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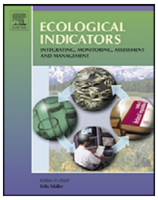

Recovery of UK lakes from acidification: An assessment using combined palaeoecological and contemporary diatom assemblage data

Richard W. Battarbee*, Gavin L. Simpson, Ewan M. Shilland, Roger J. Flower, Annette Kreiser, Hong Yang, & Gina Clarke

Environmental Change Research Centre, University College London, Gower St., London WC1E 6BT, United Kingdom

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ABSTRACT

We assess the recovery of UK lakes from acidification using the combined data from sediment cores and sediment traps to track changes in diatom assemblages in 11 UK upland lakes from pre-acidification times (prior to ca. 1850 AD) to the present (2008 AD). We projected the data into a Principal Component Analysis (PCA) of diatom assemblage data from 121 low-alkalinity lakes in the UK to show how the floristic composition of the core and trap diatom assemblages for each site has changed through time. The results show that the degree of recovery from acidification varies amongst sites but in all cases its extent is limited when compared with the pre-acidification reference. In most cases the recovery, although usually slight, is characterised by a decline in acid tolerant taxa and a return towards taxa that occurred previously at each respective site. In a few cases, however, the floristic composition of recent samples is different from those that occurred during and before the acidification phase. The reasons for this are not yet clear but it is possible that nutrient enrichment from atmospheric N deposition and/or climate change is beginning to play a role in driving water quality as acidity decreases. More generally the results show that annually recovered samples from sediment traps can be successfully combined with sediment core data to provide a continuous record of environmental change in lake systems, and that diatoms collected in sediment traps can be used to provide a very powerful lake monitoring tool.

1. Introduction

Surface water acidification became a major environmental issue in Europe after Odén (1968) and Almer et al. (1974) attributed the loss of salmonid populations in southern Swedish rivers and lakes to acidification caused by sulphur deposition from fossil fuel combustion ("acid rain"). Similar losses of fish populations in Norway (Jensen and Snekvik, 1972) and Canada (Beamish and Harvey, 1972) were also ascribed to acid deposition. Although alternative hypotheses were advanced to explain the acidification of surface waters (Krug and Frink, 1983; Pennington, 1984; Rosenqvist, 1978), major multinational research programmes both in Europe and North America (Mason, 1990; NRC, 1984) concluded that the primary cause of acidification was indeed acid deposition from fossil fuel combustion.

Following the introduction of legislation to reduce emissions of sulphur and nitrogen gases from fossil fuel combustion sources, acid deposition has declined markedly in Europe including the UK (RoTAP, 2012; Vestreng et al., 2007), and there is increasing evidence that acidified lakes and streams are beginning to recover, both chemically and biologically (Driscoll et al., 2007; Forsius et al., 2003; Nierzwicki-Bauer et al., 2010; Skjelkvåle et al., 2005).

Over the last 20 years in the UK data from the Acid Waters Monitoring Network (AWMN) show that there has been significant reductions in the concentrations of non-marine sulphate and concomitant increases in pH, acid neutralising capacity (ANC) and dissolved organic carbon (DOC) along with a significant decrease in the concentration of toxic labile aluminium at the most acidified sites (Monteith et al., 2012).

Biological recovery is most clearly seen by trends in benthic diatom populations (Kernan et al., 2010), by the appearance of new aquatic plant species in seven of the lake sites and four of the stream sites (Kernan et al., 2010) and by significant changes in invertebrate populations at about half of the 22 AWMN sites (Murphy et al., this issue). In addition new populations of brown trout (*Salmo trutta*) have appeared at a number of the most acidified sites (Malcolm et al., 2012). All changes are consistent with chemical trends towards less acidic conditions.

Key questions now concern the extent of recovery, whether there are barriers to continued recovery, whether a complete recovery can be achieved or whether other pressures and processes will lead to the emergence of novel ecosystems that differ in their structure and function from those in the past (Hobbs et al., 2009).

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* Corresponding author. Tel.: +44 20 7679 0582.
E-mail address: r.battarbee@ucl.ac.uk (R.W. Battarbee).

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Table 1
AWMN lake sites including location, altitude, calcium concentration (mg/l), pH, sulphur deposition (kg S/(ha yr)) and the code of the sediment core used for the diatom data in Figs. 3 and 4). Data are mainly from Kernan et al. (2010). S deposition for 1990 is 10 km Institute of Terrestrial Ecology data (1989–1991) and Centre for Ecology and Hydrology CBED data (2006–2008). Coire nan Arr ceased to be an AWMN site in 2007 so data from 2009 are not available (na). For Blue Lough, Ca and pH 1989 data are for 1991. CBED = Concentration Based Estimated Deposition.

	Location	Alt (m)	Ca 1989	Ca 2009	pH 1989	pH 2009	S dep 1990	S dep 2007	Core code
Coire nan Arr	N57°24.99′, W005°39.08′	125	1.04	na	6.36	na	12.5	3.8	ARR5
Blue Lough	N54°9.53′, W005°58.13′	340	1.10	0.44	4.63	5.03	13.1	5.6	BLUE5
Round L of Glenhead	N55°5.62′, W004°25.84′	298	0.76	0.45	4.88	5.14	21.4	7.6	RLGHK5
Llyn Llagi	N53°0.86′, W004°0.92′	375	1.06	0.80	5.20	5.59	24.4	6.1	LAG3
Scoat Tarn	N54°28.9′, W003°17.95′	598	0.66	0.43	5.00	5.25	21.4	7.7	SKT1
Lochnagar	N56°57.54′, W003°13.88′	788	0.70	0.38	5.40	5.58	10.3	7.2	NAG6
Loch Chon	N56°12.87′, W004°32.91′	92	1.72	1.36	5.25	6.01	18.7	7.0	CHON11
Loch Tinker	N56°13.65′, W004°30.51′	418	1.80	1.23	5.88	6.03	18.7	7.1	TIN5
Burnmoor Tarn	N54°25.7′, W003°15.58′	253	1.89	1.49	6.62	6.51	21.4	6.6	BURN1
Loch Grannoch	N55°0.14′, W004°16.85′	214	1.22	0.58	4.71	4.71	19.9	6.3	GRAN89/1
Llyn Cwm Mynach	N52°47.76′, W003°57.63′	287	1.63	1.00	5.47	5.07	18.8	6.0	MYN6

Answers to these questions require an understanding of pre-acidification conditions that can be used to assess both the extent of acidification and the extent of recovery. As no direct observations of the chemistry and biology of upland waters are available for the relevant periods in the past, pre-acidification conditions need to be inferred using either space-for-time substitution techniques (Simpson et al., 2005) or palaeoecological techniques (Battarbee et al., 2005). Palaeoecological methods have been used to assess the effectiveness of liming as a restoration measure for acidification (Flower et al., 1990; Guhren et al., 2007; Norberg and Bigler, 2008) and to evaluate the response of acidified lakes to the reduction in acid emissions (Arseneau et al., 2011; Ek and Korsman, 2001; Juggins et al., 1996).

One of the problems of using palaeoecological techniques to track the response of lakes to the reduction in acid deposition is the low rate of sediment accumulation (often <1 mm/yr) that is characteristic of many upland lakes. Surface sediments can also undergo bioturbation from benthic invertebrates and can be mixed as a result of wind-induced sediment resuspension. Consequently, samples, even from very finely sliced sediment cores (e.g. 0.25 cm) are likely to contain material representing several years of deposition, and the mixing of sediment upwards and downwards by bioturbation and resuspension tends to smooth out signals. For example, in a multi-core study of the Round Loch of Glenhead, Allott et al. (1992) demonstrated that diatom evidence of recovery was only registered in cores that had an accumulation rate greater than 0.7 mm/yr.

The limited evidence of recovery indicated by an earlier study of sediment cores from the lakes in the AWMN (Juggins et al., 1996) was partly due to the relatively short time that had elapsed between the beginning of significant efforts to reduce acid emissions in the UK and the date of sediment coring, but also due to such time-averaging and sediment mixing processes. In this present study, not only has more time now elapsed but we also have data from annually emptied sediment traps that have been deployed in the AWMN lakes since 1991. They are designed to collect an integrated sample of diatoms from all lake habitats in a way that closely mimics the formation of accumulating sediments but that also provides a discrete sediment sample representing a fixed time period. They are invaluable in tracking recovery on annual time-steps and the time-series data can be combined with the sediment core data to generate long-term records that uniquely track both the acidification and recovery trajectories at each site.

Here, approximately ten years after our first evaluation of the recovery of the lakes in the AWMN (Juggins et al., 1996) we use these combined sediment trap-sediment core datasets from the 11 lakes to assess the extent of recovery from acidification that has now occurred relative to the pre-acidification reference state. We also consider whether additional influences such as nitrogen deposition leading to nutrient enrichment or climate change may be confounding recovery or might lead to the emergence of new communities and new ecosystem functions.

2. Sites

The primary sites used in this study are the 11 lakes in the AWMN (Table 1, Fig. 1). The AWMN has been operating continuously since 1988 (Monteith and Evans, 2005) and now provides a multi-decadal time-series for key chemical and biological variables (Kernan et al., 2010). Sediment trap data, however, are only available from 1991. Detailed site descriptions and data assembled so far for all the AWMN sites can be found on the AWMN website (http://awmn.defra.gov.uk/). Table 1 summarises the key data for the sites monitored.

In the data analysis we have used a dataset of diatom assemblages from 121 lakes (Fig. 1). These data have been used in a Principal Components Analysis into which the sediment core and sediment trap data from the 11 AWMN sites have been entered passively. The dataset has been previously described by Battarbee et al. (2011). It has been compiled from the results of many different projects on many sites over a period of years. Consequently the sites are neither a random sample of all possible sites that could have been included nor are they evenly ordered along any specific geographical or chemical gradient, but they do include sites representative of the full range of low alkalinity lakes found in the UK today with respect to, e.g. size, altitude, marine proximity (sea-salt influence), base cation concentration, dissolved organic carbon (DOC) concentration and degree of acidification. As such the diatom assemblages in the 121 lake dataset are likely to include the full range of diatom taxa found in UK low alkalinity waters today and in the past and are thereby assumed to form a suitable training set for comparison with the AWMN core and sediment trap data. It allows the temporal change in diatom assemblages indicated by the core and trap data to be compared with analogous contemporary samples that span a gradient of pH from sites across the UK (Fig. 1).

3. Methods

3.1. Laboratory and field methods

Although the diatom data used here were generated by different analysts at different times the slides were prepared according to the same standard techniques (Battarbee et al., 2001). The slides were counted using 100× oil immersion objectives in either phase contrast, differential interference contrast or brightfield. The

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