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Afforestation and lake acidification: a comparison of four sites in Scotland

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Palaeolimnological techniques including diatom analysis were used to examine the acidification and atmospheric contamination histories of four lakes in Scotland. Results from an afforested and a moorland (control) site in a region of high acid deposition are compared with results from two similar sites in an area receiving lower acid deposition levels. Results show that afforestation of a catchment in the higher acid deposition area has increased the rate of lake acidification. There is no evidence for acidification as a result of forest growth alone in the area of lower acid deposition.

Introduction

There has been a considerable increase in coniferous afforestation in the U.K. during the twentieth century, particularly in upland areas previously covered by heath or moorland. Many of these afforested upland regions are inherently vulnerable to surface water acidification because of their slow weathering, base-poor bedrock and high rainfall (Kinniburgh & Edmunds 1986). In addition, afforestation itself might promote acidification through processes associated with tree growth (Nilsson *et al.* 1984), ground preparation techniques (especially drainage (Hornung & Newson 1986)), and the combined effects of acid deposition and forestry, such as the enhanced capture of dry deposition by the canopy and the foliar uptake of sulphur dioxide and subsequent leaching of sulphate (Lindberg & Garten 1988). Forests in upland locations are also efficient collectors of fine acid mist droplets from low cloud (Unsworth 1984).

Evidence exists that afforestation can lead to increased acidification of streams. In Wales and Scotland studies show that streams draining forests have lower pH and higher aluminium and sulphate concentrations than streams with moorland catchments (Harriman & Morrison 1982; Stoner *et al.* 1984), an effect that appears to increase with the age of the plantation. However, although palaeolimnological techniques have been successfully used to show that lakes in the U.K. have acidifed as a result of acid deposition (Battarbee *et al.* 1988), similar studies of afforested sites have so far failed to show any conclusive evidence to link afforestation with lake acidification (Flower *et al.* 1987) as most had acidified before afforestation.

This study was specifically designed to ascertain whether afforestation could lead to lake acidification. Two regions of Scotland known to be geologically sensitive to acidification were selected, one receiving high levels of acid deposition and the other significantly lower levels. In each region a lake with an afforested catchment was chosen along with an adjacent undisturbed moorland site as a control.

The sites

The Trossachs region of central Scotland was chosen as the area of high deposition with two study sites in the Loch Ard forest area; Loch Chon (forested) and Loch Tinker (moorland control site). These lakes are compared with Loch Doilet (forested catchment) and Lochan Dubh (moorland control) in the Loch Sheil area on the west coast of Scotland, an area receiving moderate to low levels of acid deposition. Conifer planting began in 1920 at Loch Doilet and in 1952 at Loch Chon. No other major changes in the catchments have taken place within the last 150 years (Patrick *et al.*, this symposium). Table 1 provides a summary of the

Table 1. Summary of site characteristics and water chemistry

	Loch Chon	Loch Tinker	Loch Doilet	Lochan Dubh
S deposition/(g m^{-2} a^{-1})	1.2	1.2	0.8	0.8
altitude/m	100	420	10	230
forested area (%)	51	0	41	0
mean measured pH	5.2	6.0	5.9	5.6
Ca^{2+}/(μeq l^{-1})	79	78	47	33
SO_4^{2-}/(μeq l^{-1})	85	62	68	40

physical and chemical characteristics of the four sites. The analytical techniques used are outlined in Stevenson *et al.* (1987) and the pH was reconstructed by using weighted averaging (Birks *et al.*, this symposium).

Loch Chon and Loch Tinker

The first sign of acidification in Loch Chon is indicated by the loss of the planktonic taxon *Cyclotella kuetzingiana* in the early nineteenth century (figure 1*a*). Continued but gradual acidification is indicated by the decline in other circumneutral taxa from 1850 onwards. An acceleration in acidification follows catchment afforestation in the 1950s and is marked by the increase in the more acid-tolerant taxa *Navicula leptostriata* and *Eunotia incisa* above 2 cm depth; pH reconstruction from the diatom data suggests a decline from pH 6.5, starting in the early nineteenth century, but the most rapid rate of change occurs from 1960 onwards when pH decreases from pH 5.8 to pH 5.2 at the surface (1985), a value that agrees well with the recent mean measured pH. Additionally, cladoceran analysis of this core shows clear evidence of pH decline in the range pH 6–5. (Nilssen & Sandøy, this symposium).

Loch Tinker also shows an early decline in *Cyclotella* before 1850 (figure 1*b*). Following this, a shift to more acidic conditions is indicated by an increase in *Tabellaria flocculosa* after 1850 and an increase in *Frustulia rhomboides* var. *saxonica* at 12 cm depth (1900). Some further acidification is indicated by the reduction in *Achnanthes minutissima* but there is no overall change in species composition above 8 cm depth (1930). The rapid expansion of acid-tolerant taxa seen in Loch Chon has not occurred in Loch Tinker. The reconstruction of pH from the diatom data suggests a steady decline of pH throughout the nineteenth century and early

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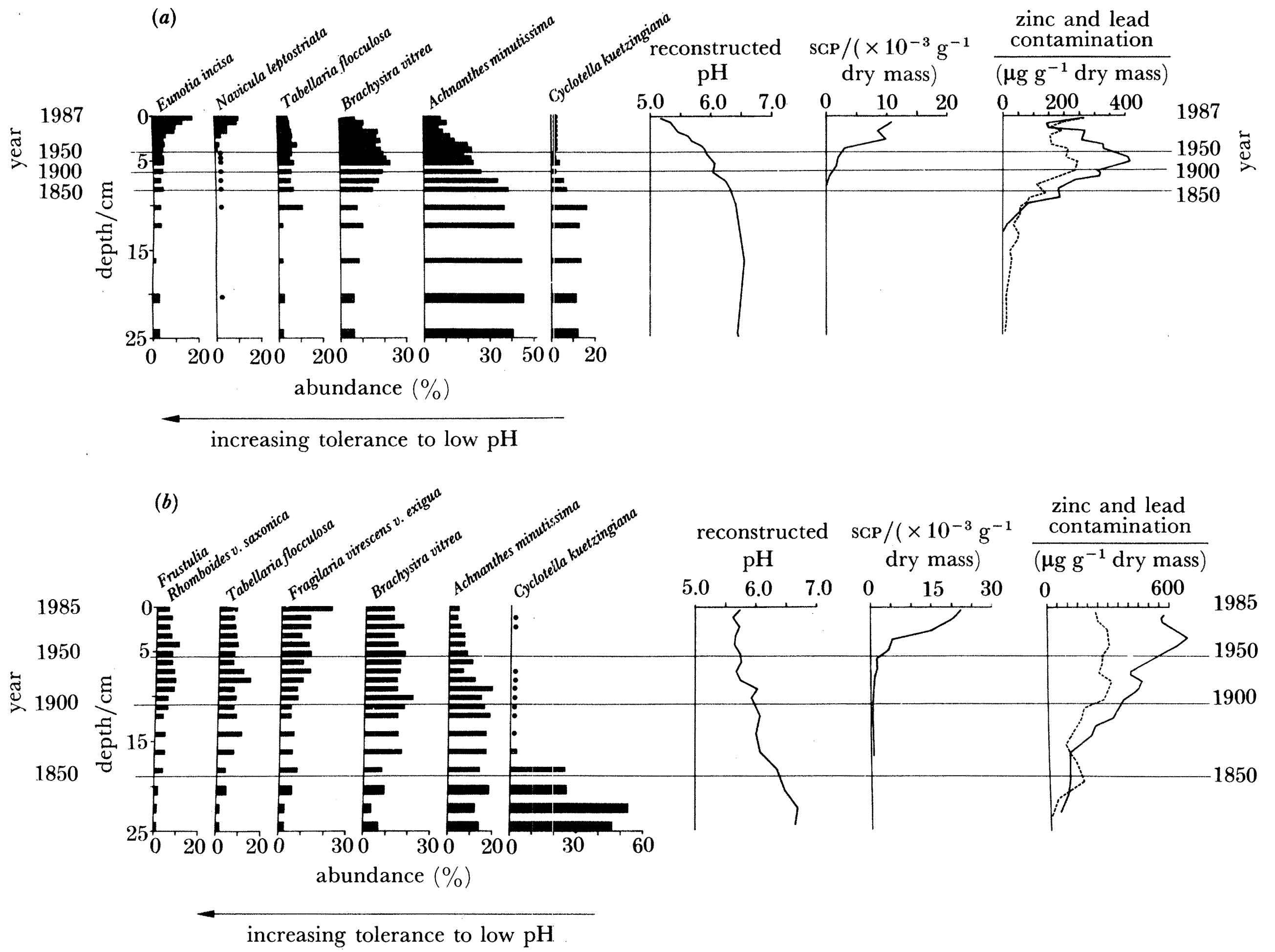

FIGURE 1. Summary diagrams showing the diatom taxa with greater than 10% abundance, reconstructed pH, spheroidal carbonaceous particle (SCP) concentrations and atmospheric zinc (solid line) and lead (dotted line) contamination profiles for (*a*) Loch Chon and (*b*) Loch Tinker. Background trace metal values were calculated by using a regression of zinc and lead concentrations against concentrations of a major cation in pre-nineteenth century sediment. The background values were then subtracted from the total concentrations of lead (dotted line) and zinc (solid line) to give the contamination component in the recent sediment.

twentieth centuries from pH 6.6 to pH 5.7 by 1930, after which pH has fluctuated between pH 5.6–5.7 until the present. The mean measured pH (pH 6.0) is slightly higher than that reconstructed at the surface. The cladoceran data from this core also suggest that pH has not declined over the past fifty years (J. P. Nilssen, personal communication).

Profiles of spheroidal carbonaceous particle concentration and atmospheric zinc and lead contamination (with catchment-derived zinc and lead removed) for Loch Chon and Loch Tinker are shown in figure 1*a*, *b*. Both lochs record an increase in carbonaceous particle deposition from the late 1940s in accordance with the trends found at sites receiving high levels of acid deposition in southwest Scotland (Battarbee *et al.* 1988). Deposition of zinc and lead from the atmosphere begins in the sediments at depths below the limit of ^{210}Pb dating and reflects contamination from early industrial sources. In both lakes the concentrations of lead and zinc increase throughout the nineteenth and twentieth centuries. The decline in zinc and lead concentrations between 1950 and 1970 in Loch Chon is due to dilution by inorganic material probably derived from the catchment during afforestation.

Loch Doilet and Lochan Dubh

The diatom flora of both lakes is very similar, with no evidence of a past planktonic diatom population at either site. In Loch Doilet the first indication of acidification is a mid-nineteenth century increase in *Tabellaria flocculosa* and a decrease in *Achnanthes minutissima*. A shift towards

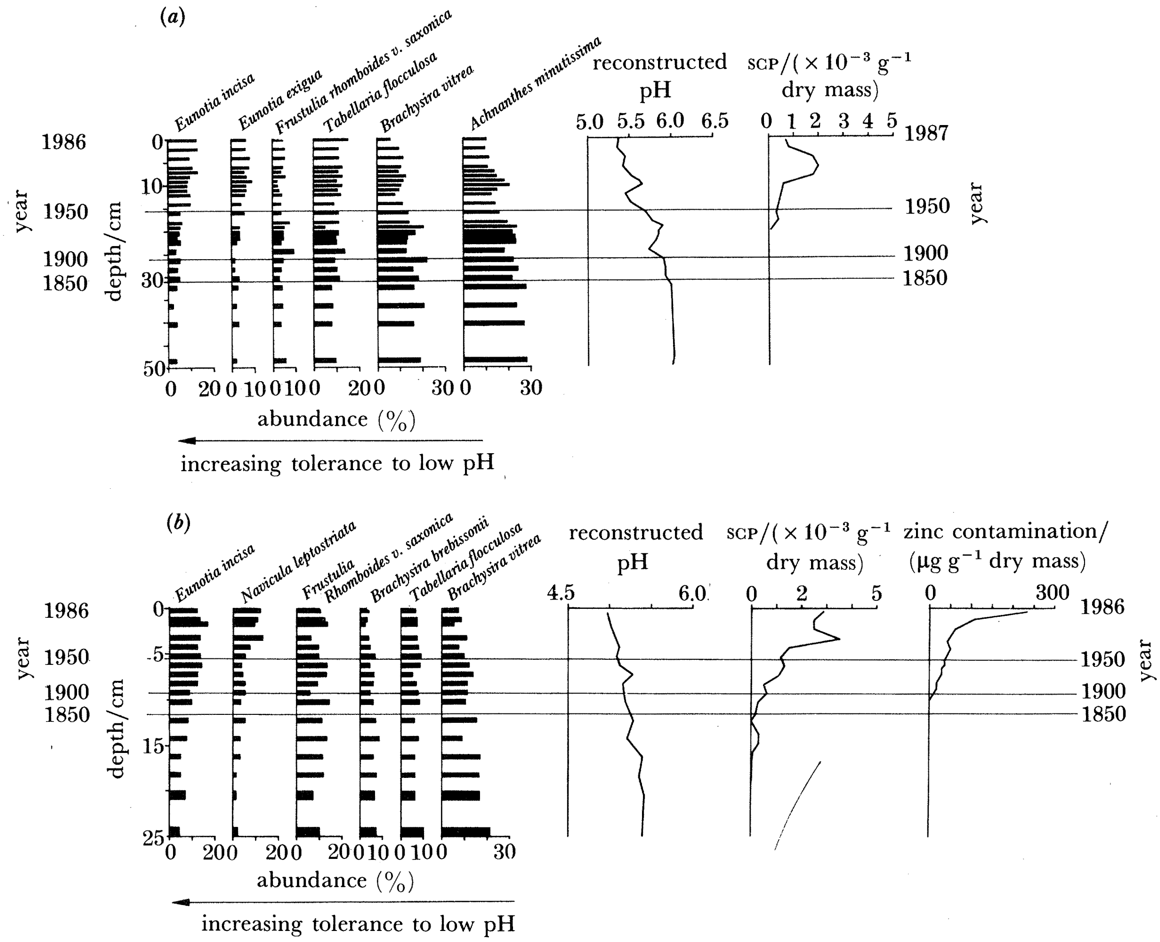

Figure 2. Summary diagrams showing the diatom taxa with greater than 10% abundance, reconstructed pH and spheroidal carbonaceous particle (SCP) concentrations for (*a*) Loch Doilet and (*b*) Lochan Dubh. Trace metal contamination was calculated as for figure 1. Zinc contamination is shown for Lochan Dubh but there is no detectable atmospheric trace metal contamination in Loch Doilet.

slightly more acidic conditions from 1930 onwards is indicated by a further decrease in *Achnanthes minutissima* plus increases in the more acid tolerant taxa *Eunotia incisa* and *Eunotia exigua* (figure 2*a*). Reconstruction of pH for this lake shows a slight acidification from pH 6.0 in the mid-nineteenth century to pH 5.8–5.9 in the 1930s. From this point, pH declines further to a reconstructed pH of 5.4 at the surface, an overall change of 0.6 pH units.

In the case of Lochan Dubh the proportions of acid-tolerant taxa are generally greater throughout the core. The sedimentary diatom record for this lake is described in Jones *et al.* (this symposium). The main floristic changes occur between 18 cm and 14 cm when *Navicula leptostriata* and *Eunotia incisa* begin to increase accompanied by a decline in the circumneutral taxa (figure 2*b*) and this trend continues up to the sediment surface. The time of the point of change cannot be dated as it lies below the limit of the unsupported ^{210}Pb record at 11.5 cm. Reconstruction of pH suggests a pH decline from a pre-1850 value of pH 5.4 to pH 5.0 at present. Evidence for long-term acidic conditions below pH 5.5 is also provided by the cladoceran data for this site (Nilssen & Sandøy, this symposium).

The reconstructed pH for the surface sediments of Loch Doilet and Lochan Dubh are both 0.6 pH units lower than the mean measured pH values. The reason for this is not clear but as there are no problematic diatom taxa and the ecological ranges of the taxa are well described, the diatom-inferred pH may be a better indication of water quality than the mean pH calculated from a small number of water samples.

The carbonaceous particle record for Loch Doilet shows a small increase in particle concentration at 18 cm (about 1940) but the main increase occurs above 10 cm (1966). The decrease in particles above 4 cm (1980) is due to both an increased sediment accumulation rate and a reduced flux of particles to the sediment. In Lochan Dubh the concentration of carbonaceous particles increases throughout the twentieth century until 1970 when both the concentration and flux of particles begin to decrease. In both these lakes the concentrations of carbonaceous particles in the sediments (less than 5×10^3 particles per gram dry mass) are very low compared with the sites in the Trossachs where concentrations exceed 20×10^3 particles per gram dry mass.

There is no measurable contamination by zinc or lead in the sediments of Loch Doilet. The high sedimentation rate may have obscured any small atmospheric flux. In Lochan Dubh, where the sediment accumulation rate is slower, there is a record of zinc contamination starting in the later nineteenth century but no evidence of lead contamination.

Discussion

All four of the lakes studied have acidified since the mid-nineteenth century, although the initial changes in Loch Doilet and Lochan Dubh are very slight. The records of industrially derived atmospheric contamination in the sediments suggest that both regions have been subject to acid deposition from industrial sources, with contamination beginning earlier in the Trossachs region. In the absence of any additional nineteenth century sources of acidity from the catchments, it is reasonable to conclude that, with the exception of Lochan Dubh, the onset of acidification was caused by acid deposition. The reason for the much earlier acidification at Lochan Dubh is less clear as evidence for atmospheric contamination cannot be detected in the sediments before the late nineteenth century.

The pattern of pH decline throughout the twentieth century varies considerably between the four lakes (figure 3). In the region of high acid deposition, the pH of Loch Tinker does not appear to have altered substantially after 1930, whereas at the afforested site, Loch Chon, the greatest pH change occurs after 1960 (figure 3*a*). Because there has been no major change in the catchment of Loch Tinker over this period and the trends in atmospheric input have been broadly similar for both lakes it would appear that the acceleration in acidification in Loch Chon is linked to the planting of conifers in the catchment area in the 1950s.

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In the region of lower acid deposition, the afforested site, Loch Doilet, is the less acid of the two sites (figure 3*b*). From the mid-nineteenth century onwards, the pH of Loch Doilet appears to have declined only 0.2 pH units until after 1930 when the rate of acidification increased. By comparison Lochan Dubh has acidified gradually over two centuries. The post-1930 pH change in Loch Doilet occurs at a similar rate over the same period as the continued

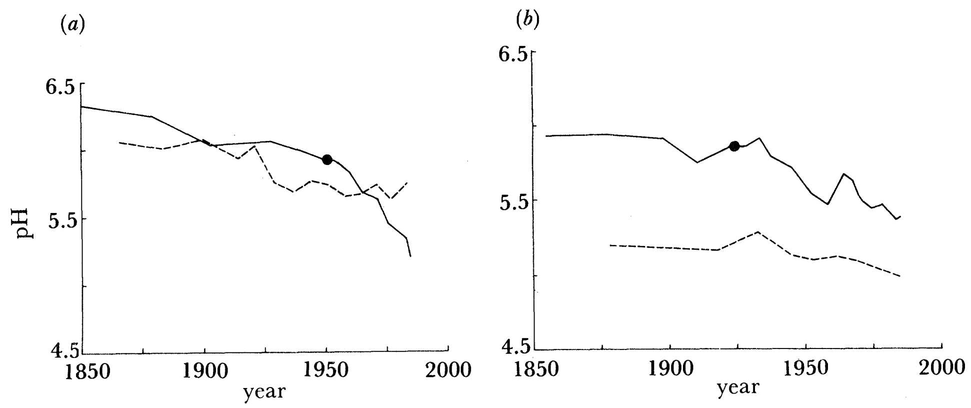

FIGURE 3. Reconstructed pH against time for (*a*) Loch Chon (solid line) and Loch Tinker (dotted line) and (*b*) Loch Doilet (solid line) and Lochan Dubh (dotted line); (●), afforestation.

acidification of Lochan Dubh (in terms of changes in hydrogen ion concentration), suggesting acid deposition could be the cause in both cases. The timing of the acceleration in acidification in Loch Doilet a decade after afforestation is similar to that found in Loch Chon. However, the post-afforestation acidification at Loch Chon was far greater despite being the less sensitive of the two afforested sites to acidification. It can therefore be concluded that the rapid acidification of Loch Chon was largely due to the forest increasing the flux of atmospherically derived acidity to the lake as the presence of forestry at Loch Doilet (where acid deposition is lower) has not resulted in a similar degree of acidification. These results suggest that at the afforested sites discussed here, any acidification caused by forest growth itself has been minimal, compared with the combined effects of forestry and acid deposition.

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