Using palaeolimnological and limnological data to reconstruct the recent history of European lake ecosystems: Introduction

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SUMMARY

1. As future climate change is expected to have a major impact on freshwater lake ecosystems it is important to assess the extent to which changes taking place in freshwater lakes can be attributed to the degree of climate change that has already taken place.
2. To address this issue it is necessary to examine evidence spanning many decades by combining long-term observational data-sets and palaeolimnological records
3. Here we introduce a series of case studies of seven European lakes for which both long-term data-sets and sediment records are available. Most of the sites have been affected by eutrophication and are now in recovery.
4. The studies attempt to disentangle the effects of climate change from those of nutrient pollution and conclude that nutrient pollution is still the dominant factor controlling the trophic state of lakes.
5. At most sites, however, there is also evidence of climate influence related in some cases with natural variability in the climate system, and in others with the trend to higher temperatures over recent decades attributed to anthropogenic warming.
6. More generally and despite some problems the studies indicate the value of combining limnological and palaeolimnological records in reconstructing lake history and in disentangling the changing role of different pressures on lake ecosystems.

Introduction

Meteorological records show that global mean temperatures have increased by 0.8 ^{o}C since 1950 and climate models predict that temperatures will continue to increase in the future (Ipcc, 2007). Indeed under some scenarios global mean temperature may reach 2 ^{o}C over the 1960-90 baseline within two decades and the warming projected to the end of the century, should greenhouse gas emissions not be significantly abated, could be well beyond the highest planetary temperatures that have occurred over the last 500,000 years (Ipcc, 2007).

The probability that future climate change will cause major changes to the structure and functioning of freshwater ecosystems is very high. Assessing the impact of changes in temperature and precipitation in particular is a central challenge for freshwater ecology. Part of such an assessment is to understand the extent to which changes in freshwater ecosystems can be attributed to climate change that has already occurred.

The evidence so far is mixed. Long-term records indicate that there have been changes in the physical characteristics of surface waters, including increasing surface water temperatures (Fang and Stefan, 1999; Livingstone, 2003), hypolimnetic warming in large lakes (Dokulil *et al.*, 2006) and decreasing ice cover in northern and high-altitude lakes (Magnuson *et al.*, 2000). There is also palaeolimnological evidence from changes in the composition of diatom assemblages of arctic and alpine lakes that warming over recent decades may be having a significant effect on freshwater ecosystems in remote high latitude and high altitude regions (Smol *et al.*, 2005; Solovieva *et al.*, 2005; Sorvari *et al.*, 2002).

However, in populated regions of the world where most if not all lakes are suffering or recovering from the consequences of human activity such as nutrient enrichment or acid deposition, identifying the unique influence of climate change is more problematic (cf.Jeppesen *et al.*, 2010). Climate change in these systems is yet to become the dominant driving force and disentangling a climate effect from the effects of other pressures is difficult, either because the climate effect is masked by the strength of other impacts or because climate change is causing ecosystem responses similar to those that could equally be caused by other pressures. This is especially so where changing temperature and precipitation regimes strongly influence the nutrient dynamics of lakes creating symptoms identical to those caused by cultural eutrophication (Moss *et al.*, 2011).

Addressing these questions needs long-term records of lake behaviour that span many decades. For some sites long-term observational records are available (e.g.George *et al.*, 2007; Jeppesen *et al.*, 2005; Straile, 2000) but although such records are becoming longer as time passes they are usually too short to provide the full time perspective needed. Lake sediment records offer a complementary source of information. However, although the time perspective offered by sediment records is unlimited in this regard they can also have significant deficiencies especially where sediment accumulation rates are very slow and preservation of biological material poor. In the EU-funded Euro-limpacs Project (Kernan *et al.*, 2010) on the future impact of climate change on European freshwater ecosystems, we attempted to avoid these problems by selecting study sites that contained rapidly accumulating, biologically rich sediments and that also have been the subject of long-term monitoring programmes over several decades. The combination of records potentially offers the best opportunity for disentangling the relative importance of different pressures on lake ecosystems over time. More specifically in the case studies presented here it enables the separate and combined role of climate change and nutrient loading on ecosystem behaviour to be examined.

Case studies

The sites described in the following papers are located in different geographical regions in Europe (Fig. 1), ranging from Mývatn in Iceland in the north to Lago Maggiore in Italy in the south. They range considerably in size and depth (Table 1), but are similar in that, with the exception of Mývatn, they have all experienced eutrophication and are now in different stages of recovery.

Mývatn is a relatively shallow but large eutrophic lake in a volcanic area in the northeast of Iceland. Monitoring of the lake since 1975 has revealed extreme fluctuations in its food web, most notably in the populations of chironomids and Cladocera. The fluctuations have a periodicity of 5-8 years and are thought to be driven by in-lake processes associated with food-web dynamics where chironomid abundance depends on the availability of diatoms and organic matter.

Hauptfleisch *et al*. (2012) use chironomid egg and cladoceran carapace abundance in the sediments to show that the observed population fluctuations from monitoring are recorded in the Mývatn sediments, and then to show that the cyclical pattern of food-web dynamics has a longer history. Although the authors do not rule out the role of climate variability they argue that the observed cyclicity is best explained by natural variations in the internal dynamics of the lake ecosystem. Matching the cycles with records of climate variability is hindered at the site by the difficulty in establishing a robust sediment chronology.

In contrast to Mývatn, Mjøsa is a very deep lake. It is situated in eastern South Norway and has a history of eutrophication. Regular monitoring of lake water quality began in 1972 tracking the rapid eutrophication of the lake during the early 1970s. A successful campaign to reduce phosphorus loading resulted in a decline in concentrations after 1976, followed by a decline in algal biomass.

Mean epilimnion temperature over the summer stratification period in the lake has increased by about 1.5 °C over the monitoring period and temperature data compiled from a range of documentary and instrumental sources indicate the region has experienced a slight increase in early spring temperatures from around 1830, another slight increase around 1900, a decline towards 1960, and a more rapid increase about 1990.

The eutrophication history of the lake is clearly represented in the lake sediments by both the diatom and pigment records (Hobaek *et al.*, 2012). The data show that a significant recovery towards more oligotrophic conditions has taken place as a result of a reduction in phosphorus loading but the lake has not yet reached its pre-eutrophication status, either because nitrogen concentrations remain high and/or because of climate change.

A redundancy analysis (RDA) of the diatom data from the sediment core shows that Chl *a*, used as a proxy for production, combined with temperature explains 60% of the variance in the species data, indicating that climate change may be an increasingly important influence on the lake.

Loch Leven is a relatively large but shallow eutrophic lake in lowland Scotland. The lake has suffered from severe eutrophication from both point and diffuse nutrient sources. P loading has been reduced since 1985 and there has been a decrease in TP concentrations from ca 100 μg L^{-1} in the 1970s to 33 μg L^{-1} in 2008.

The lake has been monitored weekly or fortnightly since 1968 and is one of the most well-studied lakes in the UK (Carvalho *et al.*, 2012). Climate data show that there has been a highly significant increase in spring temperature and significant increases in summer and autumn air temperatures over the monitoring period. Winter rainfall amounts have also increased.

A sediment core collected from the lake in June 2005 and two previous cores were used for the analyses presented in this special section by Bennion *et al*. (2012). The 2005 core was sliced at 2.5 mm intervals to provide a high resolution record of changes in diatom assemblages to match against the nutrient and climate data.

The palaeolimnological data indicated that enrichment of the lake started in the early 19th century, most likely from changes in catchment land-use, with a more marked phase of eutrophication since ca.1940-50 caused by increased phosphorus inputs from sewage treatment works, land drainage and the effluents from a woollen mill. The diatom data indicate a degree of recovery from eutrophication following the reduction in P loading in the mid-1980s, but the contemporary flora is still characterised by taxa associated with nutrient-rich conditions.

The core data agree well with the long-term monitoring series of water chemistry and phytoplankton. Both data sets indicate that the eutrophication signal in the sediment record outweighs any evidence of climate as a control on the diatom community at least on a decadal time-scale. However, Bennion et al. (2012) argue that the inter-annual variability in the diatom composition may be influenced by climate, especially with respect to evidence for wetter and possibly windier conditions in recent years.

Esthwaite Water is a relatively shallow lake in the Cumbrian Lake District of north-west England. It has been monitored since 1945 (Maberly *et al.*, 1994). Eutrophication, characterised by regular cyanobacterial blooms, became a serious problem in the 1970s following the discharge of waste-water from a local sewage treatment plant and, in 1981, the installation of a fish farm on the lake. Tertiary treatment to remove phosphorus was introduced in 1986, but recovery has so far been limited (May *et al.*, 1997).

The monitoring data track the increase in nutrient concentration in the lake in detail with winter SRP maxima remaining very low at an average of 2 μg L^{-1} before 1970 rising to 12 μg L^{-1} for the period 1970-2004. Air temperature has been variable over this time period with average temperatures after 1987 of 9.3 °C being somewhat higher than the average of 8.7 ^{o}C for 1945-87.

Several cores have been taken from Esthwaite (Bennion *et al.*, 2000; Dong *et al.*, 2012b) over the last decade. The data presented by Dong *et al*. (2012a) were obtained from a core taken in 2006. Analysis focused on the sediment diatom record covering the time interval from 1945 to the present day affording a direct comparison with the period of monitoring.

The core data showed a clear compositional change in the diatom assemblages through time with significant changes occurring from ca. 1975 and ca. 1996. Redundancy analysis (RDA) of the diatom and environmental datasets showed that the most important variables explaining diatom species compositional change were winter concentrations of SRP and air temperature, independently explaining 22% and 8% of the diatom variance respectively.

Additive models showed that winter SRP was the most important factor controlling the diatom assemblages for the whole monitoring period but that air temperature became an important regulating factor since the mid-1990s.

White Lough in Northern Ireland is a small kettle lake with a predominantly agricultural catchment. The lake is sheltered and monomictic with a high TP concentration (>50 μg L^{-1}), pronounced hypolimnetic anoxia during summer stratification and associated internal P-loading. The lake has been well-studied (Foy, 1985; Rippey *et al.*, 1997) but lacks the long-term continuous monitoring data available at other sites. However, it benefits from its location close to the Armagh Observatory which houses one of the longest meteorological records for the UK dating back to 1838 (Butler *et al.*, 1998; 2005). Consequently it not only provides an excellent record of local air temperature but, because of its proximity, also a record of precipitation that can be reliably assumed to represent the amounts and trends in precipitation experienced by the lake itself.

Anderson *et al.* (2012) use palaeolimnological methods to reconstruct the ecological response of the lake to changes in nutrient P-loading (derived from documentary evidence, geochemical analyses and hydrological modelling) and climate (precipitation variability) over approximately the last 100 years.

The core, taken in 2007, was sampled at high resolution and analysed to determine diatom assemblage variability and biogenic silica concentration. The data showed relatively stable conditions until about 1960 but thereafter the lake became more eutrophic due to increased diffuse nutrient inputs from the catchment. Anderson *et al*. (2012), however, also show that climate variability, primarily through the impact of precipitation change on lake retention time and internal nutrient loading, is also important in controlling changes in primary production. The effect of the 1974–75 droughts was especially marked, although there was no discernible evidence of the 1932 drought. Diatom production, measured in the sediment record as biogenic silica, exhibited a seven-year cycle and a weak relationship to the temporal pattern of dry summers seen in the Armagh record and in the NAOI. An analysis of long-term monitoring data from 1971 to 2007 of nitrate exports from the Blackwater River showed that these too followed a roughly seven-year cycle at least to 2000, in which dry summers were followed by sharp increases in nitrate export. It is argued that the seven-year cycling of diatom production in White Lough reflects the cyclic behaviour in nitrate loading and the constraints that nitrogen availability places on the spring diatom bloom in a lake that is dominated by cyanobacteria.

Piburger See is a mountain lake situated in the Central Eastern Alps at an elevation of 913 masl. Its catchment is dominated by coniferous forest lying on granite and gneiss bedrock. The lake became increasingly eutrophic during the 20th century especially during the 1950s and 1960s as a result of the growth of tourism and the use of fertilisers in the catchment. Following measures taken to reduce nutrient loading that began in 1970 the lake is now recovering although there is evidence for increased primary production since 2000.

To evaluate the long-term changes in the trophic state of Piburger See, Thies *et al*. (2012) combined contemporary limnological data with data from a sediment core taken from the lake in 2004. The core was analysed for geochemistry, algal pigments and diatoms.

The core data showed that moderate eutrophication during the 20th century had occurred followed by a slow re-oligotrophication since the mid-1980s. The uppermost sediments showed clear evidence for a very recent increase in the planktonic diatom *Asterionella formosa* Hassall in agreement with the limnological data, and associated with the recent increase in productivity. The authors relate this to epilimnetic warming and an increase in the stability of the water column as a result of the recent increase in air temperature in the region. Given that nutrient loading to the lake has now been significantly reduced Thies *et al*. (2012) suggest that climate change may now be becoming the dominant driver of the lake's trophic state.

The last case study is concerned with the history of flooding in Lago Maggiore, Italy. Lago Maggiore lies to the south of the Alps along the border between Italy and Switzerland. It is a very large, deep lake that has been extensively studied (Guilizzoni *et al.*, 2012). Limnological data are available from 1950 documenting the history of eutrophication during the period from 1965 to 1980, followed by re-oligotrophication in the 1990s (Manca *et al.*, 1992; Salmaso *et al.*, 2007). Data from a network of meteorological stations around Lago Maggiore and its catchment show there has been a warming trend during the last 60 years of 1.0 °C (Ambrosetti and Barbanti, 1999). Also the lake water temperature in the upper 20 m showed an increasing trend around 0.8 °C on annual basis (Ambrosetti *et al.*, 2006).

Lago Maggiore is subject to frequent and severe flood events especially in autumn. In the study of Kampf *et al*. (2012), evidence for the past frequency and magnitude of past flood events is presented based on the presence of visible detrital layers in sediment cores taken from the Pallanza Basin in the northwestern part of the lake. In all 20 cases the detrital layers can be matched with instrumental data for past floods derived either from instrumental lake-level data or from the discharge history of the R. Toce. However, seven recorded floods during that time period were not detected in the sediment record, in some cases due to multiple floods occurring in the same year.

The study indicates that the sediments provide a relatively faithful archive of flood history, offering the possibility of using the record to assess whether the frequency and magnitude of flooding is increasing as a result of climate change and whether flooding has a discernible impact on the lake's ecology independently of the impact of warming.

The final paper in the special section (Battarbee *et al.*, 2012) reviews the results from these different case studies and discusses the generic issues that influence the precision with which palaeolimnological data can be matched with limnological data. It then examines the extent to which the palaeolimnological data provide evidence for the impact of climate change on European lakes over recent decades separately from the effect of nutrient loading. The paper highlights the importance of accurate sediment core dating, the use of sediment cores with high sediment accumulation rates, the need for compatibility of limnological and palaeolimnological measurements, the problems associated with the assembly of independent data on the behaviour of environmental drivers, especially nutrient concentration, and the statistical confidence with which explanatory and responses variables can be compared.

Despite these concerns the authors conclude that combining observational and palaeo-data in the way illustrated by the papers in the special section can provide unique insights into lake ecosystem history. It is clear from the case studies that increased nutrient loading, or its legacy, associated with cultural eutrophication, remains the dominant controlling factor on the trophic state of lakes. At most sites, however, there is evidence of climate influence related in some cases with natural variability in the climate system, and in others with the trend to higher mean temperatures over recent decades that has been attributed to anthropogenic warming. Although the climate effect is not as marked as for arctic and alpine environments, it is anticipated that as lakes progressively recover from cultural eutrophication the relative importance of climate change on lake ecosystems will increase should the trend to higher mean global temperatures continue.

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Figure legends

Fig. 1. Location of study sites.

Tables

Table 1. Main characteristics of the seven study sites. **Mývatn**: Depth is maximum natural depth, excluding dredged area, TP is mean concentration at outlet March 2000-March 2001; chl *a* is mean value in South Basin June-August 1972; temperature is mean air temperature 1931-1960; ice-cover is mean 1932-1976. **Mjøsa**: TP and Chl *a* are mean epilimnetic (0-10 m) concentrations, May-October 2005; temperature and precipitation are 1961-90; ice cover is mean for 1990-2009 (1970-1989 mean was 59 days). **Leven**: data are mean for 1999-2008; full ice cover, ice-cover data refer to partial ice-cover. **White**: precipitation annual mean and July mean temperature are 1960-2000; TP and Chl *a* are from September 2008; continuous lake monitoring 1978-1982. **Esthwaite**: TP and Chl *a* mean for 2008; temperature and precipitation are 1961-1990. **Piburger See**: TP and Chl *a* are mean 1998-2004; temperature and precipitation are 1961-90; ice cover is range 1961-90. **Maggiore**: TP and Chl *a* mean for 2010; temperature and precipitation are 2010.

Site	Lat/Long	Area (km^2)	Maximum depth (m)	Total phosphorus (µg L^{-1} mean)	Chl *a* (µg L^{-1} mean)	Mean July temperature (^oC)	Annual precipitation (mm)	Ice-cover (days yr^{-1})	Start of record
Mývatn	63°35`N, 17°00`W	37	4.0	26.2	15	10	470	189	1970-1977
Mjøsa	60.41N 11.02E	369	453	3.7	2.3	15.2	585	28	1972
Leven	56.12 N, 3.22W	13.3	25.5	57	35	14.3	1074	14	1968
White	54.416° N, 6.915° W	0.074	10.7	76	57	15.3	817	rare	1978-1982
Esthwaite	54°22'N 2°59 W	1	15.5	28.3	17.2	17.5	1900	rare	1945
Piburger	47°11' N, 10°53' E	1.59	24	7	3	16	700	100-120	1975
Maggiore	45°57'N; 8°38'E	213	370	10	3.3	26	2247	na	1950

Fig. 1


0
300 Kilometers
0
300 Miles
N
Myvatn
Mjøsa
Loch Leven
White Lough
Esthwaite
Water
Piburger See
Lago Maggiore