Recent Acidification and Biological Changes in Lilla Oresjon, Southwest Sweden, and the Relation to Atmospheric Pollution and Land-Use History

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Phil. Trans. R. Soc. Lond. B 1990 **327**, 391-396
doi: 10.1098/rstb.1990.0080

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Printed in Great Britain

Recent acidification and biological changes in Lilla Öresjön, southwest Sweden, and the relation to atmospheric pollution and land-use history

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Palaeolimnological techniques were used to study the recent acidification history of Lilla Öresjön in southwest Sweden, and its relation to the deposition of airborne pollutants and land-use. The sediment analyses suggest that water quality began to deteriorate at the beginning of the 20th century and resulted in an acute acidification phase in the 1960s. An indifferent (circumneutral) diatom flora with some planktonic taxa was replaced by a non-planktonic acidophilous and acidobiontic flora; diatom inferred pH decreased from 6.1 in the 19th century to the present value of about 4.6. The history of acidification and of major biological change in the lake is reinforced by the analyses of chrysophyte scales and cladocera and chironomid remains, which show that alterations of species composition and an impoverishment of faunal communities took place. There is close stratigraphic agreement between these biological changes and indicators of the deposition of atmospheric pollutants. The concentration of Pb, Zn, Cu and S increased from the beginning of the 19th century to peak values during the 1960s and 1970s. Spheroidal carbonaceous particles, polycyclic aromatic hydrocarbons (PAH) and 'hard' isothermal remanence, indicative of oil and coal combustion, peaked during the 1970s and 1980s, respectively. The increased deposition of airborne pollutants from fossil fuel combustion and industrial processes is suggested as the main cause of the acidification of the lake, although vegetation changes, such as a recent expansion of spruce–pine forest, have also occurred during the 200–300 year period studied.

INTRODUCTION

More than twenty years of monitoring and research in Sweden has contributed to a broad understanding of surface water acidification (Monitor 1986), but palaeolimnological investigations, which provide a longer, retrospective view of acidification in specific lakes, are very few (Charles *et al.* 1989). This project of the Surface Water Acidification Project (SWAP) Palaeolimnology Programme (Battarbee & Renberg, this symposium) was designed to study acidification and biological changes over a 200–300 year perspective; the aim was to contribute answers to the question of whether land-use or acid deposition is the main cause of recent surface water acidification. This question has been debated since Rosenqvist (1977) claimed that changed land-use, vegetation and soil are the key factors for the acidity of freshwater.

Originally, we attempted to find an acidified lake with a catchment with restricted land-use, or one where land-use had not changed significantly during this century, and hence to have the land-use factor constant and to study the temporal relation between atmospheric deposition of air pollutants and the changing chemistry and biology of the lake. Other criteria for lake selection were; (i) minimal influence of extreme local air pollution, which could otherwise distort the signal of more regional pollution from large-scale fossil fuel combustion and industrial processes, (ii) sediments suitable for palaeolimnological investigations and, importantly, (iii) the lake should not be limed. Unfortunately, lakes meeting all these criteria could not be found easily because so many lakes were already limed (about 5000 in Sweden in 1989). Lilla Öresjön, which has some agriculture in the catchment, was chosen as a compromise. It is a reference lake for the Swedish liming programme to allow future studies of, for example, lake response to a reduction in the deposition of sulphur and nitrogen.

Study site and methods

Lilla Öresjön is situated 25 km S.E. of Göteborg in southwest Sweden. Details of the lake and its catchment are given by Battarbee & Renberg (this symposium).

Eight cores of the recent sediment were taken from the deepest part of the 12.3 m deep basin in the N.W. end of the lake in February 1986 from ice by using a freeze corer (Renberg 1981). These cores were carefully correlated by using sediment-colour variations, and contiguous subsamples were taken (Renberg 1981).

Several palaeolimnological analyses were done by specialists; pollen by Wallin, sediment chemistry by Rippey (this symposium), spheroidal carbonaceous particles by Wik (see Wik & Natkanski, this symposium), 'hard' isothermal remanence ($\text{SIRM}+\text{IRM}_{-300\ \text{mT}}$) by Oldfield & Richardson (this symposium), diatoms by Renberg, chrysophytes by Cronberg (this symposium), cladocerans by Nilssen & Sandøy (this symposium), chironomids by Brodin (1990 and this symposium) and ^{210}Pb dating by El-Daoushy (this symposium). Pollen and diatom analyses were done according to standard methods and about 500 pollen and diatom valves were counted, respectively. Diatom nomenclature follows Williams *et al.* (1988). For other methods see papers by co-authors referred to above.

Results and discussion

(*a*) *Land use and vegetation*

Pollen analysis and radiocarbon dating suggest agriculture started in the area about 2300 years ago (Renberg, this symposium) and expanded significantly a millenium later (interpolated date). *Calluna* heaths formed gradually, and probably already covered large areas 700–800 years ago; pollen values in the sediment from that time are as high as during the 18th century, when a map shows that large *Calluna* heaths were present. Pine–spruce forest took over during the 20th century, and became more and more closed until the 1980s when large areas were clear cut. Agriculture is still in practice, and no significant area of agricultural land has been abandoned, at least since 1950 according to aerial photos, but forest grazing decreased during the 1930s and ceased during the 1940s. In 1982, coniferous forest covered about 60% of the catchment (15% clear cut), deciduous trees, 10% and arable land, 10%.

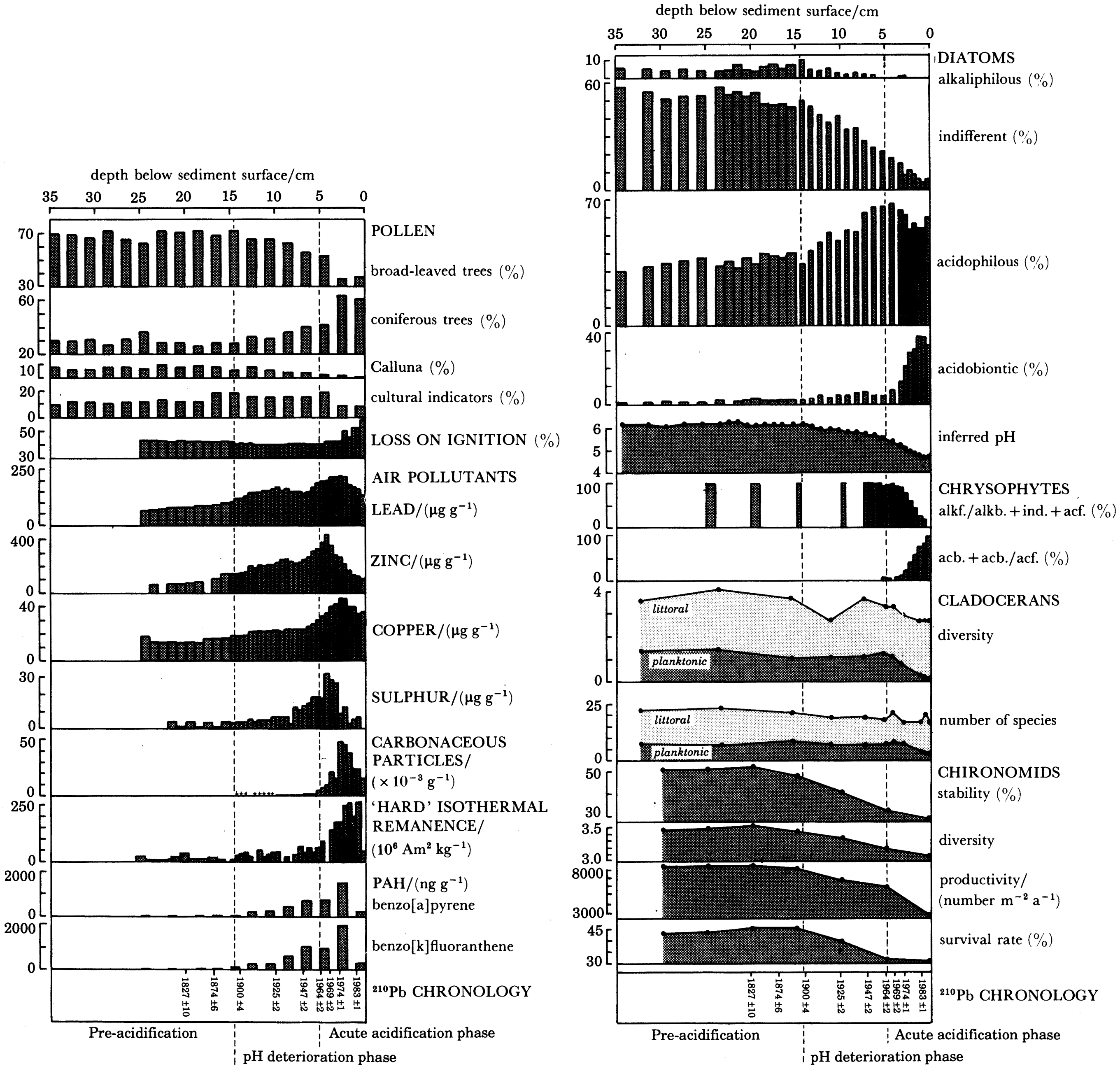

FIGURE 1. Results of analyses of sediment cores from Lilla Öresjön, S.W. Sweden. Left; a schematic pollen diagram, which gives an indication of how vegetation and agriculture have changed during the last 200–300 years (broad-leaved trees are mainly birch, oak and alder; coniferous trees are Norway spruce and Scots pine; cultural indicators are cereals, weeds and plants favoured by cultural activity). Lead, zinc and copper derive from various industrial and combustion processes and give a general indication of increased fall-out of atmospheric pollutants from the 19th century to modern times. Spheroidal carbonaceous particles, 'hard' isothermal remanence ($\text{SIRM}+\text{IRM}_{-300\,\text{mT}}$), polycyclic aromatic hydrocarbons and sulphur, are indicators for deposition of pollutants derived from fossil fuel combustion (all concentrations are per unit dry sediment mass); ^{210}Pb dates were calculated by using the GRS model. Right; results from analyses of algae and animal remains. Diatoms were classified into Hustedt's pH categories and these clearly illustrate the increasing acidity of the lake and agree with the diatom inferred pH trend obtained by using weighted averaging, a method that does not involve this pH classification. Chrysophytes were grouped following Siver & Hamer (1989). The changing communities of cladocerans and chironomids are presented as diversity, number of species recovered, stability, productivity and survival rate, for explanations see Nilssen & Sandøy (this symposium) and Brodin (1990). A pre-acidification, a pH deterioration phase and an acute acidification phase have been distinguished, primarily by using the diatom stratigraphy. Their presence is supported by the chrysophyte and animal records (see also Renberg (this symposium)).

(*b*) *Atmospheric deposition*

The concentrations of lead, zinc, copper and sulphur increase upwards in the 25 cm long core, with peaks between 3 cm and 5 cm. An analysis of the concentration–depth profiles and of flux estimates indicates that contamination starts at about 15 cm depth and increases strongly above 7.5 cm. The surface decrease is probably due to a combination of reduced fall-out (Rühling, in Monitor (1987)), accelerated sediment accumulation rates (El-Daoushy, this symposium) causing concentration changes, and changes in the lake as a result of acidification. For example, the efficiency of zinc sedimentation decreases as lake pH drops (Tessier *et al.* 1989) and sulphur-depth profiles are not simple straightforward records of pollution history, as a recent Swedish survey has shown (M. Wik & I. Renberg, unpublished results).

Spheroidal carbonaceous particles (SCP) are one of the best stratigraphic indicators of the deposition of air pollutants derived from fossil-fuel combustion. In Lilla Öresjön, SCP show the same characteristic pattern as at other sites in Sweden, with increasing values during the 1950s and peak values in the 1970s (Wik & Natkanski, this symposium). Fossil-fuel combustion, particularly coal burning in power stations, as well as several industrial processes, also produces magnetic minerals that are deposited in lake sediments. The best indicator of magnetic deposition in Lilla Öresjön is the 'hard' isothermal remanence component ('haematite') (Oldfield & Richardson, this symposium). After a small increase above 7.5 cm, values rise steeply from 5 cm to 2.5 cm and reach peak values above this level. Compared with the spheroidal carbonaceous particle concentrations, the main steep rise is synchronous, but peak values of 'haematite' persist above the 2.5–3 cm peak in SCP and decline only in the top 0.5 cm.

The analyses of polycyclic aromatic hydrocarbons show that contamination starts around 14 cm and increases strongly above 9 cm. The main source of PAH is long-distance transport from fossil-fuel combustion (see, for example, Bjørseth *et al.* (1979)).

(*c*) *Biological changes*

Diatom assemblages change considerably within the 35 cm long core presented here. Common species in the lower part include *Cyclotella kuetzingiana*, *Achnanthes minutissima* agg., *Brachysira vitrea*, *Fragilaria virescens* var. *exigua*, *Tabellaria flocculosa* agg., *Eunotia incisa*, *Asterionella formosa* and *Frustulia rhomboides* agg. In particular, percentages of *Cyclotella* start to decrease from about 15 cm, whereas species such as *Eunotia incisa*, *Peronia fibula*, *Eunotia naegelii*, *Tabellaria quadriseptata*, *Navicula leptostriata* and *Asterionella ralfsii* var. *americana* increase. A marked change takes place at about 4–5 cm, where *Tabellaria quadriseptata*, *Eunotia naegelii*, *Navicula leptostriata* and *Tabellaria binalis* become dominant.

The results of the diatom analyses are summarized here as Hustedt pH categories. The relative frequency of diatom valves of taxa classified as acidophilous starts to increase at about 15 cm and acidobiontic taxa increase markedly at about 4–5 cm. Reconstruction of pH by using weighted averaging (Birks *et al.*, this symposium) suggests a pH decrease in the lake from about 6.1 before recent acidification, to 4.6–4.7 at the top of the core, and agrees well with measured summer pH values for 1983–1985, which are 4.6, 4.6 and 4.8, respectively. The 15 cm level is dated to *ca.* 1900 and 4 cm to *ca.* 1970 with ^{210}Pb (El-Daoushy, this symposium).

The chrysophyte flora has also changed markedly according to the subfossil scales (Cronberg, this symposium). *Mallomonas crassisquama* and *M. caudata* are abundant below

7.5–10 cm. Between *ca.* 2.5–7.5 cm is a transitionary period, where *M. caudata* peaks, *M. crassisquama* almost disappears and new species such as *Synura sphagnicola*, *M. hamata*, *M. allorgei* and *M. canina* appear, the latter two becoming very abundant in the top 2.5 cm of the core. Acidophilous and acidobiontic taxa increase markedly in the recent sediments.

Cladoceran and chironomid remains reinforce this picture of acidification and biological change. Decreasing diversity and species numbers of Cladocera are found towards the sediment surface, indicating an impoverished community in recent years. A distinct change in community composition takes place at 4–5 cm. *Bosmina longispina* totally dominates the planktonic community in the topmost levels (> 96 %). *Holopedium gibberum*, *Bosmina longirostris* and the acid-sensitive *Daphnia longispina*, which are quite common further down, are absent above 3–4 cm. Numbers of the acidobiontic macrothricid, *Acantholeberis curvirostris*, increase considerably above 3 cm, strongly indicating recent lake acidification (Nilssen & Sandøy, this symposium).

The chironomid fauna begins to change between levels 10 cm and 15 cm. Major alterations of the species composition occur at about 4–5 cm, when some previously abundant taxa such as *Parakiefferiella bathophila*, *Stempellinella minor* and *Tanytarsus sp.* II disappear completely and new species appear, such as *Ablabesmyia longistyla*, *Macropelopia goetghebueri*, *Psectrocladius* sp. E and *Sergentia longiventris*. Faunal stability, diversity, productivity and survival rate all decrease. Other insect groups such as mayflies, phantom midges, biting midges and caddisflies, as well as water mites, also show decreased stability, diversity and productivity during the present century (Brodin, this symposium). These faunal changes indicate successively more unstable and harsh environmental conditions in the lake.

There are very few fish in the lake; a 'test-fishing' in the early 1980s resulted in only a few perch being caught; according to local people, pike, perch, roach, bream and eel previously lived in the lake. Roach and bream disappeared in the 1960s (Billing *et al.* 1981).

(*d*) *Causes of acidification*

The subfossil remains of diatoms, chrysophytes, cladorerans and chironomids and data about loss of earlier fish populations, clearly show that the lake acidified during the post-war period. The situation became acute during the 1960s with pH values around 4.5 (since monitoring started in 1972 values above 4.7 have been recorded only twice; data from the National Swedish Environmental Protection Board). However, the sediment record also shows that deterioration had started much earlier, at the turn of the century.

Since the 19th century, major changes in vegetation, and probably in soil conditions, have occurred in the catchment. According to the 'land-use hypothesis', this alone could account for the acidification of the lake. This hypothesis, advocated by Rosenqvist in several papers (see, for example, Rosenqvist (1978, 1980)) suggests that: (i) changed land-use, such as the cessation of cattle farming and forest grazing, has caused regeneration of coniferous forest vegetation and the increase of acid raw humus; (ii) ion-exchange reactions in the raw humus layer and the influence of cation uptake by plant growth are the most important factors in determining the pH of runoff water and (iii) the acidic precipitation during the last decades is responsible for only a minor part of the acidity of surface water.

However, at Lilla Öresjön support for the principal role of airborne acidic pollutants comes from several factors.

1. Although vegetation has changed, agricultural activity has not ceased (10 % of the

catchment is still cultivated). Other disturbances have been introduced, such as building of roads and houses that have exposed unweathered soils, and clear cutting that increases leaching and runoff of base cations and nutrients (Grip 1982). These new disturbances would counteract possible acidification effects caused by vegetation and soil changes in other areas of the catchment.

2. In addition to the temporal correlation between increased atmospheric deposition and lake-water acidification, as demonstrated in this study, there is a geographic correlation in Sweden between these two parameters, but no such correlation between lake acidification and changed land-use. The latter has taken place all over Sweden, but surface water acidification is mainly restricted to S. Sweden where acid deposition is greatest.

3. The land use hypothesis has been rejected by several palaeolimnological investigations specifically designed for testing it (Battarbee, this symposium).

Although this investigation can neither refute the land-use nor the acid-deposition hypothesis, because changed land-use and increased acidic atmospheric deposition occurred simultaneously, it is most likely that the recent acute acidification at least, is caused by the acid precipitation. The recent acid phase has no similarity in the history of the lake (Renberg, this symposium). Whether the deterioration phase before the recent acute phase also results from deposition of airborne pollutants that consumed alkalinity derived from agricultural and other catchment disturbances, or can be ascribed to the land-use factor *sensu* Rosenqvist, cannot be assessed from this study. The increased pH in Lilla Öresjön about 2300 years ago, at the same time as a cultural expansion (Renberg, this symposium), shows, however, that human land-use and catchment disturbance can be important for lake pH. Significantly, however, the magnitude of this earlier change was smaller than that associated with the recent acidification.

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