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ORIGINAL PAPER

Global change revealed by palaeolimnological records from remote lakes: a review

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Abstract Over recent decades, palaeolimnological records from remote sites have provided convincing evidence for the onset and development of several facets of global environmental change. Remote lakes, defined here as those occurring in high latitude or high altitude regions, have the advantage of not being overprinted by local anthropogenic processes. As such, many of these sites record broad-scale environmental changes, frequently driven by regime shifts in the Earth system. Here, we review a selection of studies from North America and Europe and discuss their broader implications. The history of investigation has evolved synchronously with the scope and awareness of environmental problems. An initial focus on acid deposition switched to metal and other types of pollutants, then climate change and eventually to atmospheric deposition-fertilising effects. However, none of these topics is independent of the other, and all of them affect ecosystem function and biodiversity in profound ways. Currently, remote lake palaeolimnology is developing unique datasets for each region investigated that benchmark current trends with

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A celebration of Prof. Rick Battarbee's contributions to palaeolimnology, edited by Holmes et al.

This paper has been written as a contribution to celebrating Rick Battarbee's influence on palaeolimnology. Some of us have benefitted from his leadership (and friendship) in transnational European projects during the last decade (e.g., ALPE, ALPE2, MOLAR, CHILL-10000, EMERGE, EUROLIMPACS), which together with some other initiatives spawned pan-European remote lake research. Others have respected Rick as a teacher, colleague and a friend. To some extent, this review follows the chronological order of topics addressed in these projects, which also respond to the growing social awareness about each issue. Rick also facilitated bridges between North American and European schools, and beyond. We expect his attitude towards collaboration will pervade and persist through the palaeolimnological community for years to come, and global change will certainly provide stimulating and challenging questions with which to do so.

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respect to past, purely natural variability in lake systems. Fostering conceptual and methodological bridges with other environmental disciplines will upturn contribution of remote lake palaeolimnology in solving existing and emerging questions in global change science and planetary stewardship.

Keywords Remote lake palaeolimnology · Climate change · Nitrogen cascade · Acidification · Long-range atmospheric pollution · Arctic lakes · Alpine lakes · High latitude · High altitude

Introduction: global change and remote lakes

Since the Industrial Revolution, beginning in the late eighteenth century, a new era has arisen in which humans are the main drivers of global environmental change. During the last 10,000 years, the Earth has experienced a period of unusual environmental stability compared to previous millennia, which exacerbates the uncertainties regarding what may happen in the near and distant future. Current global change is multidimensional by nature (Rockström et al. 2009). The inexorable rise of atmospheric carbon dioxide and other greenhouse gases and attendant climate warming are the most evident components, but they are not the only ones. The depletion of stratospheric ozone and the increase of the reactive nitrogen pool on the planet represent other key dimensions of global atmospheric changes. Together, these can be catalogued as systemic: they intrinsically involve a modification of the Earth system. In addition, other human impacts, which were initially regional in nature, have become global as they progressively extend across a large part of the planet. Resource overexploitation, soil erosion, acidification, eutrophication, toxification, urbanization and facilitation of organism dispersion are all examples of changes with increasingly widespread environmental footprints and potential influence on a planetary scale. Furthermore, many of these impacts intersect and result in emerging, and at times synergistic, processes that have the potential to influence ecosystem function, biodiversity, species invasions, and the emergence of new diseases. The planet is undergoing a variety of regime shifts, the consequences of which remain difficult to predict,

Fig. 1 Human landscape change. Early landscape changes recorded in mountain lakes located at the timberline migration zone are illustrated by multi-proxy sediment records from the Sägistalsee (1935 m a.s.l.), Swiss Alps, a remote lake that was chosen to reconstruct temperature changes over the Holocene from diatom and chironomid records (Heiri et al. 2003). However, it appeared that the different abiotic and biotic proxies clearly reflect the human impact that already started around 4000 cal yr BP with deforestation by slash-and-burn, affecting erosion, soil stabilization, and the lakes productivity and oxygen content (Koinig et al. 2003; Wick et al. 2003). For further details, refer to the Electronic Supporting Information ▶

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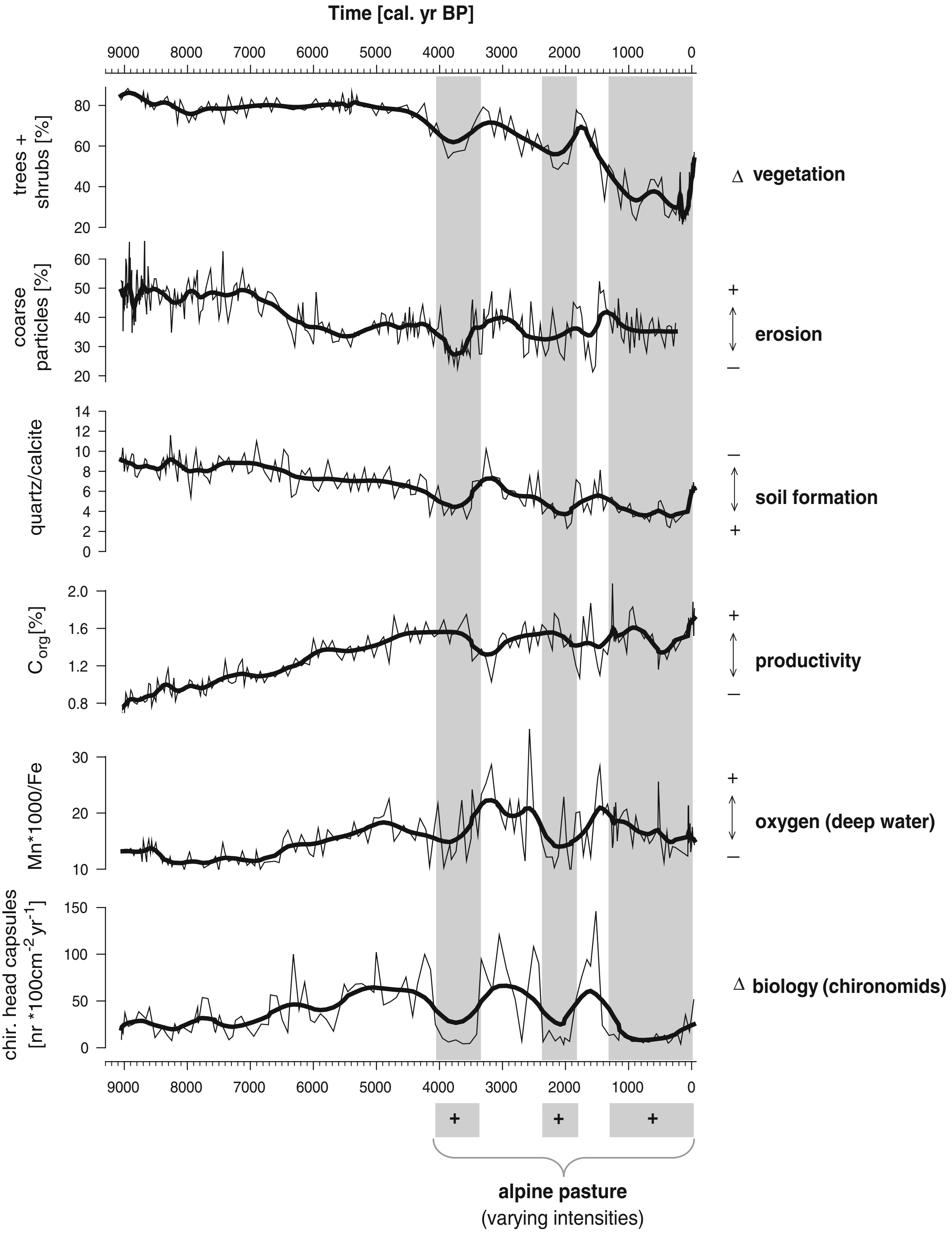
Time [cal. yr BP]
9000
8000
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3000
2000
1000
0
trees + shrubs [%]
20
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80
Δ vegetation
coarse particles [%]
20
30
40
50
60
+
erosion
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quartz/calcite
0
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soil formation
+
C$_{org}$ [%]
0.8
1.2
1.6
2.0
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productivity
–
Mn*1000/Fe
10
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oxygen (deep water)
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chir. head capsules [nr *100cm^{-2}yr^{-1}]
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Δ biology (chironomids)
+
+
+
alpine pasture
(varying intensities)

although many changes have already occurred that are sufficient to consider them as harbingers of a new epoch, the Anthropocene, which follows the relatively stable Holocene within which present society has developed (Steffen et al. 2011a).

Monitoring of some of the suspected key drivers of global change provides indications about the mode and pace at which global change is proceeding. For instance, atmospheric CO_2 concentrations, at stations such as the Mauna Loa observatory, have become an icon of global change even beyond scientific circles. However, ecosystem changes and the consequent whole-biosphere response to multiple stressors cannot be evaluated exclusively based on these records. Ecosystem response has to be directly evaluated (Barnosky et al. 2012). However, how can local variability be disentangled from planetary regime shifts? At sites in which human activity takes place, the confounding effects due to local activities may obscure more subtle, but ultimately more powerful and longer-lasting impacts. There is, therefore, a need for biospheric sentinels of global change (Williamson et al. 2008). Species migration (e.g., birds, butterflies, Debinski et al. (2006)) provides indications that ecological processes are accelerating rapidly for some organisms, but the ecosystem perspective is missing. Ecosystems at sites isolated from immediate human pressure may provide a more comprehensive view than single species changes. Currently remote sensing can cover those areas and provides rich information (Coppin et al. 2004). However, the time-series available provide relatively short temporal perspectives (a few decades at best) and, moreover, only a limited number of variables that pertain to ecosystem processes. Proxies contained in sediment archives from remote lakes provide a complementary view, with a much longer temporal perspective and a richer array of information, including biodiversity (Axford et al. 2009).

Lake sediments register environmental and ecological dynamics far beyond the lake itself. Exports from the surrounding terrestrial environment at the catchment scale, as well as processes within the airshed of any given locality, influence lake ecosystems to a high degree. Ultimately, terrestrial and aquatic systems both respond to atmospheric influences (Leavitt et al. 2009), which can be tracked efficiently, if local human disturbances are minimal. Temporal variations in remote lakes, namely those at high altitude or high latitude, depend mostly on ecological and biogeochemical responses to atmospheric forcings conditioned by the ontogenic development of the ecosystems through time (Birks et al. 2000). Therefore, in the context of current global change, remote lakes are excellent ecological sentinels because their sediments contain an invaluable record of post-industrial changes that can be benchmarked against early, pre-disturbance, time intervals (Smol 2008). In this paper, we review how palaeolimnological records of remote lakes have contributed to the global change science agenda, and comment on their current and future role in global change monitoring and processual understanding. Although we aim to highlight the palaeolimnological contribution, the review is by no means comprehensive, and some relevant themes are only marginally addressed (e.g., UV impacts; Leavitt et al. (2003)). The sections approximately follow the chronological development of awareness and interest for some main topics, particularly in Europe and North America.

Ideally, the definition of remote lake should embrace those in which direct human impact in the catchment is irrelevant for studying any of the processes implied in global change (Battarbee et al. 2002a). Generally, we may expect that the higher the elevation and the farther north (or south), the more remote. However, especially in alpine regions, human influence on these seemingly natural landscapes becomes more prominent and earlier in history as studies intensify (Anderson et al. 2011; Koinig et al. 2003; Schmidt et al. 2008). In mountains, humans have fostered the establishment of high altitude pastures, and the treeline has been shifted down in many valleys (Fig. 1). Fire was usually the tool used to produce such landscape changes (Carcaillet et al. 2009). Contrasts between fire regimes before and after the appearance of humans in a region are well archived in lake sediment records. On occasion, the local human impact is subtle, e.g., a slight increase in erosion rates due to the occasional sheep grazing (Camarero et al. 1998), while at other sites it is a more direct manipulation of the whole lake community, e.g., fish stocking (Schindler et al. 2001). In many respects, the decline of "remoteness" is in and of itself a meaningful component of global change, as both improved access and warming temperatures lure human occupation and facilitate a diversity of encroaching activities. Operationally, remote lakes can be considered as those for which atmospheric forcing is currently the main driver of lake and catchment processes.

Long-range atmospheric pollution

Acidification: the first signs of ecosystem vulnerability

Human impacts on the Earth system are frequently mediated through the atmosphere, and emissions from fossil fuel combustion are the primary cause of much of the resulting recent global change. However, historically, concern about long-range atmospheric impacts did not arise because of greenhouse-gas emissions, but rather because of strong acid emissions and their acidifying effect. Many remote lakes are situated on catchments of crystalline bedrock with low natural buffering capacities and thus are sensitive to acid deposition. Consequently, remote lakes often recorded impacts of long-range atmospheric pollution in their sediments, particularly by diatoms, one of the main microfossil components of the sediments in theses lakes. The assemblage composition of these algae is extremely sensitive to pH changes (Battarbee et al. 2010; Flower and Battarbee 1983).

The acidification problem stimulated the development of a range of new techniques and conceptual approaches in palaeolimnology. Developments in high-resolution age-depth modelling (Appleby et al. 1986) and numerical methods (Birks 1998), mostly using space-for-time regression and calibration approaches known as training sets, are tools pioneered in this period and later adapted for other applications. Beyond technical improvements, the acidification issue fuelled the credibility of palaeolimnology as a powerful method for framing current observational changes and testing competing theories and hypotheses in the context of long-term variability. The problem was clearly stated: is long-range transport of atmospheric pollution the cause of pH decline at sites distant from industrial point source emission? The answer was an unambiguous yes, and together with the neo-limnological evidence, settled debates invoking alternative hypotheses such as “natural ontogenic” acidification (Battarbee and Renberg 1990). Despite the sobering final message, the scientific success of palaeolimnology in acid rain research conferred considerable credibility to the field in general, a firm rooting within the environmental sciences, and a rich trajectory for subsequent growth (reviewed in Smol 2008).

The acidification issue raised the question about whether truly pristine areas still exist on the planet. Palaeolimnological studies have demonstrated that Arctic lakes, in general, have shown a remarkable stability in their acidity state during the recent past and that anthropogenic acidification of Arctic lakes is commonly restricted only to the vicinity of some point sources of pollution, such as the smelter industry on the Kola Peninsula, Russia (Weckström et al. 2003). However, the presence of soot, spheroidal carbonaceous particles (SCP), and other trace contaminants in extremely remote lake sediments suggests that most regions of the planet are affected to some extent by human activities (Rose 1995). In any case, awareness that pollution was not a local issue rapidly became evident, and international regulative actions were taken across many jurisdictions. Declines in sulphur emissions and subsequent progressive pH recovery of many impacted lakes were positive consequences of these actions, and palaeorecords captured it all (Allott et al. 1992). However, palaeolimnological records also showed that biological recovery takes longer than chemical recovery (Fig. 2) (Monteith and Evans 2005), particularly for species that totally disappeared from the system (e.g. some chironomids and cladocerans, Stuchlík et al. (2002)). In fact, it is still not clear whether confounding effects may override competitive effects for species with similar niche in these lakes (Levine and D’Antonio 1999). Therefore, it may be that, even with a complete chemical recovery, a return to background reference conditions will not occur, and rather the lake regime shifts to a new configuration. In the current context of coupled effects associated with climate change, the eventual return to initial conditions is even more unlikely (Battarbee et al. 2005; Smol 2010). Continued monitoring of acidification recovery thus remains an important item in the scientific agenda (Bennion et al. 2011).

Metals: the first form of long-range atmospheric pollution

Although acidification was the first recognized long-range atmospheric pollution problem, palaeolimnological data confirmed that metal pollution long pre-dated the Industrial Revolution in many regions (Brännvall et al. 1999; Renberg et al. 1994). Early mining and metallurgy was not environmentally friendly, and the signature of long-range atmospheric metal pollution can be traced back at least to the Roman period in sediment records from remote sites in

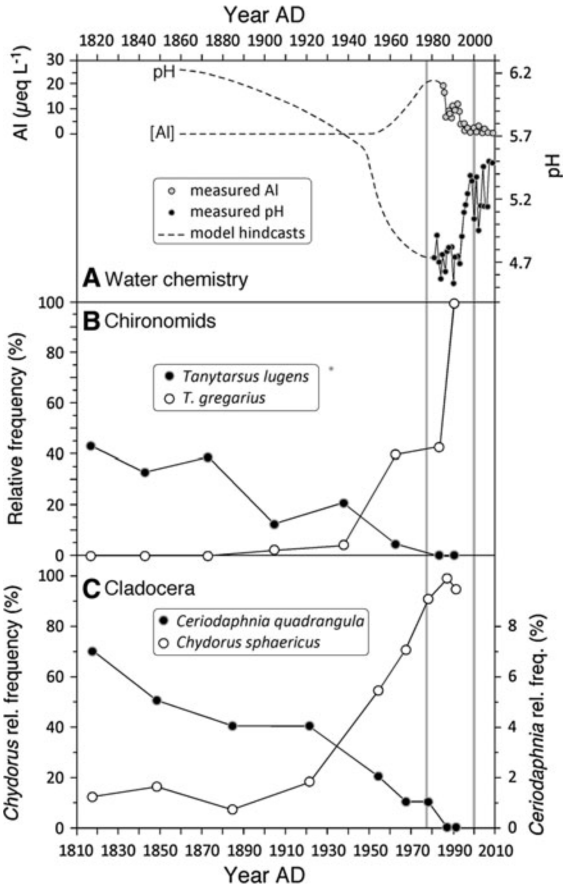

Fig. 2 Acidification and recovery of Lake Starolesnianske (Tatra Mountains, Slovakia). **a** Historical concentrations of lake-water Al and pH and their reconstructed values using the MAGIC model (*dashed lines*) (Stuchlík et al. 2002). **b** Relative frequencies of the dominant chironomids. **c** Relative frequencies of head shields of *Chydorus sphaericus* and ephippia of *Ceriodaphnia quadrangula*. *Vertical grey lines* show the period in which water quality recovered, but taxa such as *Tanytarsus lugens* and *C. quadrangula* did not rebound. For further details, refer to the Electronic Supporting Information

Europe (Renberg et al. 2000) and Pre-Columbian empires in South America (Cooke et al. 2009). Although lake acidification studies outnumber those on atmospheric deposition of metals, evidence exists of current long-range transport of lead, mercury and other trace metals in both high altitude and high latitude records (Camarero et al. 2009). Lead (Pb) stable isotope studies allow the distinction between catchment natural sources and atmospheric pollution (Bindler et al. 2001; Camarero et al. 1998). As in the case of acidification, for metal pollution one can geographically identify a general diffuse component related to some historical period of technological development (e.g. Roman period), and another depending on distance to the particular mining, and metallurgical centres of each period.

Whereas lake and catchment ecological impacts of acid deposition are clearly recorded in sediments (in fact, we reconstruct the impact not the loading), the direct effects of trace metals are difficult to evaluate from the sediment record, unless they are associated with acidification, such as in some intensive mining areas of early industrialization (Ek and Renberg 2001). Long-range metal pollution is generally evaluated using a historical rather than an ecological perspective (Renberg et al. 2002). Natural metal concentrations in lake sediments can fluctuate markedly (Koinig et al. 2003) and atmospheric metal deposition must therefore be extremely high to create an observable disturbance in the system. However, this is not simple because multiple interactions can also occur in the soils (Bindler et al. 2008).

The soils in polluted catchments have stored deposited metals over long-periods of time. The anthropogenic trace metals accumulated in catchments can be several orders of magnitude higher than the current yearly atmospheric deposition over the area (Bacardit et al. 2012; Klaminder et al. 2005). Under changing conditions, the accumulated metal inventory can be released to surface waters, and delayed contamination of aquatic systems may occur. Local climate may affect the release rate from soil metal pools in different ways. Increased transport from soils to lakes may happen because of leaching or soil erosion. Enhanced winter precipitation, drier summers, and higher frequencies of extreme rainfall events have increased soil erosion in the Scottish uplands, and, as a consequence, trace metal records are not showing the decline expected as a result of the massive reduction in emissions since the 1970s (Rose et al. 2012). Palaeolimnological evidence from Greenland indicates that aeolian redistribution of metal deposits under changing climate may also be significant (Lindeberg et al. 2006). Another possible mechanism increasing the load of metals such as Hg from soils to aquatic systems is an increase in soil moisture and anoxic conditions occurring during wet periods, which increases Hg methylation. In addition to soils, there are other potential reservoirs of metals that can be mobilised by changing climate. For instance, currently there is a surprisingly high metal release coming from rock glaciers in Alpine areas (Thies et al. 2007). Other remote reservoirs may be associated with unexpected transportation vectors such as birds with large foraging areas or that migrate from polluted areas (Foster et al. 2011).

Sediment records may provide reference conditions for what has occurred under similar changing climate conditions and less atmospherically polluted periods. This is relevant because changing characteristics of soil and other metal catchment deposits under changing climate may confound the evaluation of regional measures to reduce emissions. From a global change perspective, it is challenging to discern whether the metal loads (e.g., Hg) at high latitudes follow the recent decreasing trends in some regional emissions (e.g., Europe) or whether the load is still high because of continuing global emissions (Lindeberg et al. 2007). Sediments are system recorders and also sinks of materials. Determining how stable that sink is for metals is a matter of considerable interest (Rydberg et al. 2008). Metal pollution has permeated remote ecosystems over the last ~150 years, including some parts of the Arctic. Future research should aim to find out whether the extra metal loading has had an additional effect to that of other stressors (Fig. 3).

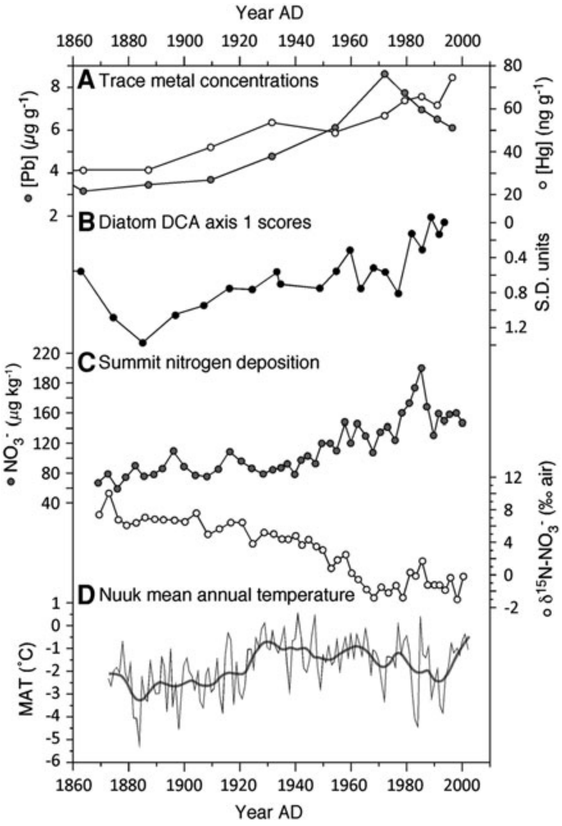

Fig. 3 Synthesis of palaeolimnological records from the Kangerlussuaq lake district of south-western Greenland. **a** Long-range atmospheric pollution witnessed by Pb and Hg concentrations trends. **b** Evidence of recent ecological change captured by the leading axis of Detrended Correspondence Analysis (DCA) from diatom assemblages dominated (40–60%) by the *Discostella stelligera* complex (Perren et al. 2009). **c** Changing atmospheric nitrogen inputs recorded from the Summit of the Greenland Ice Sheet (Hastings et al. 2009). **d** Mean annual temperature from Nuuk. For further details, refer to the Electronic Supporting Information

Synthetic pollutants: an overlooked side of global change?

Prosperity following the Industrial Revolution has been based on the increased use of energy and also in the continuous development of new compounds. These synthetic substances were not present before in nature and hold many uncertainties about their impacts on ecosystems and the biosphere as a whole. Toxicity is not a feature inherent to the nature of any particular compound, but it is defined for the particular interaction of the compound and a specific organism. There are substances that are clear candidates to being poisonous for most (if not all) living beings, but there are others whose high toxicity came as a surprise to the scientific community (e.g., polychlorinated biphenyls, PCBs). Particularly challenging are those substances that show high affinity for organic solvents (hydrophobic), are persistent (chemically recalcitrant in the environment) and are relatively volatile allowing transport over long distances. These persistent organic pollutants (POPs) tend to bioaccumulate in organisms across the planet with uncertain consequences. They have been found at high latitude and high altitude, with the additional feature that some compounds predominantly accumulate in cold environments.

The respective higher POP volatilisation in warm, and condensation in cold areas can be seen as a "global distillation" process (Wania and Mackay 1993), which in high mountains results in altitudinal gradients (Blais et al. 1998). The lake sediments show a concentration increase in DDTs and some PCBs of about an order of magnitude per km elevation (Grimalt et al. 2001). The number of organic synthetic substances is high and will certainly increase in the future. If they are relatively labile but massively used, they are likely to be continuously transported to remote sites, where high pools can be maintained by sustained loading despite the short life of the compounds. On the other hand, for some highly stable molecules, it is difficult to accurately estimate the volatility. Apparently non-volatile substances (e.g., polybromodiphenyl ether 209) have been found in the sediments of remote sites after only a few years of use (Bartrons et al. 2011).

Pollutant release from melting glaciers is currently a topic of interest (Blais et al. 2001). Dated sediment cores from glacier-fed lakes in Swiss Alps (Bogdal et al. 2009; Schmid et al. 2011) have shown that fluxes of all organochlorines increased in the 1950s, peaked in the 1960s–1970s, and decreased again to low levels in the 1980s–1990s as expected from the emission and regulation history of these compounds. However, since the late 1990s, input of all compounds has increased sharply, being even higher than in the 1960s–1970s, supporting the hypothesis that there is a release of persistent organic chemicals from melting glaciers.

We know little about the ecological and physiological impacts that environmental POPs may be causing. Even though individual quantities of each compound may not appear dangerous, the toxicological potential of the resulting cocktail of pollutants progressively accumulating in remote sites is largely unknown. Organohalogen pollutants (PCBs, DDTs, PBDEs, and others) add to the above-mentioned metals and to polycyclic aromatic hydrocarbons (PAHs) resulting from natural and anthropogenic combustion (Fernandez et al. 2000). Sediments are useful for assessing the inventory of pollutants to which lake communities have been exposed, although it remains difficult to elucidate their impacts. However, it is possible to obtain direct evaluations of toxicological potential of sediments using recombinant yeast assays (Garcia-Reyero et al. 2001). Palaeolimnological attention to pollution by organic chemicals will probably grow in parallel with interest for global consequences of continued release of volatile synthetic substances, which up to now is an overlooked aspect of global change (Rockström et al. 2009).

Climate change impacts

Early warming, early warning and the case of *Cyclotella* increases

Although global change is multivariate in nature, climate change linked to the enhanced greenhouse effect of gas emissions is currently garnering the most attention of any environmental issue. However, evidence of climate change impacts on ecosystems is showing up at a slower pace than other human-induced disturbances, and with more uncertainty and controversy. This was not unexpected. Climate is a weather statistical construct over a certain time (usually 30 years). This period is usually longer than the time response of ecosystem processes that are conditioned, directly or indirectly, by weather. Therefore, one can resolve the link between climate and many ecological processes, but this needs a long time series of observations, which are not usually available. The palaeolimnological record at remote sites is extremely valuable in this context.

Despite difficulties, some astonishing regularities have been observed in a large number of lakes, first observed in Arctic and alpine regions, and later in less remote sites. One example is the increase in small planktonic diatoms with climate warming (e.g. *Cyclotella sensu lato*, including representatives of *Cyclotella*, *Discostella*, and *Puncticulata*) (Rühland et al. 2008). Many studies have reported their increase and, in some cases, a concomitant decline of large filamentous diatoms (e.g. *Aulacoseira* taxa). The exact mechanism suggested in the studies reporting these tendencies may differ but a common feature is an increase in the length of the growing season and periods of high stability of the water column (compared to those of intense mixing). For Arctic lakes, the changes are related to decreased ice cover duration (Prowse et al. 2011b; Smol and Douglas 2007) and hence a higher heat content in the water column during the summer that may also increase water column stability. In other cases, the warming tendency is restricted to the growing season of the small diatoms, and their population densities follow the interannual temperature oscillations of the growing periods (Catalan et al. 2002a). Several neo-limnological studies show that contemporary climate warming is exhibiting a selection pressure on diatom cell size in the same direction as observed in the palaeolimnological studies. Small-sized diatoms are able to outcompete large-sized cells and so expand under intensified stratification. An empirical model has shown that such shifts are consistent within different water column depth strata, and that altered nutrient concentrations were not responsible for the change (Winder et al. 2009).

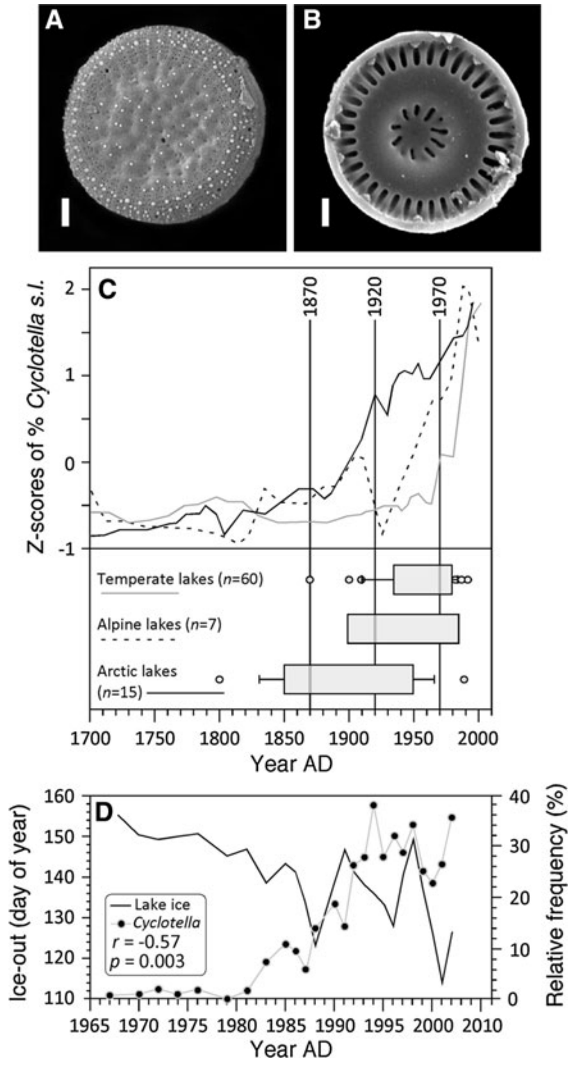

Fig. 4 The case of *Cyclotella sensu lato* diatoms. Scanning electron micrographs of *Cyclotella comensis* (**a**) and *Discostella stelligera* (**b**), (*scale bars* are 1 μm). **c** Timing of increased relative frequencies of summed (z-scores) small *Cyclotella s.l.* taxa from a selection of lakes in Arctic (*black line*), alpine (*dashed line*) and temperate (*grey line*) regions. Vertical lines indicate median age of change in each ecoregion (AD 1870 Arctic, AD 1920 alpine, and AD 1970 temperate), based on 82 diatom profiles included in a meta-analysis spanning the Northern Hemisphere (Rühland et al. 2008). *Boxplots* in the lower panel display range in timing of change within each ecoregion. (**d**) Relative abundances of *Cyclotella s.l.* taxa from dated sediments compared with historical ice-out dates (Whitefish Bay, Lake of the Woods, Ontario, Canada). For further details, refer to Electronic Supporting Information

It is also possible to find localities with declining abundances of *Cyclotella*. These species, as any other phytoplanktonic species, respond neither directly to weather nor climate, but to proximal growing conditions (nutrients, light, temperature, mixing regimes, grazing), which can appear or disappear under different combinations of factors forcing the lake system. Therefore, *Cyclotella* or any other diatom taxon cannot be used as a lake thermometer by itself. Not surprisingly, there are lakes dominated by *Cyclotella* throughout their history despite climate fluctuations (e.g., Gossenköllesee, Tyrolian Alps, Austria (Koinig et al. 2002); Lake Saanajärvi, Finnish Lapland (Korkonen pers. comm.)). Nonetheless, such a large number of similar cases around the Northern Hemisphere may be symptomatic of rather extended shifting conditions (Fig. 4).

The average timing of the *Cyclotella* rise differs statistically between high latitude, high altitude and temperate lakes (Rühland et al. 2008). The median increase at high latitudes occurred about 50 years earlier than at high altitudes and 100 years earlier than at temperate latitudes (Fig. 4). This supports the evidence that Arctic lakes register an early indication of current climate-related changes compared to other parts of the planet (Douglas et al. 1994; Smol and Douglas 2007) and that mountains may be regions of early response at lower latitudes (Battarbee et al. 2002b; Hobbs et al. 2010). In fact, temperature records of the Arctic meteorological stations show that the Arctic amplification (ratio of the Arctic to global temperature trends) is not a constant, but varies in time on a multi-decadal time scale (Chylek et al. 2009). The early Arctic warming from 1880–1940 proceeded at a significantly faster rate than the current 1970–2008 warming, with the ratios of the annual mean low Arctic to global temperature trends being 5.4 and 2.0 for the early and more recent warming periods, respectively. This rapid, early twentieth-century warming (ETCW) in the Arctic has been widely studied, yet its cause-effects still requires full explanation (Bengtsson et al. 2004).

Abrupt changes

Climate impacts currently occurring may suddenly accelerate because of the potential non-linearity of climate change *per se* and because of the interaction with additional variables and the ecosystem's own dynamics. If today's pronounced warming is triggering unprecedented ecological changes, would we not expect to find evidence for similar changes (e.g., algal shifts in lake systems) in the past? Climate forcing mechanisms (e.g., insolation, ice sheet distribution, sea level, aerosol and atmospheric greenhouse gas concentrations) in the past were different (Bigelow et al. 2003) and seasonality today is also different from the past (see below), thus true analogues do not exist. However, high magnitude fluctuations in past climate have induced pronounced shifts in diatom assemblages, similar in nature to recent *Cyclotella-Aulacoseira-Fragilaria* shifts (Ampel et al. 2010; Huber et al. 2010; Lami et al. 2010; Rudaya et al. 2009; Wang et al. 2008; Wilson et al. 2008). These palaeolimnological records, which span thousands of years, suggest that these current taxon-specific shifts are in response to an overriding effect of climate and, perhaps, they are an early indication of expected abrupt and general ecosystem shifts (Barnosky et al. 2012). In fact, Holocene and Late Glacial sediment records show that abrupt and large vegetation changes may occur in response to climate fluctuations within the range projected for the coming decades (Giesecke et al. 2011). Complete replacement of prominent landscape species, including forest trees, can occur within a few centuries, which implies that there are periods of extreme dynamism in the vegetation. A more ecologically oriented examination of the Holocene records may result in uncovering new clues for understanding on-going changes and improving projections for midterm future.

Seasonality

One of the features of current warming is its contrasting seasonal character at different sites (Battarbee et al. 2002b). Is seasonality actually changing? For example, it has been suggested that circulation modes in the Alps are unstable in time and space, causing decoupling of autumn and spring climates at the southern slopes of the Alps starting during Medieval times (Schmidt et al. 2008). On geological timescales, climatic changes are often conceptually simplified to cold/dry and warm/humid stereotypes, which can be useful for framing current changes (Wilson et al. 2012). However, these stereotypes lack the sophistication for understanding the full spectrum of climate variability. The analysis of the latter requires a decoupling of temperature and moisture and an independent consideration of cold and warm seasons. At high latitude and high altitude, seasonality is better understood when considering ice/snow (winter/spring) and ice/snow free (summer/autumn) periods, which represent the latent and growth periods for many organisms. Vegetation and most catchment processes mainly respond to weather during the growth period, and the proxies they leave in the sediment record (e.g., pollen) mostly indicate fluctuations during this period. However, high latitude and high altitude lakes are particularly sensitive to the duration of the ice cover (Catalan et al. 2002b; Prowse et al. 2011a; Smol and Douglas 2007) and this makes them valuable for reconstructing the cold/warm transient season. Lake ice phenology is closely tied to winter and spring air temperatures, and in many recent climate records, winter and spring months often experience the largest magnitude temperature increases (Thompson et al. 2009). Contrary to expectation, it is not what is occurring under the ice that is the most relevant for recording cold season effects in the sediments, but rather how lake ice phenology links to subsequent ecological seasonal succession. It is for this reason that chrysophytes, growing during the ice-free period, are extremely good recorders of the winter/spring climatic fluctuations (De Jong and Kamenik 2011; Pla-Rabes and Catalan 2011). Winter/spring climate during the Holocene (Kamenik and Schmidt 2005; Pla and Catalan 2005), reconstructed using chrysophyte cysts, contrasts with the commonly reconstructed summer/autumn conditions (Fig. 5). The ecological implications of different trends in the two seasons throughout the Holocene could provide a foreshadowing of upcoming changes.

Biogeochemical analogues

Although vegetation changes have attracted much interest, the Holocene can also serve as a reference for biogeochemical dynamics. We may ask whether biogeochemical analogues would be more likely than community analogues. Climate amelioration at the transition from Late Glacial to Holocene resulted in development of vegetation and soils and pronounced changes in terrestrial export of DOC, P, and organically bound metals to lakes, leading to their oligotrophication (Norton et al. 2011). Photochemical cleaving of Al-DOC complexes caused $Al(OH)_3$ precipitation in lakes and its increasing accumulation in sediments. Because phosphate adsorption to $Al(OH)_3$ sequesters P regardless of sediment redox

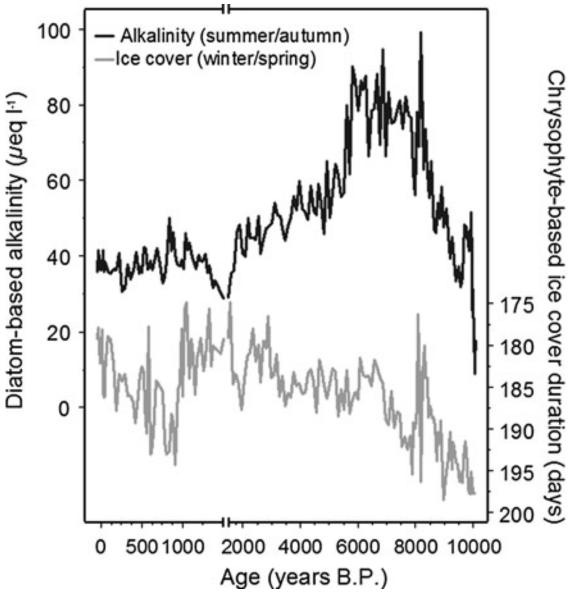

Fig. 5 Change of seasonal climate throughout the Holocene (Lake Redon, Pyrenees). Alkalinity changes reconstructed using diatoms (Catalan et al. 2009) follow the general temperature trends expected from pollen records in the Pyrenees, while ice-cover duration, reconstructed using chrysophyte cysts, shows an opposed tendency for this period, indicating that winter and spring temperatures increased from the onset of the Holocene to about 2,000 years BP (Pla and Catalan 2005). Note that the ice-cover duration scale in the plot has been inverted to indicate colder conditions downwards. For further details, refer to the Electronic Supporting Information

conditions, in-lake concentrations of bio-available P decline with Al supply (Kopáček et al. 2007). However, the future climate amelioration may have the opposite effect on P loading of lakes than in the early Holocene, due to the changed environmental conditions. Current catchments have largely depleted pools of easily weathered minerals such as (hydroxyl) apatite, compared to the early postglacial time. Terrestrial P-loading in high altitude lakes is generally low. Consequently, the elevated DOC exports from their catchments, resulting either from the current ecosystem recovery from acidification or from potential vegetation and soil development under a milder climate in the future, could have eutrophication effects for lakes. Elevated DOC leaching is accompanied by increased P export from soils, which may increase primary production. In addition, photochemical production of bioavailable DOC from allochthonous organic matter may promote bacterial biomass. These changes may affect C and P availability in lakes, the resulting seston stoichiometry, and food web structure. P will be more available in the water column and less in the surface sediment; more C will support bacterial production; both changes will decrease the C:P ratio of seston due to higher bacteria to algae biomass ratio in seston. We can observe similar gradients in C and P availability along an elevation gradient on mountain slopes (Kopáček et al. 2011). The question is how the forcing of these stoichiometric changes will interact with rising water temperatures, length of ice-off period, and whole-lake primary production.

Atmospheric fertilization

The nitrogen cascade

Industrial fixation of atmospheric nitrogen following the widespread introduction of the Haber-Bosch process has revolutionized modern agriculture. In concert with increased emissions from fossil-fuel combustion, the global nitrogen cycle has been fundamentally altered (Galloway et al. 1995). For example, the global pool of reactive nitrogen (Nr, which includes all fixed bio-available forms) has at least doubled since pre-industrial times. Nr is sequentially transferred through environmental systems and results in environmental changes as Nr moves through or is temporarily stored within each system; this phenomenon is referred to as the nitrogen cascade. This must be considered as a systemic change with many unknown consequences.

Remote lakes are not immune to the effects of enhanced Nr deposition (Fig. 6). N-limitation under natural conditions appears more prevalent than previously suspected (Elser et al. 2009). This means that even modest increases in Nr deposition have the potential to alleviate N-limitation and exacerbate P-limitation, with attendant shifts of primary producers towards taxa favoured by high N/P resource ratios. It appears that lakes may have considerably lower critical loads for responding with community changes to Nr deposition than terrestrial ecosystems (Saros et al. 2011). This implies that palaeolimnology can provide early warnings of chronic effects before they pervade the broader landscape.

Recent evidence from nitrogen stable isotope ($\delta^{15}N$) excursions suggests that anthropogenic Nr is

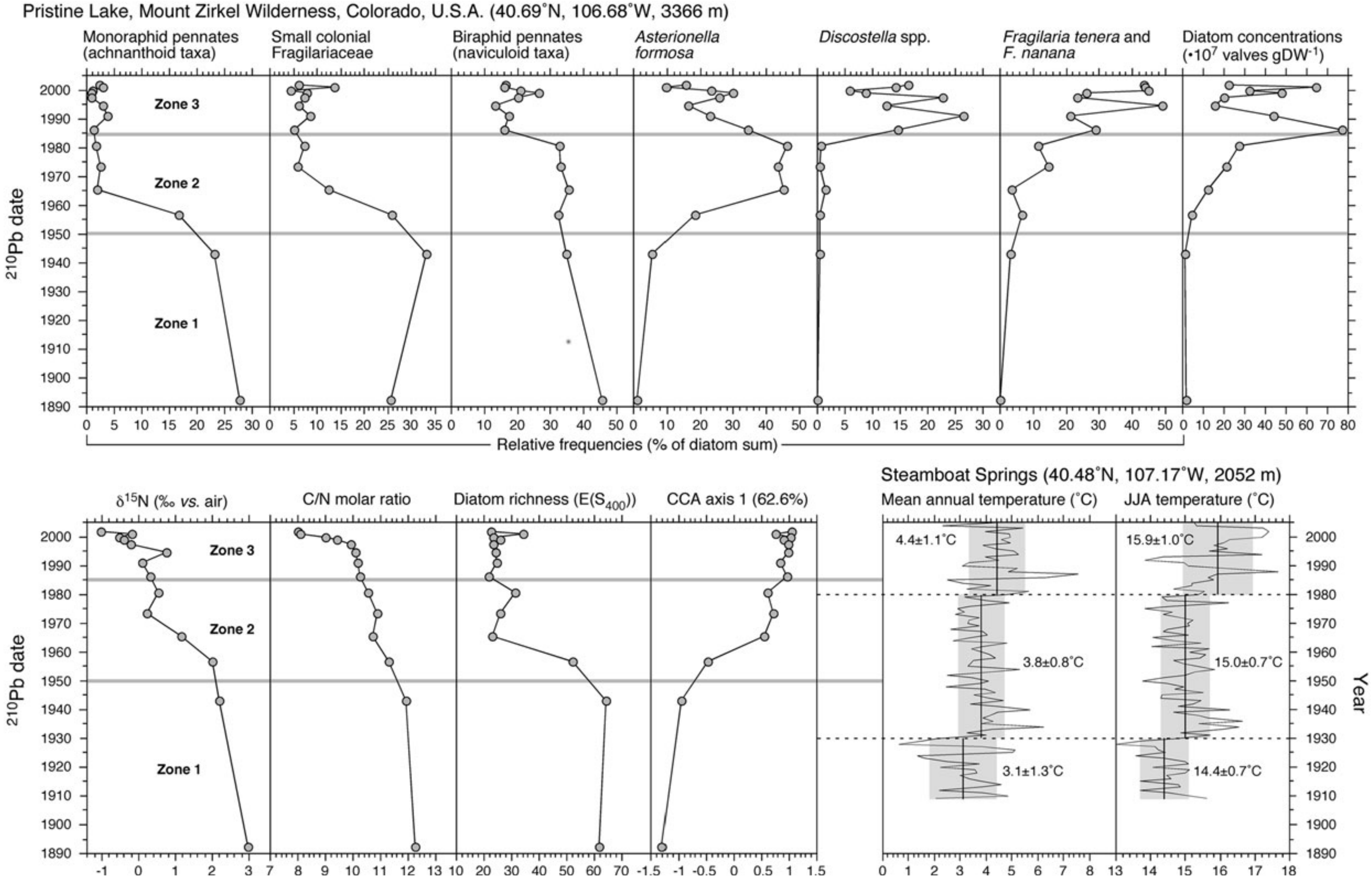

Fig. 6 The twentieth-century palaeolimnological record from Pristine Lake (Rocky Mountains of northern Colorado, USA) illustrates N deposition effects. In the upper row are summary relative frequencies of the dominant diatom taxa and total diatom concentrations. The lower row depicts sediment $\delta^{15}N$, bulk sediment C/N molar ratios, diatom taxonomic richness determined by rarefaction analysis normalized to a count size of 400 valves, and sample scores of the first axis of Canonical Correspondence Analysis (CCA) constraining diatom assemblages to sediment $\delta^{15}N$. To the right are mean annual and mean summer (June, July and August) temperatures from Steamboat Springs, the nearest long-term climate station. For further details and references, refer to the Electronic Supporting Information

disseminated to remote lakes of the Northern Hemisphere in a temporally coherent way (Holtgrieve et al. 2011). The isotopic signature in some lakes reveals an earliest inflection at 1895±10 AD, followed by a pronounced acceleration in the second half of the twentieth century, coincident with the "Great Acceleration" of global environmental change (Steffen et al. 2007). It is plausible that this isotopic change fingerprints an increase of atmospheric nitrogen loading or, as a minimum, the relative anthropogenic contribution to total Nr inputs.

For remote areas that have neither warmed nor acidified, there is no conclusive evidence that nitrogen deposition has affected the diatom assemblages (Smol and Douglas 2007; Smol et al. 2005). For example, in contrast to the rest of the circumpolar Arctic region, the western subpolar North Atlantic (e.g. around Hudson Bay, northern Quebec, Labrador, and southern Greenland) experienced little or no warming (even a slight cooling), up until ~mid-1990s (Chapman and Walsh 1993). Consistent with this lack of warming, palaeolimnological records throughout northern Québec and Labrador have consistently yielded diatom profiles with little assemblage change over at least the past few hundred years (Laing et al. 2002; Smol et al. 2005), although diatom communities across Baffin Bay in southwest Greenland witness trends that parallel nitrogen deposition in ice cores during the last two centuries (Fig. 3). Remarkably, within the last ~15–20 years, the Hudson Bay region has undergone unprecedented warming and significant thinning of Hudson Bay sea ice resulting in a shift to a new climate regime (Hochheim and Barber 2010). Lakes in this region are now recording increases in primary production and the first appearances of small, *Cyclotella s.l.* taxa as well as pennate planktonic diatoms in notable abundances in the topmost sedimentary intervals (~mid-1990s to present) (Rühland et al. pers. comm.).

In environments with low biological N fixation, even modest increases in N deposition may trigger ecosystem changes from the bottom-up. However, beyond fingerprinting the arrival of anthropogenic Nr at sites extremely distant from populated regions, more insight is required on evaluating how the nitrogen cycle has been modified and what are the consequences for the lake and catchment ecosystems. This is a challenging question for remote lake palaeolimnology.

Elusive nitrogen palaeolimnology

Reconstructing the onset and intensification of Nr deposition effects on lakes using the sediment record is complicated due to the nature of the nitrogen cycle and the lack of an easily interpretable response in the fossil record by organisms providing fossil remains. Nitrogenous compounds do not precipitate in sediments as inorganic forms in the way, for instance, that phosphorus does in association with either iron and aluminium hydroxides or calcium compounds. Nitrogen remains highly labile in lake sediments, where it is actively recycled between organic and inorganic forms by microbial processes, affecting both the total quantities archived as well as their stable isotopic composition. However, issues of nitrogen palaeolimnology can best be tackled in remote lake sites where the confounding effects of N catchment loading by human activities are lacking.

At first glance, the influence of N deposition on final bulk isotopic composition can be gauged by how different its isotopic composition is from catchment pools resulting from biological fixation. However, it has to be recognized that the final δ^{15}N of bulk sediment is the result of a complex suite of processes. On one hand, although naturally fixed N and N from industrial pollution show distinctive mean values, large seasonal and "event-by-event" variability exist in NH_4^+-δ^{15}N and NO_3^--δ^{15}N of deposition (Bartrons et al. 2010). On the other hand, the degree to which δ^{15}N changes during atmospheric transport, runoff, biological uptake, and sediment diagenetic processes is only beginning to be understood (Gälman et al. 2009). At high latitudes, mixing between stratospheric and tropospheric nitrogen oxides may influence the eventual δ^{15}N of nitrate in snow (Heaton et al. 2004). The pathways followed by runoff water may significantly change the original deposition δ^{15}N values of dissolved inorganic (Bartrons et al. 2010) and organic nitrogen forms (Bunting et al. 2010). Finally, steady-state δ^{15}N in soils and plants depends on precipitation and temperature (Amundson et al. 2003). However, little is known about how terrestrial and aquatic nitrogen-fixers respond to climate. Despite these realities, there are cases where anthropogenic Nr derived from far-field atmospheric emissions seems to retain a sufficiently distinct source isotopic composition as to remain discernible in remote lake sediments. Recent declines in sediment δ^{15}N are observed in many lakes (Holtgrieve et al. 2011). Nonetheless, there are populations of nearby lakes with similar limnological features showing alternately declining and rising twentieth-century trends in $\delta^{15}N$ (e.g. eastern Baffin Island, Canadian Arctic Archipelago, (Briner et al. 2006; Thomas et al. 2008; Wolfe et al. 2006)). Stable isotopes appear powerful, but must be complemented with other indicators of N-cycle dynamics.

There is a need to increase knowledge about the N influence upon aquatic organisms and communities. Biological remains, useful as proxies for investigating the nitrogen cycle, are scarce. A few diatom taxa have been considered nitrophilous. For instance, *Asterionella formosa* is likely to have been stimulated in alpine lakes by atmospheric N deposition (Wolfe et al. 2001) or from enhanced catchment N export during periods of climate change (Schmidt et al. 2002). However, diatom communities are influenced by other factors, particularly pH and P availability, and also by light and Si. Diatom transfer functions developed specifically for nitrate consequently suffer several handicaps, for instance, the high inverse correlation between dissolved organic carbon (DOC) and nitrate at both regional and local scales (Curtis et al. 2009), and the poor performance of inference models at relatively low nitrogen concentrations (Arnett et al. 2012). Revealing species sensitivities to C:N:P:Si ratios through experimental approaches seems to indicate one way forward (Saros et al. 2005), with the potential to assist in differentiating changes in response to increased Nr availability from those mediated by climate change.

Towards a stoichiometric palaeolimnology

Clearly, a relevant question is whether increased N deposition has a net fertilization effect in lakes. This is most likely to be the case in naturally P-rich, N-limited lakes; for example, those situated in meadows receiving high DOC and P loading (Kopáček et al. 2011). However, if P loading is low, higher N deposition may not have a direct influence in productivity, given that P limitation is more likely to remain the key factor. Most likely, the nitrogen cycle in both aquatic and terrestrial spheres is capable of reorganizing itself in ways that remain difficult to predict with current understanding. In addition, the response to atmospheric N loads may differ according to the overall chemical composition of atmospheric deposition, i.e., concentration ratios of other elements to Nr. If the deposition is not buffered, transient fertilization of aquatic ecosystems will be followed by base cation depletion, species changes, and loss of acid-neutralizing capacity (Baron et al. 2011). In contrast, if the deposition is enriched in Nr, but also contains abundant cations and phosphorus, as occurs when dust contributions are important (Camarero and Catalan 1996), then the fertilisation action may be enhanced and systems may revert to P-limitation (Camarero and Catalan 2012). The issue of Nr impacts thus requires full consideration of the coupling between C, N and P biogeochemical cycles under different circumstances, and their implications for aquatic organisms, including connections between aquatic and terrestrial ecosystems (Peñuelas et al. 2012).

Ecological stoichiometry links biogeochemical processes to community ecology (Sterner and Elser 2002). Alteration of C:N:P ratios may have multiple biological consequences. Different adaptive strategies may be selected for according to the prevalent situation. For example, plankton in Himalayan lakes do not produce microsporine-like amino acids (for UV protection) as occurs in the Alps, but rather produce melanin because of insufficient nitrogen compared to the excess Nr in the Alps (Sommaruga 2010). Elemental ratios may also modify food quality with community composition consequences. In the context of current global change, N deposition extends beyond fertilization and acidification effects to regulating the complex processes that modify terrestrial and aquatic ecosystem stoichiometry. Palaeolimnology at remote sites can provide a long-term perspective to this topic.

Atmospheric fertilization at the global scale is likely to remain an issue of continued research in coming years. It may well be that pre-industrial intervals do not constitute an adequate reference for the nitrogen cascade and stoichiometry ecology in remote ecosystems. Recent estimates indicate that the majority of the total cumulative Nr flux from anthropogenic sources over the last 10,000 years occurred in the preindustrial period and could have increased soil N pools of some remote ecosystems much earlier than is currently assumed (Kopáček and Posch 2011).

Double forcing: climate change and atmospheric fertilisation

Palaeolimnology of remote sites has much potential to increase knowledge on climate interactions with biogeochemical processes, because lake sediments record both lake, and terrestrial ecosystem trends. Nitrogen stable isotope excursions in remote lakes of the Northern Hemisphere (Holtgrieve et al. 2011) have stimulated controversy as to whether climate warming or nitrogen deposition may be the proximate cause of recent biological changes at certain sites. However, climate change and N atmospheric deposition are not mutually exclusive as causative drivers of recent limnological change. Across different lake regions, the relative influence of each factor may differ (Curtis et al. 2009; Hobbs et al. 2010), which is directly relevant for management and mitigation strategies. For instance, the nature and timing of algal community changes recorded in the Arctic (Smol and Douglas 2007), as well as increases in planktonic diatoms across the Northern Hemisphere (Rühland et al. 2008), differ from the algal changes observed in nitrogen deposition hot spots of the Rocky Mountains (Hobbs et al. 2010; Saros et al. 2011). The Arctic shows principally a warming effect (Perren et al. 2012; Smol and Douglas 2007).

Across Europe, a mosaic of situations has been suggested based on pre- and post-industrial diatom community comparisons (Curtis et al. 2009). There are areas with nitrogen deposition as the suggested main driver of diatom change; others in which both warming and nitrogen increase are responsible, but without acidification; others where acidification occurred (Pla et al. 2009) and others where climate warming seems to be the sole driver of diatom community change. This array of responses is modulated by the situation of the lake district relative to sources of atmospheric pollution, but also to the relative influence of other factors conditioning the chemistry of atmospheric deposition (i.e., ocean, and dust land influences). Areas with large influence of dust transport (e.g. the Pyrenees) do not show acidification trends despite nitrogen loads similar to other areas with clear symptoms of acidification (Camarero and Catalan 1996). However, it seems there is a fertilising effect, which can be due to the combined effect of N from pollution and P from dust (Camarero and Catalan 2012). On the other hand, air temperature increase has been suggested as a mechanism to counterbalance the acidifying effect of atmospheric nitrogen loading in some areas of the Alps with low buffering capacity. This is because warmer situations will enhance rock weathering and biological production (Sommaruga-Wögrath et al. 1997). In summary, many ways of interaction between climate change and atmospheric fertilisation potentially exist. The variety of double forcing combinations across the world that remote areas show is an excellent opportunity for understanding synergistic effects between climate and atmospheric fertilisation.

Under a true global change perspective, whether climate or atmospheric fertilisation dominates at specific sites becomes an irrelevant question. During the last century, average northern hemisphere temperature has changed highly correlated with many atmospheric gases and, eventually, many indicators of economic growth, resource use or land conversion. This is the most challenging aspect of global change; many things are simultaneously changing at an exceptional rate. In the long run, some of the details now under consideration may become irrelevant. The question is whether site idiosyncratic responses will persist or are we approaching a generalised planetary ecosystem shift forced by the fundamental atmospheric change (Barnosky et al. 2012). The palaeolimnology of remote sites has much to offer in terms of evaluating the spatial and temporal dimensions of the Earth system change (Table 1).

Perspectives: global change and remote lake research

Compared to environmental changes in the past, only recently have humans gained the power to exert environmental modifications at the planetary scale. Presumably, this implies that humans also possess the wherewithal to mitigate the pace of global change, notwithstanding geopolitical obstacles. The objective documentation of ongoing changes thus has the potential to serve as a powerful societal feedback.

As part of global change research, palaeolimnology at remote lakes should increase focus on catchment ecosystems. High latitude areas in which organic carbon has been accumulating in the catchments offer a significant opportunity to address questions on the global carbon cycle and greenhouse gas emissions (Karlsson et al. 2010; Kokfelt et al. 2009; Rouillard et al. 2011). There is evidence of shifts in Arctic plant community composition, particularly an increase in shrubs. On the other hand, in addition to increased shrub cover, there are changes in the balance of graminoids and forbs in mid-latitude mountain

Table 1 Some current challenges in remote lake palaeolimnology

Topic	Rationale/questions
The shifting boundaries of remoteness	Remoteness is a convenient operational definition, the boundary in landscape between local and non-local human influence. This boundary has been historically shifting and will do so under current changing conditions
Impacts of metals and organic pollutants in remote areas	Palaeolimnology has documented historical pollution at remote sites. However, contrasting with other environmental problems, it has scarcely contributed to show the ecosystem impacts of this pollution. Are there ways to show these impacts?
Climate interactions with long-range atmospheric pollution	Will climate warming accelerate biological sensitivity and responses to pollutants?
Delayed pollution from environmental deposits (soils, glaciers)	For decades, atmospherically transported pollutants have accumulated in natural deposits, with climate change, they are remobilized. What are the consequences?
Development of new lakes (glacier retreat)	Lake ontogeny—comparison with early Holocene, colonisation
Disentangling what is new in current global change compared to past climatic and environmental changes	Current climate changes include a set of conditions that are new compared to past climatic changes due to its unique origin. For millennia, biogeochemical processes have been co-varying in parallel with climate. The multicomponent nature of the current global change, directly disturbing some biogeochemical cycles, creates new combinations that may have no past analogues
Palaeolimnology of the disturbed nitrogen cycle	The nitrogen cycle is a methodological challenge for palaeolimnology due to its complexity and scarce direct recording in the sediments. Development of new techniques and approaches in the coming years is required
Downscaling from global to local	Understanding and mapping the regional impacts of atmospheric forcing deserve dedication and networking in international initiative
Upscaling from regional to global	The ultimate challenge of palaeolimnology at remote sites is to upscale regional information in a coherent way to evaluate globally the state of the biosphere

regions. Such vegetation changes may result in a complex series of biotic cascades, couplings and feedbacks which are superimposed on direct responses of ecosystem components to first-order drivers of global environmental change (Wookey et al. 2009). The carbon cycle at high latitudes is a key player in suspected nonlinearities of global change. Some of the soil considerations made during the acidification debate (Krug and Frink 1983) may find renewed relevance in global change research. Permafrost melting and deepening of the active soil layer is increasing microbial habitat activity, which affects soil nutrient stoichiometry, organic matter mineralization, the release of nutrients to ground- and surface waters, and the evasion of greenhouse gases (van Hardenbroek et al. 2012). In many Arctic lakes, this is likely an important mechanistic pathway for the impacts of warming. High altitude systems show environmental gradients in a much shorter absolute distance relative to high latitude counterparts. This may exacerbate the visibility of demographic early responses in the catchments because the absolute size of populations is smaller than at high latitudes. A formal analysis of this contrasting situation is also required.

Combinations of traditional and emerging analytical techniques in palaeolimnology will contribute meaningfully to future insights. However, the way in which such analytical methods are developed and applied mandates a consideration of a broad conceptual framework that embraces the multidisciplinarity of global change research. Accordingly, there is a need for further bridging of palaeolimnology with other environmental disciplines. Remote lakes are particularly suitable for this purpose as they are usually small and simple enough to facilitate quantitative and modelling efforts (Anderson et al. 2006). This view is already emerging in palaeolimnology (Leavitt et al. 2009) and is expected to expand as global change pushes the discipline beyond its traditional boundaries (Bogdal et al. 2010).

Under a mechanistic view, there is a need for understanding the processes leading to patterns case by case. Each lake and its catchment constitute an integral system that may or may not be representative of regional behaviour. Therefore, long-term limnological observations at key sites should incorporate benthic studies and water-column profiles to palaeolimnological investigations, ideally including cores from nearby lakes in order to establish regionally representative trends. We suspect that the more we progress in understanding first principles, the more we may understand higher-scale correlations. Even at an individual site, correlations may not be stable through time—an excellent example of this is the decoupling between diatom-based pH and air temperature at the onset of acidification in some parts of the Alps (Psenner and Schmidt 1992). Therefore, dissection of the causal pathways is always desirable (Shippley 2000). Methodological progress needs to move beyond purely statistical interpretations (Saros et al. 2012), towards improving the conceptual and processual tools for interpreting sediment archives as the end-member of energy and matter fluxes from the catchment to the lake (Leavitt et al. 2009).

On the other hand, holistic approaches should not be dismissed. Causality and correlation are two concepts that are not always distinguishable in highly stochastic dynamics, such as those taking place in climate and atmospherically-driven systems. Certainly, at the proximal level of species, at short temporal and spatial scales, the physical causal link matters most. However, the stochastic nature of dynamics increases when we start to consider ensembles (communities, complex biogeochemical processes, sets of atmospheric drivers). The resulting dynamics, and eventually the way they are recorded in the sediment archive, depends on the relative contribution of many causal, not necessarily inter-connected pathways. Atmospheric forcing upon any lake (and catchment) system has a statistical nature, which impinges in causal mechanisms that may differ between lakes and eventually provide different sediment records among sites. In such cases, one must keep in mind that lakes cannot constitute formal experimental replicates, with a caveat for direct statistical comparisons. Regional climate and environmental shifts may force converging tendencies among lake communities, although stochastic responses of species and lakes are likely to remain (Fig. 7).

Remote ecosystems are pervasively affected by global change components. Warming and fertilization accelerates dynamics, which increases local temporal variability, the frequency of statistically unusual events increases (Seekell et al. 2011) and eventually the likelihood for non-linear ecosystem behaviour (Carpenter and Brock 2011). Necessarily, climate projections indicate smooth trends towards certain new states. However, the inherent non-linearity of climate and ecosystems dynamics assures that there will be some abruptness in the way. The problem is to suggest when, where and how. Examples of the past can provide some light on this issue, and again remote lake palaeolimnology is in an optimal position to offer important contributions to these questions. For instance, the mid-Holocene illustrates how vegetation changes driven by sustained trends in general climate were punctuated by accelerations in the penetration of new species due to higher frequency climatic oscillations (Pelachs et al. 2011; Tinner and Lotter 2006). As climate change progresses, the likelihood for abrupt changes may increase; the ultimate goal for remote lake palaeolimnology should be to contribute in the detection of planetary-scale regime shifts.

Local impacts of global change need not necessarily correlate strongly with one or more specific components (e.g., warming in spring, nitrogen deposition, episodic strong winds, etc.). It may happen that we simply observe a progressive shift in the ecosystem state that ultimately correlates better with some large-scale Earth system indicator (e.g., CO_2 concentrations; mean hemispheric temperature) than with any local driver. It is not enough to monitor atmospheric drivers (e.g., local weather stations) for global change understanding; the observation of the ecosystem itself is ultimately more informative. Therefore, long-term ecological studies are essential for monitoring global change (Hobbie et al. 2003) and anticipating critical transitions (Scheffer et al. 2012). In this context, remote lake studies may have an influential role (Parr et al. 2003) and international initiatives are needed to link available data with other climate and atmospheric monitoring programs. Spatial and temporal replication at the landscape scale can be achieved with palaeolimnology (Smol 2008). Global change research is not a matter of scoring percentages of individual cases that

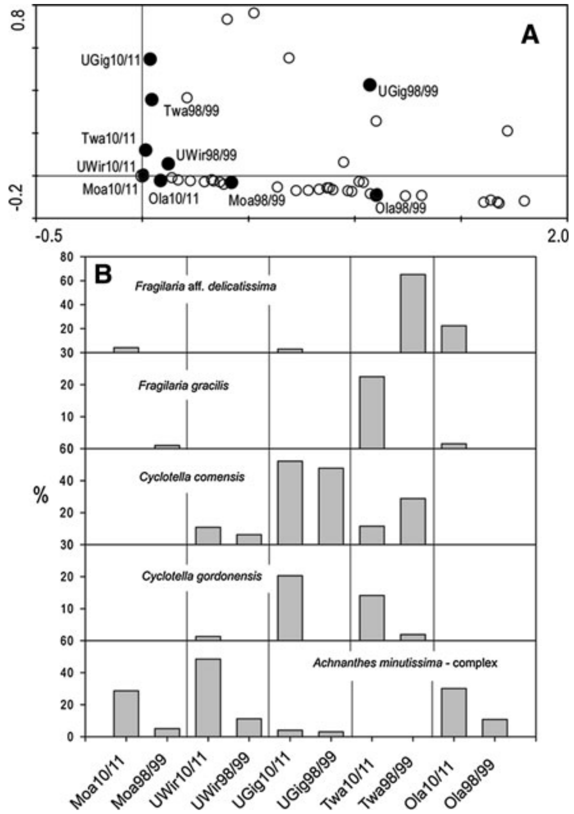

Fig. 7 Communality and idiosyncrasy in lake diatom assemblages. Five mountain lakes of a data set of 41 lakes from the Austrian Alps (Niedere Tauern) sampled in 1998/99 (Schmidt et al. 2004) were resampled in 2010/11 using sediment traps. **a** Ordination of the sample pairs (*solid black circles*) using Principal Components Analysis (PCA) and the most abundant diatom taxa (*open circles*) a convergence of the diatom assemblage composition in 10/11 compare to 98/99 probably due to climate influence. However, **b** the detailed comparison between the two sampling periods of some representative species indicates a highly idiosyncratic species response in each lake. This example illustrates the risk of mis-interpretation of single lake studies. Moaralmsee (Moa), Unterer Wirpitschsee (Uwir), Unterer Giglachsee (Ugig), Twengeralmsee (Twa) and Oberer Landschitzsee (Ola). For further details, refer to the Electronic Supporting Information

satisfy (or not) a set of predictions. Rather it represents an opportunity to nurture confidence in regional to global scale assessments about processes relevant to biodiversity preservation and for humankind to progress towards a sustainable world and planetary stewardship (Steffen et al. 2011b). One of the challenges of palaeolimnology at remote sites is how to upscale the individual lake responses to regions and, eventually, globally in order to portray a coherent understanding of large scale changes. We must seek to find ways of synthesizing palaeolimnological evidence over large regions, at the scales of continents and hemispheres, in order to best portray how aquatic ecosystems, and catchments related to them, are responding to these complex forcings.

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