MACROPHYTE SUCCESSION IN SWEDISH LAKES CAUSED BY DEPOSITION OF AIRBORNE ACID SUBSTANCES

OLLE GRAHN, Swedish Water and Air Pollution Research Laboratory, P.O. Box 5607, S-400 24 Gothenburg, Sweden

ABSTRACT

Recurrent biological investigations have been made in six lakes in two areas in western Sweden. It has been found that the supply of acid substances induces long-term biological perturbations at all trophic levels in the lake ecosystem. Among these changes, the *Sphagnum* expansion is believed to strongly affect the dynamics in the lake. A quantification of the *Sphagnum* expansion in different depth zones of a lake was made. The rate of this invasion was found to be highest in shaded and sheltered areas of the littoral. The abundance of *Sphagnum* mats is furthermore negatively correlated to the pH of the lake water.

The further consequences for the lake ecosystem of this occupation of ever-larger bottom areas by dense *Sphagnum* mats are discussed.

INTRODUCTION

In 1968, Odén presented results of studies which clearly pointed to an increasing acidity in precipitation and in a number of rivers in Sweden. He also discussed the long-term consequences of this acidification for our soil and water resources (Odén 1968). The large number of reports on this subject published since then, particularly in Sweden, Norway, and Canada, have justified the misgivings previously expressed by Odén (Henriksen 1972, Jensen and Snekvik 1972, Almer et al. 1974, Beamish 1974, Grahn et al. 1974). Consequently, in Scandinavia today a large number of lakes and running waters are suffering irreversible biological damage, with total fish kill in some areas, as a result of increasingly acid water (Hultberg and Stensen 1970, Jensen and Snekvik 1972).

For several years now, the effects on lake ecosystems of the increasing acidification have been studied within the framework of a current research project at the Swedish Water and Air Pollution Research Laboratory (Grahn el al. 1974).

The study comprises six small lakes (16-78 ha), three in the province of Bohuslän just north of Gothenburg on the Swedish west coast, and three in the province of Värmland, 300 km further north (Figure 1).

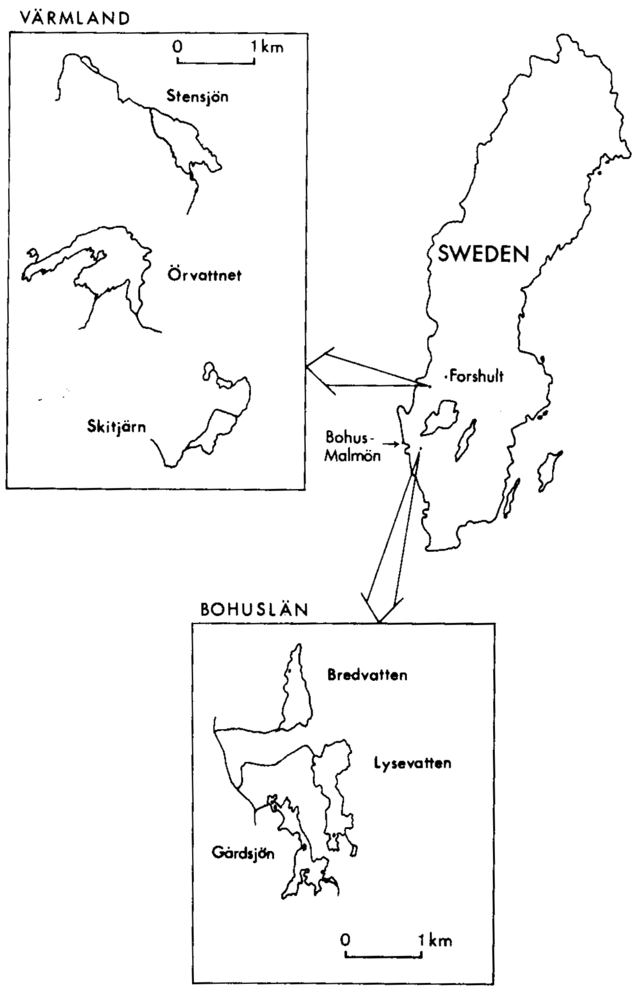


Figure 1. Investigated lakes, and stations for precipitation sampling (Bohus-Malmön, Forshult).

All the lakes except for one are clear-water lakes, situated high above sea level and surrounded by moraine ground. There are no industrial or populated areas in the surroundings, and thus no direct discharges of pollutants into the lakes.

The investigations so far have shown that disturbances occur on all trophic levels: among fish, macrophytes, bottom fauna, plankton as well as among micro-organisms. Of these ecological changes, the macrophyte succession, in particular that of *Sphagnum*, is one that may strongly affect the dynamics in the lake.

No distinction was made in this study between the different *Sphagnum* species.

Unless otherwise stated here, "*Sphagnum*" therefore refers to all *Sphagnum* species observed in this investigation.

CHEMICAL DATA

In both investigated lake areas, sulphur and nitrate in precipitation have increased, and the pH in precipitation decreased by more than one pH-unit since 1955 in Värmland and 1958 in Bohuslän (Figure 2a and b).

In Bohuslän, pH in the lake water has fallen 1.4 - 1.6 units since 1948, and a drop of the same order has occurred in Värmland since 1937-39. No pH-measurements were made during the '50s and '60s except in Lake Örvattnet, where pH fell 0.8 units from 1967 to 1973 (Figure 3 and 4b).

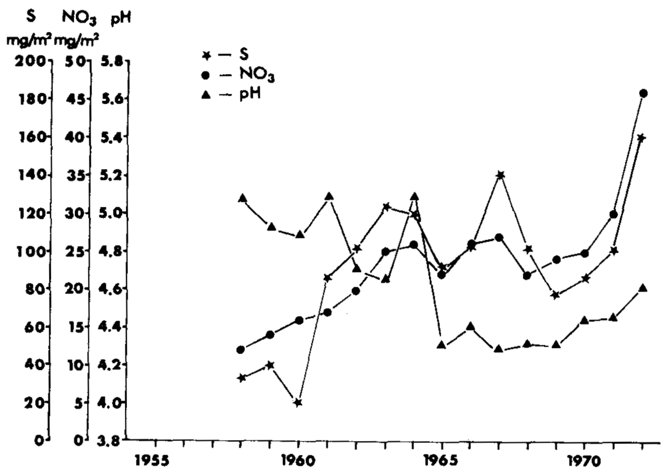
Compared to older secci-depth measurement data, transparency in all lakes, expecially those in Värmland, has increased. In Lake Örvattnet, the secci-depth in July 1939 was 4 m and in July 1973 it was 8 m. The oxygen content is high in all lakes and the oxygen curve regularly shows a metalimnial oxygen maximum during the summer stagnation.

The conductivity, which is a measure of the total salt content of the lake water, differs in the two investigated areas. In the Värmland lakes, the specific conductivity is about 30 uS and in the Bohuslän lakes the corresponding value is about 70 uS. The higher specific conductivity in Bohuslän is due to the marine influence through salt-spray and especially the ions Na^+, Mg^{2+}, Cl^- and SO_4^{2-} occur in higher concentration of HCO_3^{2-} is not measurable in any of the lakes, and SO_4^{2-} has replaced HCO_3^{2-} as the dominant anion.

MATERIAL AND METHODS

In order to study the macrophyte succession in the lakes, quantification of *Sphagnum* coverage on the bottoms was made in different depth zones at two localities in Lake Örvattnet between 1967 and 1974.

One locality is exposed to wind and sun, whereas the other is sheltered and shaded. The bottom was sampled by means of a 1 m^2 frame



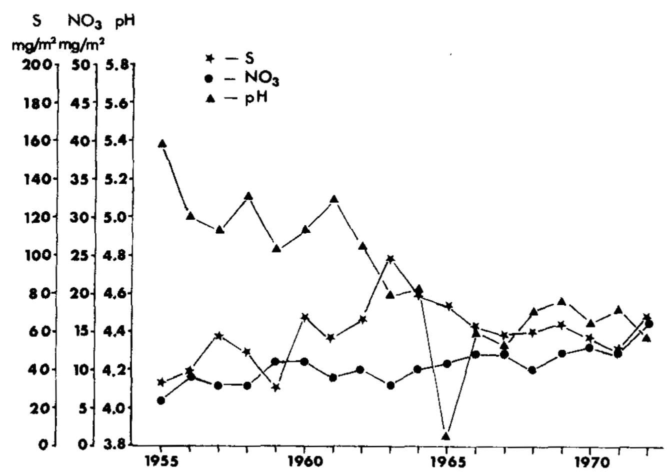


Figure 2a. Annual means of S, NO_3 and pH in precipitation at Bohus-Malmön in Bohuslän 1958-1972. (Data from the European Atmospheric Chemistry Network, Dept. of Meteorology, University of Stockholm).

Figure 2b. Annual means of S, NO_3 and pH in precipitation at Forshult in Värmland 1955-1972.

thrown out at random from a boat, and the degree of coverage determined by a diver according to a linear 7-degree scale.

Furthermore, an assessment of the *Sphagnum* coverage exceeding 40 percent was made together with an inspection of *Isoetides* throughout the lake by ocular inspection of the bottoms down to 6 m depth.

In addition, a quantification of *Sphagnum* at a shaded and sheltered locality and an inspection of the *Isoetides* were made in each of the other five lakes in 1974, employing the same technique as in Lake Örvattnet.

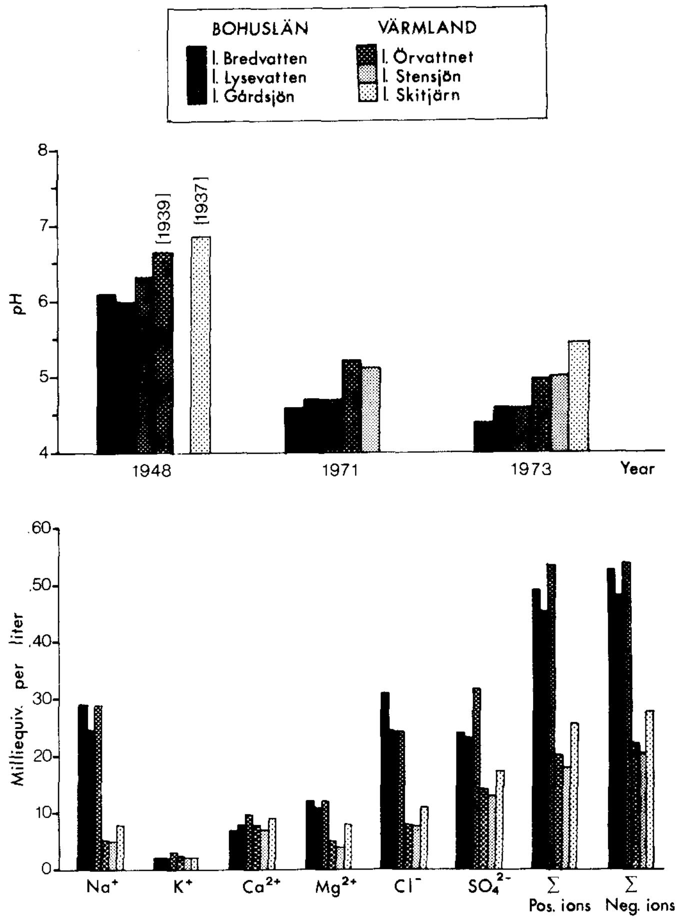


Figure 3. pH (in July 1948, 1971, 1973) and major ion constituents (July 1973) in the six investigated lakes.

RESULTS

In Lake Örvattnet there has been a considerable expansion of *Sphagnum* growth during the last seven years. Figure 5 shows the degree of coverage of *Sphagnum* in different depth zones at two localities in the lake from 1967 to 1974. Dominant among the *Sphagnum* species is *Sphagnum subsecundum* coll. Each annual value is a mean of 15 sampling squares (1 m^2). As can be seen from this figure, the expansion has been the largest in the depth zone 0-2 m at the sheltered and shaded locality of the lake. Here, the degree of coverage increased from 8 to 63% between 1967 and 1974. In the 2-4 m depth zone, a significant change from 10 to 26% occurred, whereas *Sphagnum* in the 4-6 m depth zone increased from 4 to 30%.

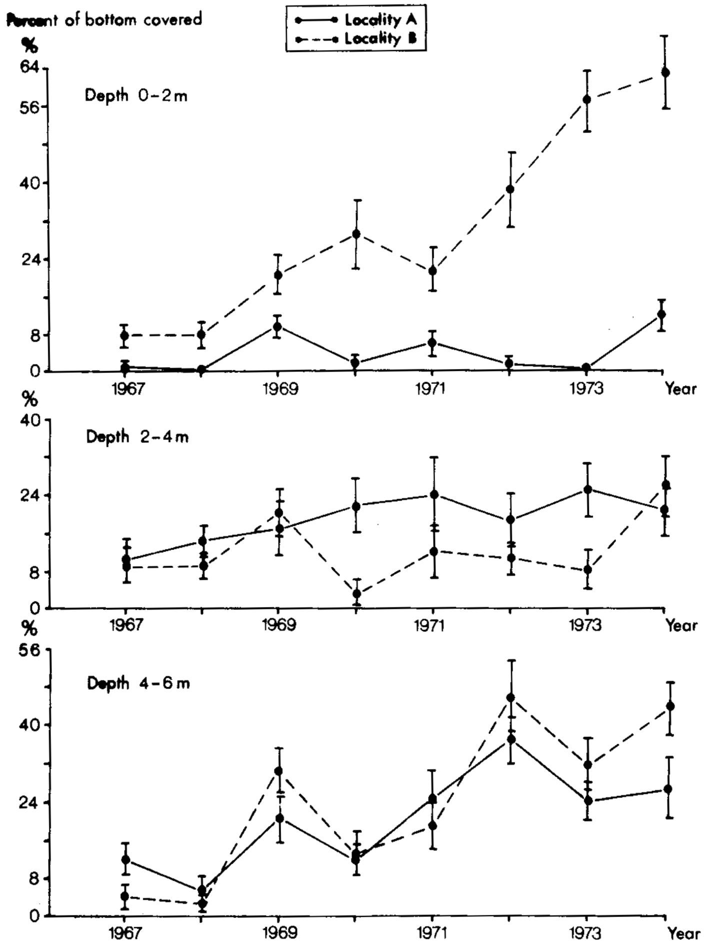


Figure 4a. Coverage of *Sphagnum* spp. on the bottom i different depth zones at two localitees in Lake Orvattnet in July 1967 - 1974. Each value is the mean of 15 sampling squares (1 m^2). Locality A: exposed to wind and sun. Locality B: sheltered and shaded.

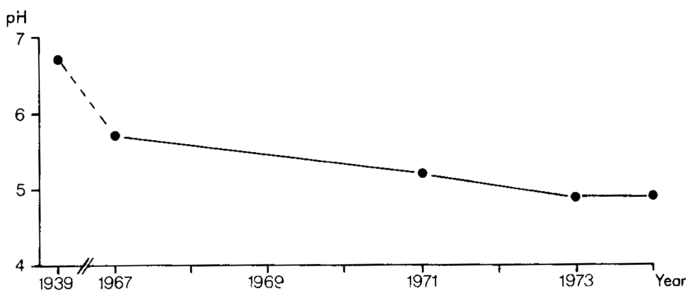


Figure 4b. pH at 1 m depth in Lake Örvattnet in July 1939, 1967, 1971, 1973 and 1974.

At the locality exposed to wind and sun, on the other hand, no significant increase occurred in the 0-2 m depth zones, whereas the degree of *Sphagnum* coverage at 4-6 m increased from 12 to 26%.

The two localities A and B in Lake Örvattnet differ with respect to both exposure to light and to wave effects. Locality A is situated on the NE side of the lake, with no tall trees near the shoreline, and is therefore exposed to the sun from the early morning hours. Southwesterly winds predominate in the area, which leads to strong wave effects. At locality B, softwoods grow all the way down to the shoreline. It is situated on the SW side of a bay, which reduces the number of sunny hours, as well as the wave effects.

At both localities, the depth zone 4-6 m is at a 100 m- distance from land and therefore exposed to the sun for the same number of hours. This makes possible a similar *Sphagnum* expansion in this depth zone at both A and B.

Areas in Lake Örvattnet covered with more than 40 percent of *Sphagnum* are represented by the dark areas on the map in Figure 5. Despite the subjective quantification it is, nevertheless, obvious that the coverage of *Sphagnum* is most extensive in shallow and sheltered bays. *Sphagnum* mats do occur on deeper bottoms down to 10-12 m, and observations of *Sphagnum* down to 18 m depth have been made.

It was found that the abundance of *Sphagnum* mats on the bottom is negatively correlated to the pH-value in five of the investigated lakes - the exception being Lake Stensjön which is humic. Figure 6 lists the six lakes in the order of their increasing pH as a function of the degree of coverage of *Sphagnum* at different depth zones in each lake. In Lake Lysevatten, Lake Gardsjön and Lake Bredvatten, *S. cuspidatum* and *S. palustre* occur beside *S. subsecundum* coll., whereas in Lake Skitjärn and Lake Stensjön, *S. subsecundum* coll. dominate. In the most acid lakes (Bredvatten, Lysevatten, Gardsjön), the coverage of *Sphagnum* at 0-2 m depth is about 70-80 percent, whereas it is about 50 percent in the least acid lake (Skitjärn). In the depth zones 2-4 m and 4-6 m, the occurrence of *Sphagnum* is less frequent than at 0-2 m in all lakes except in the most acid, Lake Bredvatten, where the coverage is about the same from 0 to 6 m.

In the littoral of oligotrophic lakes, *Lobelia dortmanna* and *Litorella uniflora* usually dominate in the depth zone 0-2 m and *Isoetes lacustris* and *Isoetes echinospora* dominate in the depth zone 2-4 m. In the investigated lakes, the *Isoetes* have, as a result of the *Sphagnum* expansion, been driven out of large littoral areas which have been overgrown with thick mats of *Sphagnum*. In July 1973 and 1974 a large number of dead plants were found under the moss in five of the six investigated lakes. Also the change induced by acidification of the micro-organism community negatively affects the *Isoetides* flora. In the acid clearwater lakes the bacteria have been largely wiped out and replaced by fungus (Grahn et al. 1974). The result has been a much retarded decom-

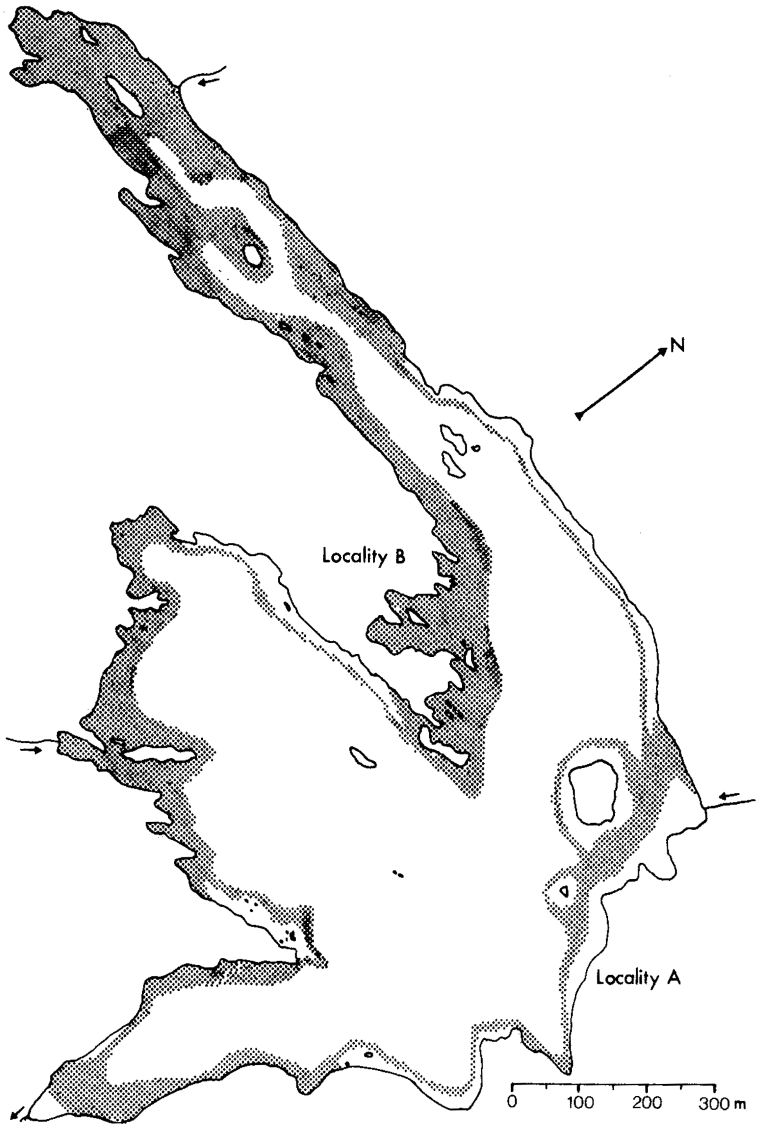


Figure 5. Bottom areas with > 40% coverage of *Sphagnum* spp. in Lake Örvattnet in 1974.

position rate and a more organic sediment. The upper sediment layer thus consists of a thick felt, where fungus hyphae, filamentous algae and remains of *Sphagnum* dominate, with *Isoetides* overgrown by or incorporated in the felt. Both the *Sphagnum* and the felt have thus contributed to the considerable reduction in the *Isoetides* flora in the littoral areas of the lakes.

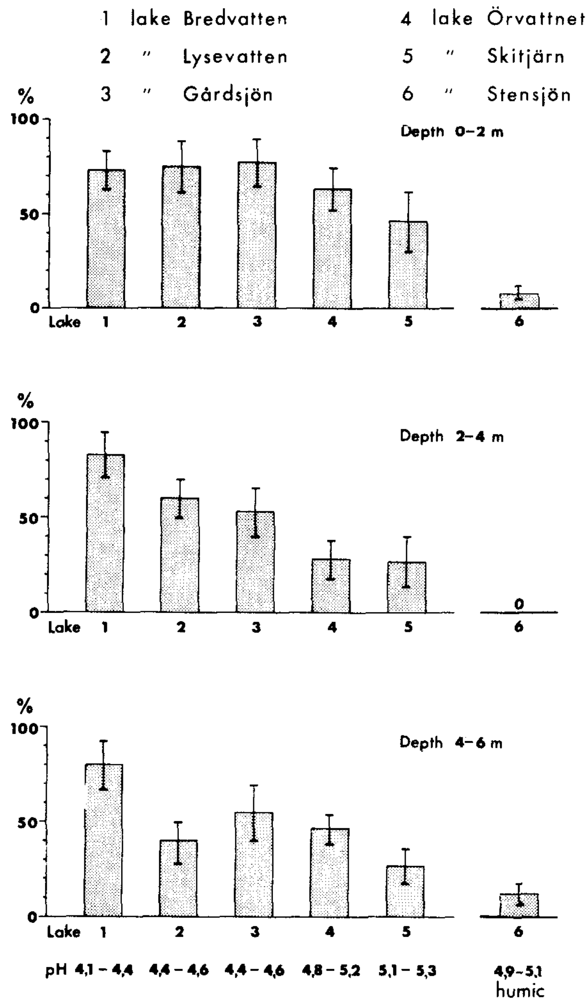


Figure 6. Coverage of *Sphagnum* spp. in different depth zones as a function of pH in the six investigated lakes, 1974.

DISCUSSION

The macrophyte surveys made during 1967 - 1974 in Lake Örvattnet clearly show that a succession of the plant community has taken place, and that a negative correlation exists between the pH of the water and the *Sphagnum* occurrence in five of the six investigated lakes. In both areas studied, the acidity of precipitation has increased during the last decades, resulting in pH-drops in the lakes. For this reason, one can assume that *Sphagnum* expansion is dependent on factors which are directly or indirectly associated with the changes in pH in the lake water.

One of these factors is the state of the hydrogen carbonate buffer system which in freshwater is often the dominant buffer system. The pH of the water is due to the relative concentration of the components of the buffer system. When pH is below 5.3, as in the investigated lakes, most of the inorganic carbon is present as free CO_2. No carbon is present as carbonate ions and the concentration of hydrogen carbonate is less than 6 percent.

There is experimental proof that many aquatic plants directly utilize hydrocarbonate ions for their carbon supply, whereas others, among them several aquatic mosses, lack this ability and must therefore use free CO_2 for their carbon assimilation (Steeman Nielsen 1944, 1946, 1947; Ruttner 1948, 1953).

The occurrence of *Sphagnum* in acid waters has been observed before: E. g. Harrison (1958) found *Sphagnum truncatum* growing in dense mats in deeper parts of a river polluted with acids, whereas in a nearby, unpolluted stream *Sphagnum* was non-existent.

In unpolluted waters, *Sphagnum* and other mosses are often found in habitats which are rich in free CO_2, such as springs, streams with subsoil-water inflow, and moorland pools (Ruttner, 1960).

Similar habitats rich in free CO_2 may be found just below the ice cover in lakes containing HCO_3^{2-}, when acid water from heavy rainfalls or from snowmelting continuously mixes with the lake water. This may be a contributing cause of the moss in certain lakes migrating to the littoral in the early stage of the acidification process, e.g. in Lake Örvattnet at a pH of > 5.8.

Another factor of importance for the *Sphagnum* expansion is the light conditions in the lake. It is well known that *Sphagnum* prefers shaded habitats (Clymo 1973). However, in acid lakes, *Sphagnum* occupies not only the shaded areas in the littoral but also deep bottoms, given more favourable light conditions through the increased transparency.

The further consequences for the lake ecosystem of this occupation of ever larger bottom areas by dense *Sphagnum* mats are that several ions, most of which are important for biological production, are bound to the moss membrane and the peat, due to their strong ion-exchange capacity (Skene 1915, Ramaut 1954, Anschütz and Gessner 1954, Clymo 1963). In order to maintain electro-neutrality between *Sphagnum* and the water, protons are emitted.

The dense mats together with the remains of *Sphagnum* and fungus hyphae may also reduce the exchange of plant nutrients between the water and the sediment, reduce the mineralizing processes, as well as drive Isoetides out of the area. The living conditions for many members of the bottom fauna also deteriorate because the moss is a very poor substratum for these organisms, especially for fish food organisms, and most of the fauna consists of small species of chironomide larvae. The recycling of nutrients bound up in the plant biomass therefore slows down.

CONCLUSION

The investigation has shown that a succession in the plant community in the lakes occurs over a short period and that these changes are correlated to the increasing acidity of the lake water.

The lakes have changed from being a kind of 'equilibrium systems' to biologically accumulating systems similar to acid biogene peat and forest soils. This type of biologically accumulating system may cause an acceleration of the acidification process, which in turn leads to further disorders in the lake ecosystem.

ACKNOWLEDGEMENTS

Thanks are due to M. Eastmond, I. Torbrink and L. Nordquist for their valuable assistance in this investigation. The investigation was financed by grants from STU and CDL.

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