Project no. GOCE-CT-2003-505540

Project acronym: Euro-impacs

Project full name: Integrated Project to evaluate the Impacts of Global Change on European Freshwater Ecosystems

Instrument type: Integrated Project

Priority name: Sustainable Development

Deliverable No. 241
Introductory paper on ‘Palaeolimnology and reference states’ to be submitted to the Journal of Palaeolimnology Special Issue “Reference states and lake restoration: the role of paleolimnology”

Due date of deliverable: Month 54
Actual submission date: Month 60

Start date of project: 1 February 2004
Duration: 5 Years

Organisation name of lead contractor for this deliverable: UCL

Revision FINAL

| Project co-funded by the European Commission within the Sixth Framework Programme (2002-2006) |
| Dissemination Level (tick appropriate box) |
| PU | Public | X |
| PP | Restricted to other programme participants (including the Commission Services) |
| RE | Restricted to a group specified by the consortium (including the Commission Services) |
| CO | Confidential, only for members of the consortium (including the Commission Services) |
Palaeolimnology and its role in defining reference conditions for lakes

R.W. Battarbee and H. Bennion

Although Lundquist (1927) in Sweden was developing methods to describe and classify lake sediments in the 1920s and Nipkow (1920, 1927) was conducting studies of laminated lake sediments in Switzerland at about the same time, palaeolimnology was a relatively under-developed science in the early part of the twentieth century. The great leap forward came as Hutchinson, together with his students and collaborators in the USA, and as Pennington in the UK (e.g. Hutchinson & Wollack, 1940, Deevey 1942, Patrick 1943, Livingstone, 1957, Pennington, 1943), began to explore the use of lake sediment stratigraphy to test ideas about the classification and natural evolution of lakes that had previously been put forward by the pioneering limnologists Thienemann (1925), Naumann (1919) and Pearsall (1921).

Evidence, principally in North America from Linsley Pond, and in England from Lake Windermere, suggested that temperate lakes went through a process of natural eutrophication related to the development of soils and vegetation in newly deglaciated landscapes, the export of nutrients from the catchment to the lake and the filling-in of the lake by sediments, including, as a consequence, changes in the functioning of lakes caused by the gradual reduction in the volume of the hypolimnion (e.g. Deevey, 1955).

“Eutrophication” was regarded as a natural process, initially rapid in the early phase and then slowing down and stabilising to establish a trophic equilibrium (Deevey, 1984). The seminal papers at this time generated substantial interest amongst palaeolimnologists about the nature of lake evolution, a debate that involved extensive examination of sediments from a wide variety of lakes, leading to many observations, not least the demonstration that for upland lakes in previously glaciated catchments long-term base depletion and oligotrophication are more likely processes than enrichment (e.g. Quennerstedt, 1955; Mackereth, 1965, 1966).

Mackereth’s arguments based on powerful deductions from innovative studies of the chemical record of lake sediments from the Cumbrian Lake District in England (reviewed and partially modified by Engstrom & Wright (1984)) were strongly supported by diatom evidence for early Holocene acidification in the UK by Round (1957), and Haworth (1969) and in Finland by Huttunen et al. (1978) and then reinforced later on, in the context of the “acid rain” debate by Atkinson & Haworth (1990), Renberg (1990) and Whitehead et al. (1986).

Few of these early studies were concerned with human impact, although Nipkow (1927) attributed the sudden appearance of *Tabellaria fenestrata* (= *T. floculosa* var. *asterionelloides*) in the upper sediments of Zürichsee to nutrient inputs and Pennington (1943) argued that the appearance and rapid increase of *Asterionella formosa* in the upper sediments of Windermere was a
response to the opening up of the English Lake District to tourism in the mid 19th century.

Whilst palaeolimnologists were debating these issues of long-term lake evolution, limnologists were beginning to point out how lakes were being altered by waste-water pollution (Hasler 1947). “Cultural eutrophication” rapidly became a major environmental concern in the 1950s and 1960s (e.g. Ohle 1953, Thomas 1957, Edmondson 1961), but palaeolimnologists, despite Nipkow’s (Nipkow 1920, 1927) and Minder’s (Minder 1938) early work on the sediments of Zürichsee, were slow to re-focus their attention on this new challenge. Examination of the uppermost records of lakes for evidence of human impact developed only slowly. Progress was particularly restricted by the lack of adequate techniques for coring the uppermost sediments of lakes without disturbance and by the lack of appropriate dating methods for non-varved sediments. Consequently palaeolimnology in the 1960s and 1970s made only a minor contribution to the cultural eutrophication debate, although several studies using a variety of biological indicators were able to demonstrate that striking changes had taken place in the uppermost sediments of lakes, providing evidence for recent eutrophication caused by human activity (e.g. Züllig, 1956, Stockner & Benson, 1967, Digerfeldt 1972, Battarbee 1973, 1978; Bradbury 1975, Pennington et al. 1977, Birks et al. 1976). In one case (Hutchinson et al. 1970) it was shown that cultural eutrophication had begun as early as the Roman Period.

By the time attention shifted to the “acid rain” debate in the 1970s and 1980s some of the problems of coring and dating recent lake sediments had been solved (e.g. Battarbee 1991, Last & Smol 2001), enabling palaeolimnologists to play a pivotal role in the debate. Indeed the importance of palaeolimnology in providing evidence for the timing, extent and causes of surface water acidification cannot be over-stated, and the acidification debate itself provided a major stimulus to palaeolimnology, especially with respect to the development of diatom-pH transfer functions (Birks et al. 1990) and the use of lake sediments to identify contamination of lakes by long distance transported air pollutants (e.g. Norton et al. 1982, Rippey 1990). The extension of the transfer function approach to diatom-TP transfer functions (e.g. Bennion et al. 1996; Hall & Smol, 1999) followed quickly enabling palaeolimnologists to re-engage with the continuing eutrophication debate, not only to provide evidence for the timing and extent of eutrophication but also uniquely to provide lake managers with estimates of past TP concentrations (e.g. Bennion et al., 2000, 2004).

Today, with an ever-increasing range of techniques and analytical methods available (Smol et al. 2001a, b), palaeolimnologists have the means to make past ecological and environmental reconstructions of high quality and high temporal resolution that are of immense value in addressing both theoretical and practical questions in limnology and lake management (Smol, 1992; Battarbee, 1999). Reconstructions can now be tested at sites where long-term (> 10 yrs) monitoring programmes allow inferences from the sediment record to be compared with observational time-series data (Bennion et al. 1995, 2005; Battarbee et al. 2008) and in some cases the fusion of limnological and
palaeolimnological approaches allows unbroken records from the present day back through the Holocene to be generated (cf. Battarbee et al. 2005a, Bradshaw et al. 2005) enabling contemporary processes to be set directly in the perspective of long-term trends and variability.

A key question that can be addressed in this context is how to attribute the causes of change in lake ecosystems between different kinds of human activity and between the overall impact of human activity and the effect of natural processes acting on different and often over-lapping time-scales. Palaeo-records can often provide rapid and unequivocal answers (e.g. Digerfeldt 1972), but often they contain ambiguities that allow hypotheses to be refined, although not necessarily refuted. The climate change debate at the present time illustrates this dilemma where diatom records from remote arctic and alpine sites that are indicative of increased algal productivity could be caused either by global warming directly, by nutrient release from catchment soils as an indirect response to global warming, or by long distance transported nutrient pollution (e.g. Smol et al. 2005, Wolfe et al. 2001, Catalan et al. 2002). In the more populated regions of the world there is added complexity resulting from changing inputs of nutrients and sediments from lake catchments, such that disentangling the roles of these different stresses is rendered exceptionally difficult.

In this context careful consideration needs to be given to the questions of ecosystem restoration, both in terms of the definition of restoration objectives, e.g. with respect to habitat quality, biodiversity and ecosystem structure and function, and to the information needed to make restoration decisions. The issue is critical in Europe and North America where legislation requires the competent authorities to restore degraded freshwater ecosystems to “good ecological status”. In the European Water Framework Directive (Pollard & Huxham 1998) this is defined with respect to the condition of similar ecosystems that are minimally impacted by human activity, often referred to as the reference state (Bennion & Battarbee 2007).

Whilst the concept is simple, the practice is complex, depending on (i) whether the reference state can be accurately defined using the different methods available; and (ii) whether the reference condition is indeed an appropriate target for restoration given the extent to which climate change may in many cases alter the boundary conditions within which lake ecosystems function (cf. Battarbee et al. 2005a). Whilst palaeolimnology can be used powerfully to tackle the first of these it is less able to deal with the second, that can only be addressed, if at all, using modelling approaches. However, even in this case the role of palaeolimnology is not diminished. Restoration planning for lakes requires an understanding of ecosystem trajectories from the reference condition to the present time, and process-based models used for planning purposes need to be verified against the observational and palaeo-records (cf. Battarbee et al. 2005b).

In this volume we focus only on the role of palaeolimnology in identifying reference conditions, leaving an evaluation of the potential influence of climate change on the definition of restoration targets for later.
In Paper 1, Battarbee et al. describe a palaeolimnological meta-database ("LakeCores") for lakes in Europe that have been cored for studies of recent (~100-200 years) environmental change. The database contains information on cores for which diatom-based pH and total phosphorus (TP) reconstructions have been derived. The summary data are used to assess the timing and extent of acidification and eutrophication of lakes across Europe and thereby to identify the period that can be considered to represent the pre-impact or reference conditions.

In Paper 2 Guilizzoni et al. explore the potential for inferring past TP concentrations in lake water from sedimentary pigments, particularly total carotenoids. A transfer function is developed from a training set of 28 Italian lakes and is subsequently applied to sediment cores to reconstruct the nutrient history and determine reference TP concentrations.

In Paper 3, Rose et al. attempt to improve our understanding of controls on sediment accumulation rates (SARs) by compiling data for 207 European lakes derived from $^{210}$Pb-dated cores. They assess how rates have changed through time (in 25 year classes) both across the dataset as a whole and for lakes of different types and, for six lake types, they estimate reference SARs.

In Paper 4, Bennion and Simpson employ diatom records to define chemical and ecological reference conditions for a range of UK lake types. They classify the compositional data from the time slice in sediment cores dated to ~1850 AD and apply existing diatom TP transfer functions to infer baseline TP concentrations for 169 sites. Additionally they estimate the floristic difference between the reference and present day (surface sample) diatom assemblages of each site to assess deviation from reference condition.

In Paper 5, Cunningham et al. use near-infrared spectroscopy (NIRS) to infer lake water total organic carbon (TOC) based on a calibration dataset of 140 Swedish lakes. The model is applied to sediment cores from four lakes to reconstruct TOC and thereby to assess changes over the last century.

In Paper 9, Bindler et al. review metal profile data, namely lead but also mercury and cadmium, from long sediment records covering up to 2000 years to determine the history of metal pollution in European lakes. Using data from Sweden and elsewhere, they determine the period during which natural background conditions prevailed and present a discussion on how these may differ from the concept of reference conditions.

Two further papers are still in the review process. These include a paper by Bennion et al. in which the pre-enrichment reference conditions (~1850 AD) of nine enriched lakes, covering a range of types across Europe, are determined using fossil diatom assemblages in dated sediment cores. An analogue matching training set of 347 European lakes and 719 diatom taxa is applied to the reference samples to explore the value of the analogue matching approach for identifying appropriate reference sites for lakes impacted by eutrophication.
The second paper in review by Battarbee et al. attempts to define a reference typology for low alkalinity lakes in the UK by clustering the ca. 1800 diatom assemblages of cores from over 100 lakes.

References


Digerfeldt, G. 1972 The post-glacial development of Lake Trummen: regional vegetation history, water level changes and palaeolimnology. *Folia Limnologica Scandinavica* 16, 1-104

Edmonson, W.T. 1961 Changes in Lake Washington following an increase in the nutrient income *Verhandlungen Internationale Vereinigung Limnologie*, 14, 167-175.


Minder L 1938 Der Zurichsee als Eutrophierungsphänomenon. *Geol. Meere Binnengewasser* 2, 284-299


