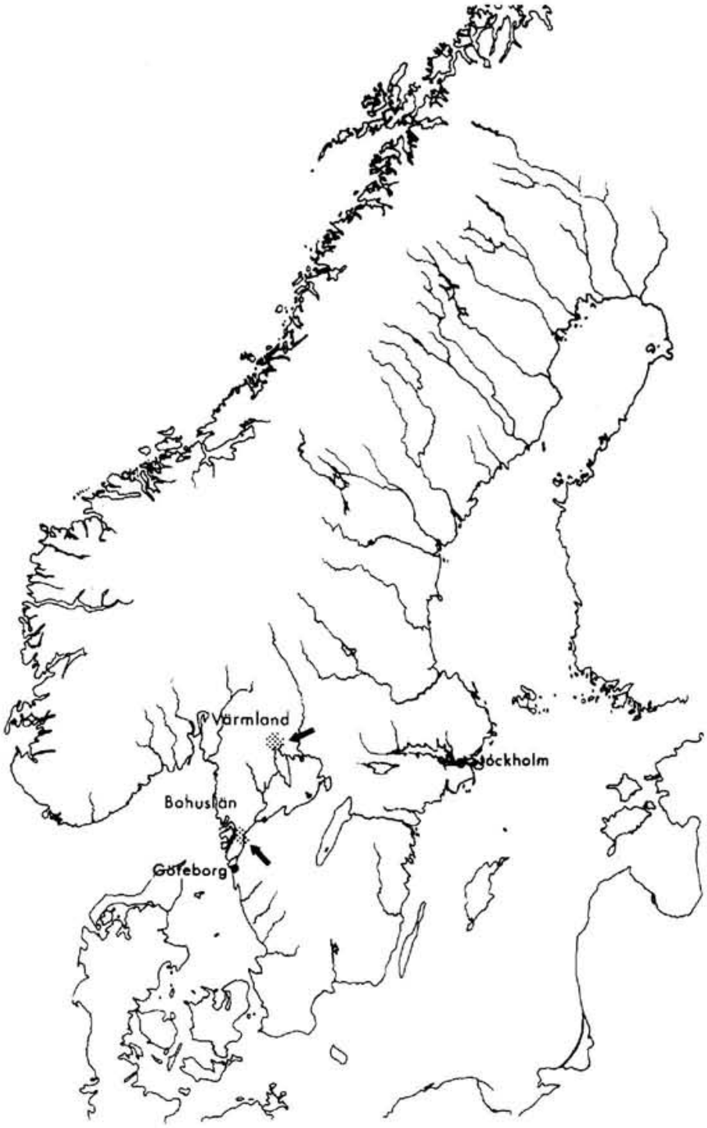

Figure 1. Scandinavia. Arrows mark investigated lake areas in the provinces of Värmland and Bohuslän in Sweden.

area was even greater. In a thin layer between the snow and the ice cover on the lakes, pH-values as low as 3.7 - 4.0 were measured. These values show that acid had been concentrated from the snow by means of ion separation at the beginning of snowmelting, forming this acid water layer. Due to mild winters and no snow cover, no such short-term, deep pH-drops have occurred in the lakes in Bohuslän since the one recorded in April 1970.

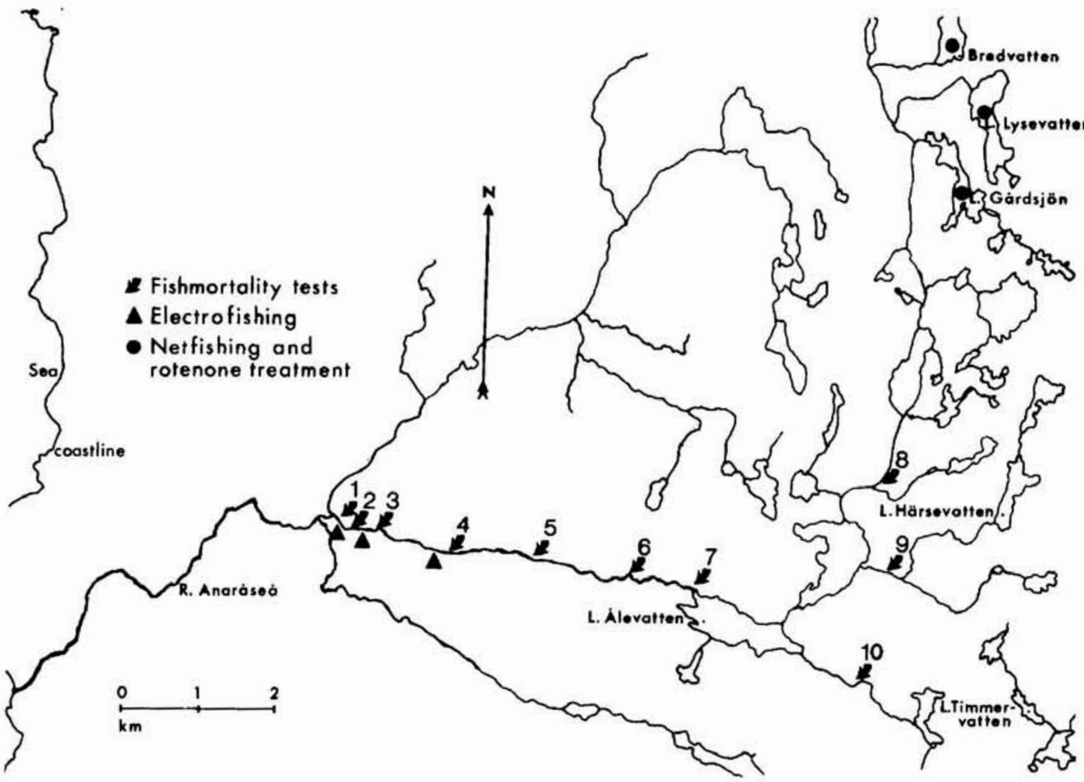

Figure 2. Tests on fish populations in the investigated lake area in Bohuslän.

As from June 1973, monthly pH-profiles have been measured in three lakes in the snow-rich province of Värmland. In all the lakes, a sudden sharp pH-drop occurred in mid February 1974. In Lake Stensjön, the drop was spectacularly deep, from 5 to 3.4 just below the ice cover, and from 5 to 3.8 at 1 m depth (Figure 5). The pH-drop was observed down to 5 m depth near the shore, but only to 3 m depth in the middle of this 34 ha lake. Comparing these low values to pH values in precipitation and in the snow pack, it is clear that during a mild period in mid February, ion separation had concentrated the acid substances from the snow into the lake. The rise in pH in the two lakes in Bohuslän and Värmland (Figures 4 and 5) following the pH-drop makes the duration of the extremely acid layer short (14-30 days) and these sharp drops can therefore be recorded only through frequent measurements.

Odén and Bergholm (1973) point out that the first fraction collected during laboratory-controlled snowmelting is a very acid salt-solution, and that the pH rises and the salt content is gradually reduced during the melting process. The last 50 percent of the melt-water is almost distilled water.

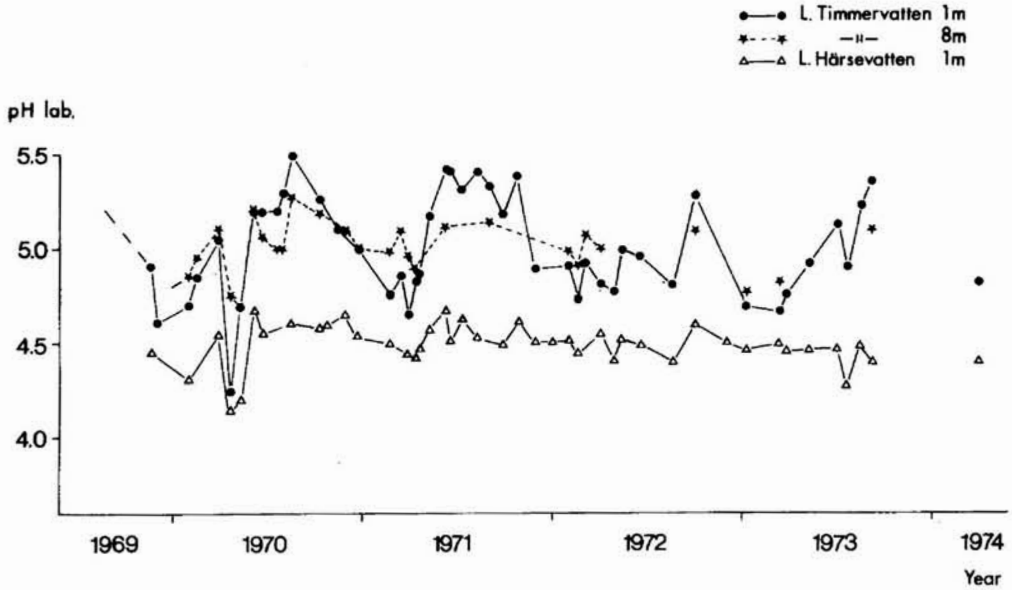

Figure 3. Yearly pH-variations (laboratory measurements) in L. Timmervatten and L. Härsevatten in Bohuslän, 1969-1970.

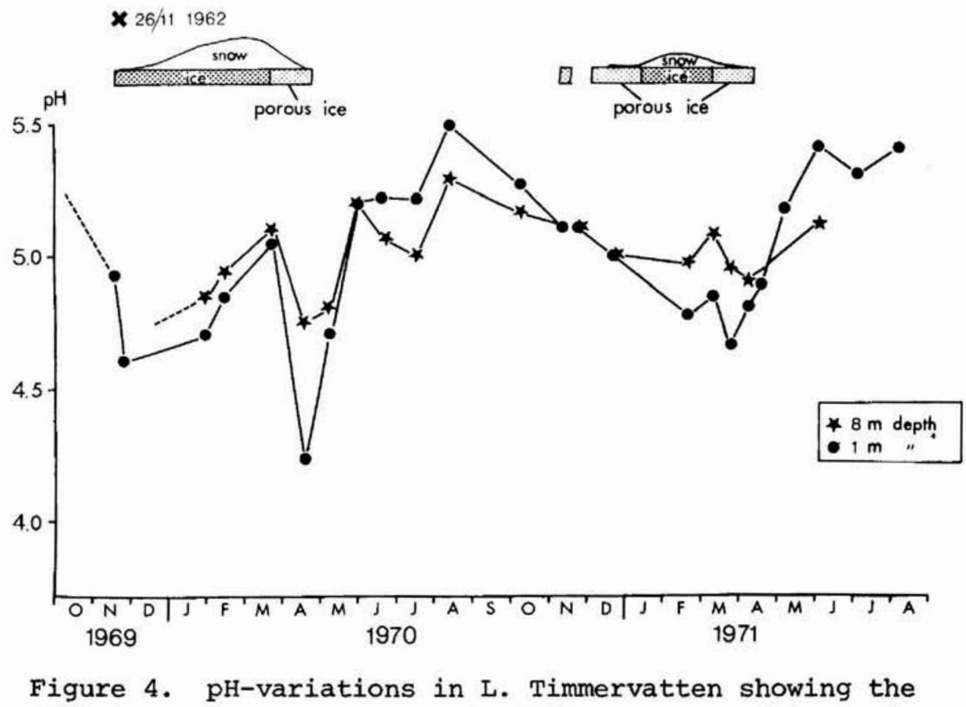

Figure 4. pH-variations in L. Timmervatten showing the sudden sharp pH-drop in April 1970 as compared to spring 1971.

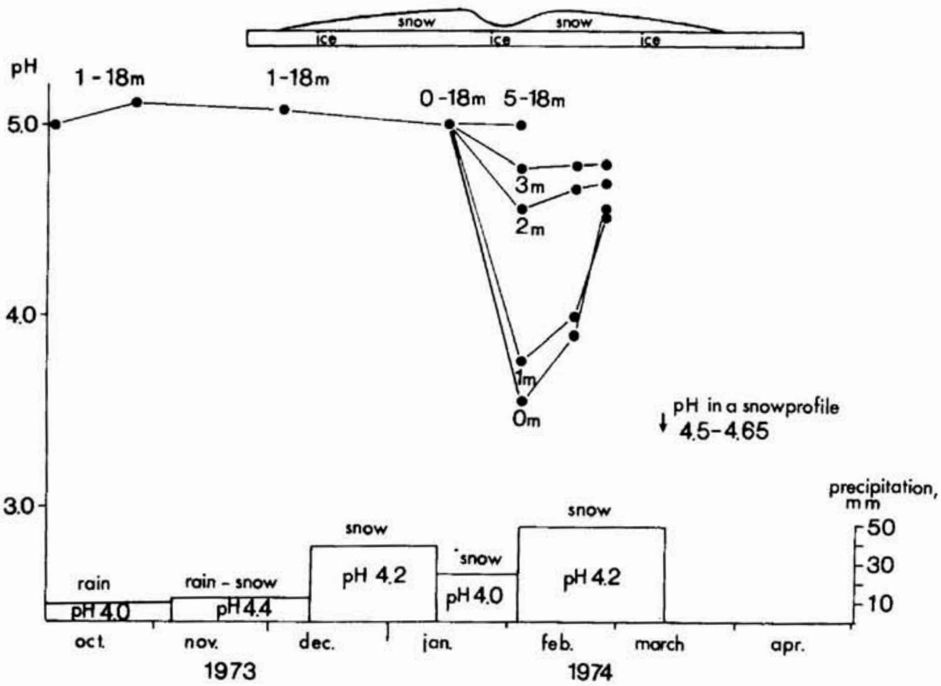

Figure 5. pH-variation during winter 1973-74 (field measurement) in L. Stensjön in Värmland. Note the pH and amount of precipitation, and pH in snow profiles.

In a similar study, Henriksen et al.(1974) show that 75 percent of the divalent and 58 percent of the monovalent ions are removed from the snow pack when only 30 and 31 percent respectively of the snow has melted in a thermostated (2.0 ± 1.0°C) lysimeter.

To study the pH-drop effects on fish populations in small running waters in Bohuslän, a test was performed with two species: seatrout *(Salmo trutta)* and minnows *(Phoxinus phoxinus)*, both with a mean length of 65 mm, and collected in the outlet of lake Ålevatten. Two-three net cages were placed at each of 10 test stations, seven along the outlet and three upstreams lake Ålevatten (Figure 2). The test was performed during the winter 1971-72 and the following pH-fluctuations were recorded:

TABLE I. pH-RANGE (FIELD MEASUREMENTS) AT TEST STATIONS 1-10, L. ÅLEVATTEN

Station No.	pH-range	Station No.	pH-range
1	5.50-6.00	6	4.80-5.60
2	5.40-6.00	7	4.65-5.10
3	5.35-5.80	8	4.30-4.70

Station No.	pH-range	Station No.	pH-range
4	5.25-5.60	9	4.40-5.20
5	5.00-5.50	10	4.40-5.50

An example from station no. 5 (Figure 6) illustrates the pH-fluctuation and the fish survival during the test. The mortality for

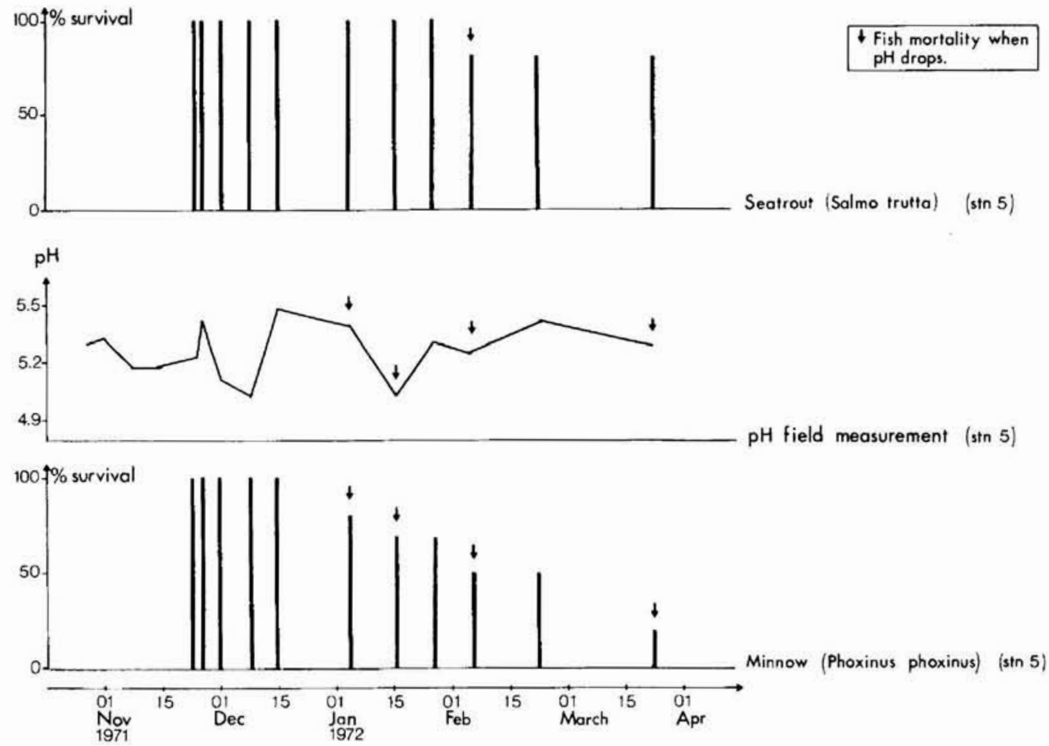

Figure 6. Fish mortality test at station No. 5 in the outlet of L. Ålevatten in the winter 1971-72

pH-drop, pH-rise, and unchanged pH was recorded. A total of 131 seatrouts and 128 minnows were tested. The pH at the least acid station (No. 1, 5 km downstreams the lake) ranged from 5.50 to 6.00, while pH gradually sank upstreams to station No. 8 where the pH-range was 4.30-4.70. 53 percent of the seatrouts and 91 percent of the minnows died during the test (Figure 7). All but three of the test stations (No. 1-3) were within localities where minnows have disappeared during the last ten-year period.

A dominating part (i.e. 68 percent of the seatrouts and 59 percent of the minnows) died when pH dropped although these drops were much less pronounced (due to lack of snow) than that in April 1970 described earlier. Obviously, fish mortality during pH-drop and pH-rise cannot

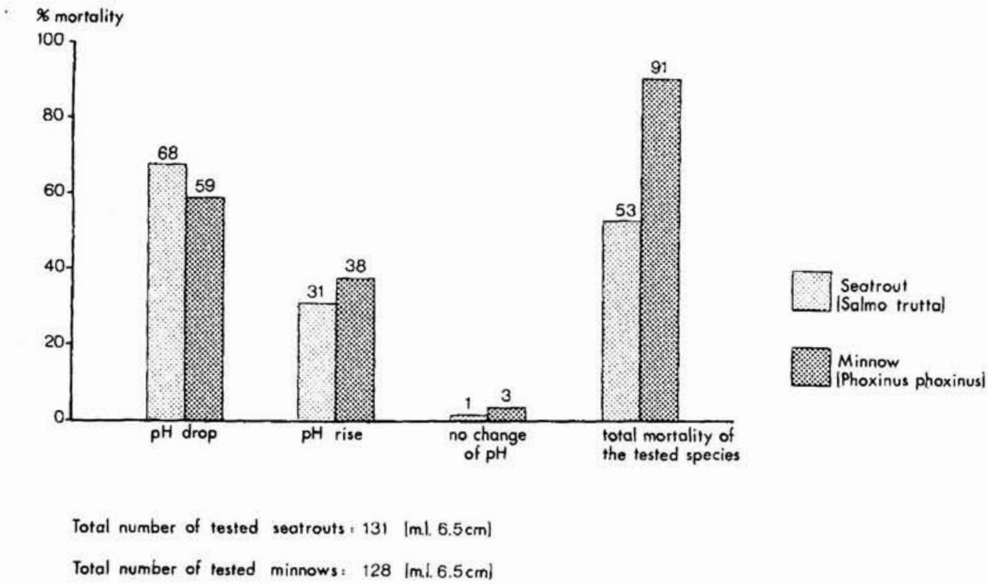

Figure 7. Percent of the number of seatrouts and minnows that died during the test period, as well as during drop, rise and unchanged pH, respectively.

be separated. However, the results indicate that pH-drops cause the most severe effects.

Already in 1957, the fishery administration in Sweden carried out electrofishing at two stations downstreams lake Ålevatten in Bohuslän to check the trout population (Edman, 1970). These checks were continued within the author's research project, starting in August 1970 about four months after the sharp pH-drop in the lakes, and electrofishing was repeated every autumn until 1973.

Compared to the results from 1957, 1971, 1972 and 1973, the trout reproduction in 1970 (number of 0+) was extremely low, and at the station nearest to the lake there were no fry at all (Figure 8).

In 1971, the reproduction was higher at all three stations, especially at 4.5 and 4.9 km downstreams the lake. The number of two-summers and older trout was seriously affected in 1971 by the limited or non-existent reproduction in 1970. As no such sharp pH-drop as the one in April 1970, when the trout fry had hatched, has occurred afterwards, and as the trout population has increased in the following years, one can argue that the thermally stratified acid water from the lakes had caused the serious effects on the trout population.

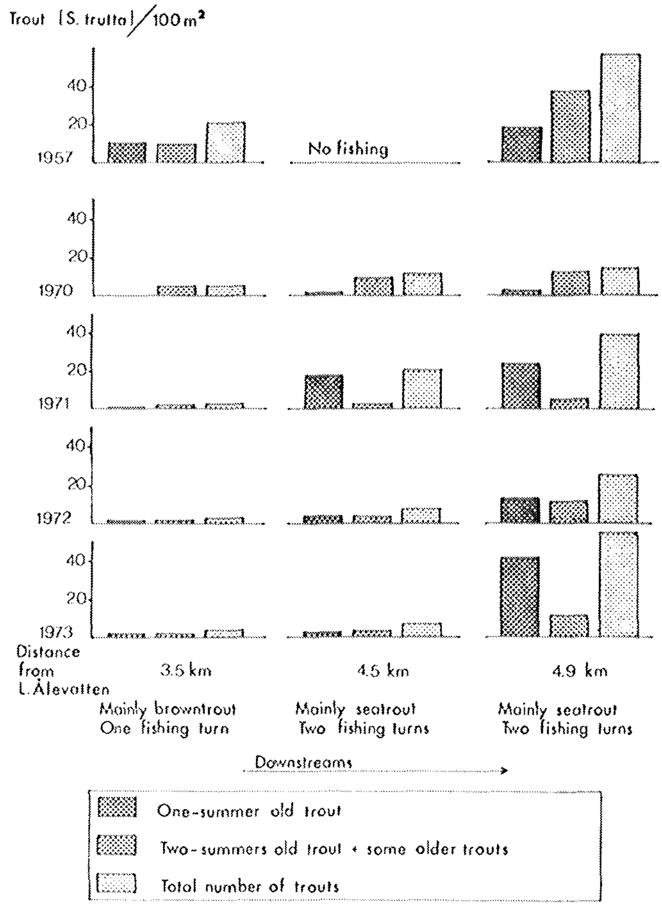

Figure 8. Number of one-summer old (0+), two-summers old and some older seatrouts as well as total number of trouts/100 m^2 at three stations in the outlet of L. Ålevatten from 1957 and 1970-73. Total catch figures are not equal to total fish biomass. The number of 0+ is probably much too low for 1957 due to fishermen catching the big ones first.

Figures 9, 10 and 11 show seatrout otoliths. These are part of the fish auditory mechanism as organs of equilibrium, containing prisms of calcium carbonate and an organic matrix.

Of the three otoliths in Figure 9, all from young of the year (0+) seatrout 5.0-5.7 cm, two have a broad zone with no calcium carbonate and are from seatrouts caught in the outlet of lake Ålevatten. The otolith without this false annuli is from a seatrout caught in a part of the watersystem where no sharp pH-drop occurred in the spring of 1970.

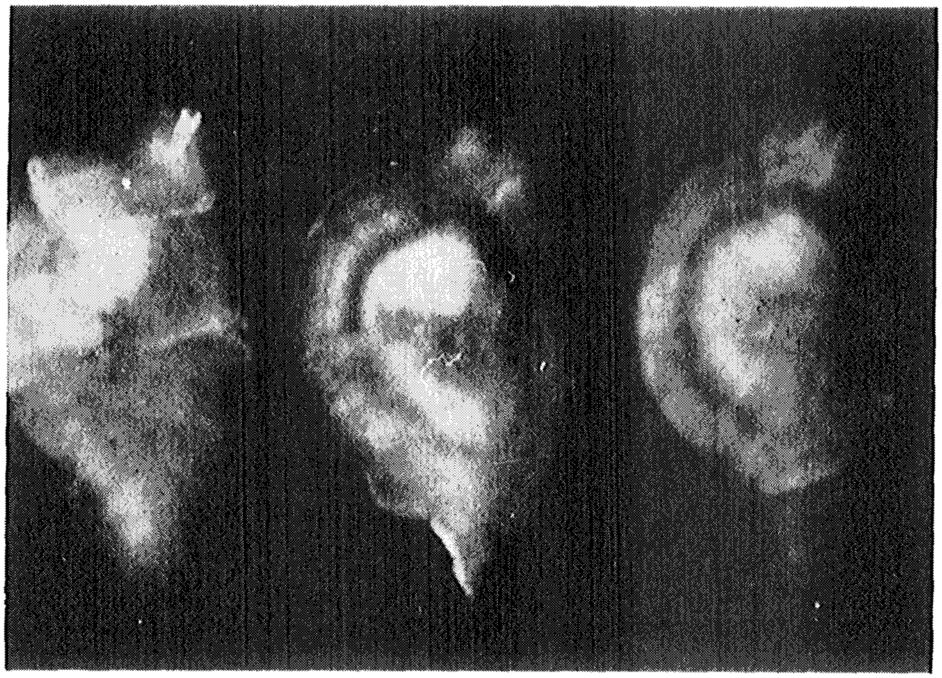

Figure 9. Three otoliths of young of the year (0+) seatrouts. The two with a broad zone (without calcium carbonate) were collected in the outlet of L. Ålevatten in August 1970, and the one without the broad zone is from a part of the water system where no deep pH-drops occurred in April 1970.

Figures 10 and 11 show otoliths from a young of the year (0+) seatrout 5.7 cm, and a two-summers old (1+) 10.4 cm, both caught in August 1970. It is obvious that the broad zones (acid zone, spring 1969, etc.) in these otoliths correspond to the annual occurrence of pH-drops in the studied area. The seatrout fry in this area actually register the acid periods, and the broad zones in the otoliths show when the acidity of the water have caused stress and death in the seatrout population.

Figure 12 shows the year of birth of 253 pearches *(Perca fluviatilis)*, some fished by net in 1970, 1971, 1972 and 1973, and some collected after rotenone treatment in the autumn of 1973 in three lakes in Bohuslän (figure 2). From 1970 and onwards, the reproduction was low or non-existent (1972). Actually there were no fish at all in one of the lakes, and only 60 and 37 respectively in the other two, in 1973. The poor reproduction in 1970 compared to the extremely good reproduction in 1969 is most probably directly or indirectly an effect of the extreme pH-drop in 1970. The abundant reproduction in 1969 is well-known from other lakes and species in other parts of Sweden, and is a result of an unusually early and warm spring that year.

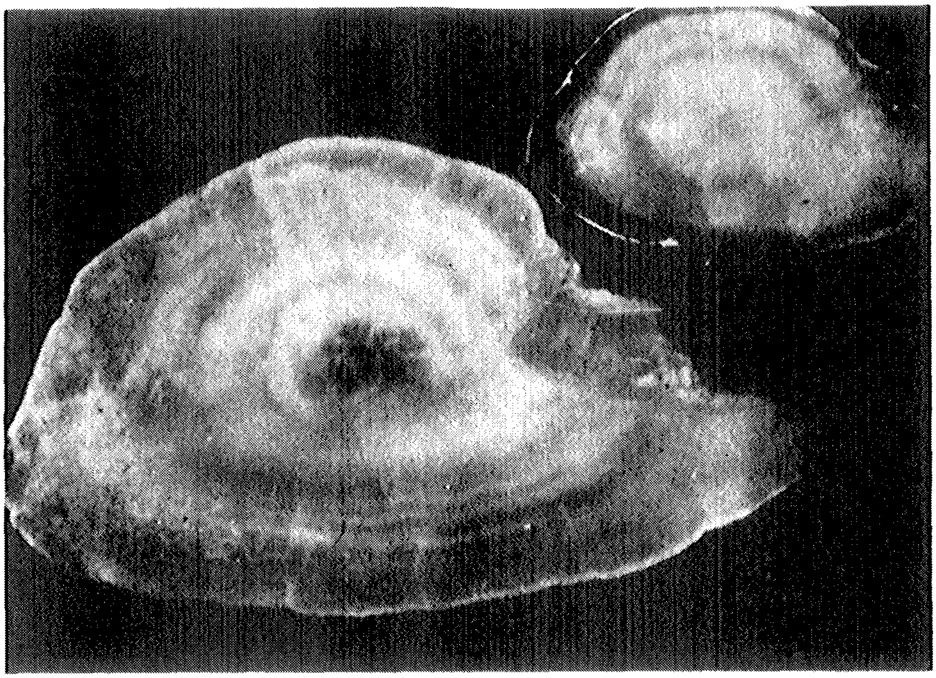

Figure 10. Two otoliths, one from a one-summer (0+) old, the other from a two-summers old seatrout, both caught in August, 1970 in the outlet of L. Ålevatten.

In acid lakes, the *Sphagnum* mats and fungus hyphae felts are thicker and cover greater bottom areas in the littoral than in the other depth zones (Figure 13). This corresponds to observations by Haugen and Langeland (1973) of acidification effects on invertebrates in the littoral and in deeper water respectively in lakes in southern Norway. As mentioned above, *Sphagnum* species invaded a lake in the snow-rich province of Värmland when summer pH-values were as high as 5.8. The pH-drop in the littoral zone in winter induces the *Sphagnum* invasion and affects the microflora, which in turn leads to further expansion of *Sphagnum* and fungus hyphae on the bottoms in shallow areas.

CONCLUSIONS

Through ion separation out of snow at an early stage of snowmelting, acid substances cover the littoral bottoms with a highly acid layer. This leads to poor fish reproduction and death among groups of invertebrates; it induces the Sphagnum invasion and affects the microflora in both lakes and running waters already at an early stage of acidification.

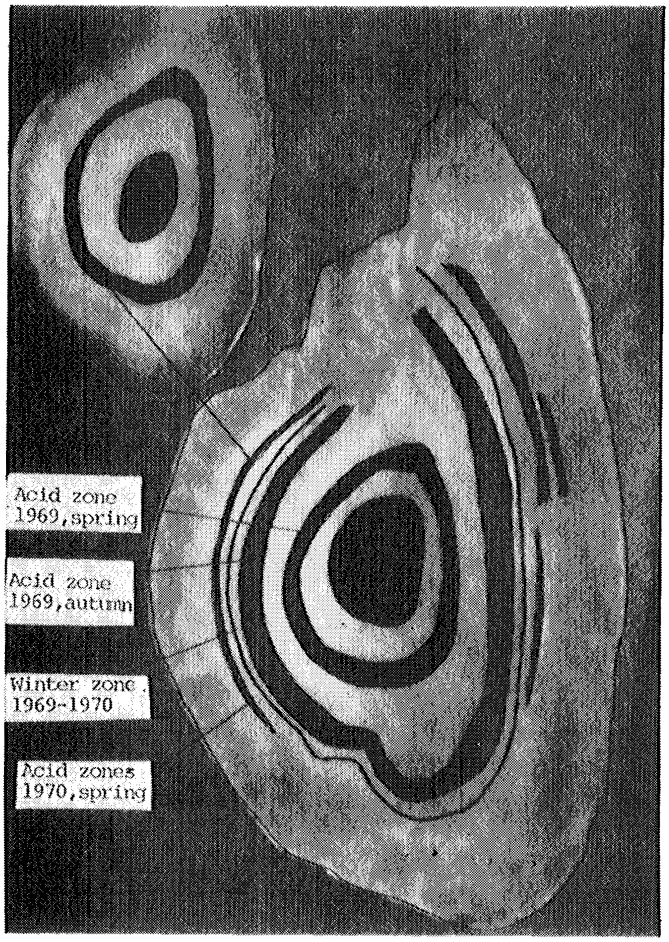

Figure 11. See figure 10.

These biological disorders brought about by thermally stratified acid water in late winter lead to oligotrophication which in turn accelerates the acidification process.

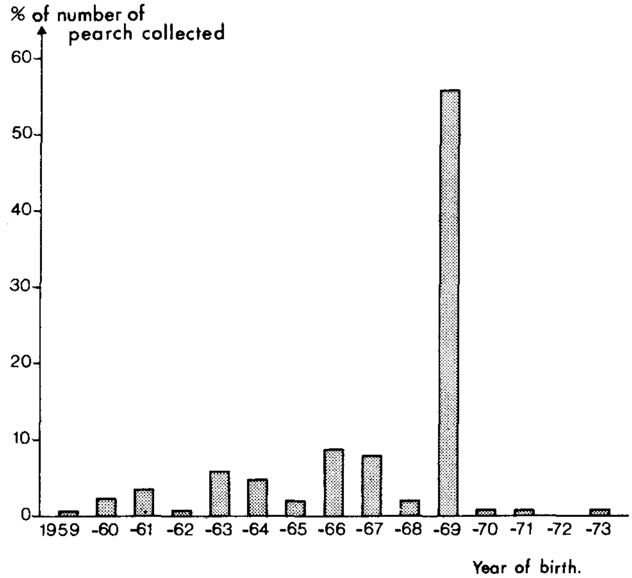

Figure 12. Year of birth and percent of the number of 253 perches caught by survey nets and collected after rotenone treatment in L. Bredvatten, L. Lysevatten and L. Gårdsjön (see Figure 2).

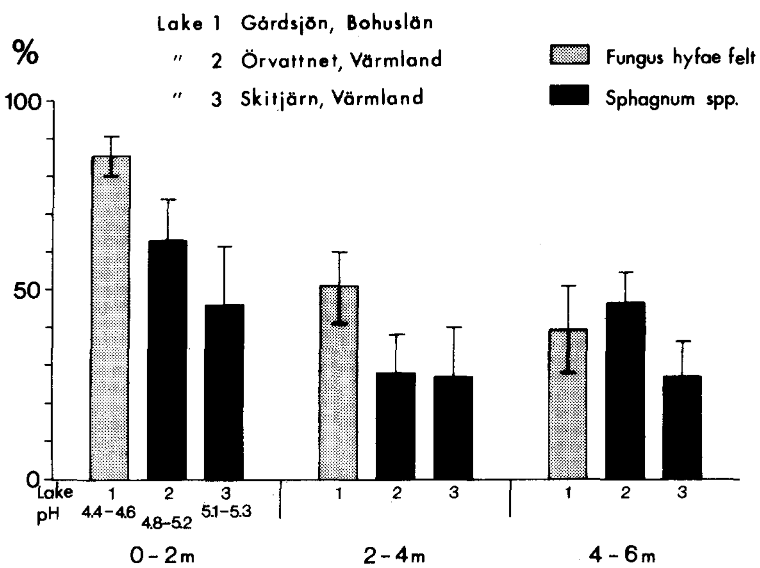

Figure 13. Coverage of fungus hyfae felt in L. Gårdsjön (Figure 2) and *Sphagnum* spp. in L. Örvattnet and L. Skitjärn in Värmland at different depth zones.

ACKNOWLEDGEMENTS

The field and laboratory work performed by L. M. Lindén and J. Kjellarson in the fish mortality tests is very much appreciated. I. Torbrink. E. Nordquist, A. Ahlfors and M. Eastmond provided valuable technical assistance in completing the investigation and preparing the manuscript.

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