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Palaeoenvironmental changes inferred from biological remains in short lake sediment cores from the Central Alps and Dolomites

P. Guilizzoni*, A. Lami, M. Manca, S. Musazzi & A. Marchetto
CNR Institute of Ecosystem Study, Largo Tonolli 50, 28922, Verbania Pallanza, Italy
*(*Author for correspondence: E-mail: p.guilizzoni@ise.cnr.it)*

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Abstract

In this paper we review research on eutrophication, acidification and climate change based on studies of lake sediments in the Alps. Studies on fossil diatoms, chrysophytes, plant pigments, Cladocera and carbonaceous particles in a number of high altitude lakes in Italy and Switzerland have been used to track environmental changes. We present an original study on fossil Cladocera in sediment cores from 29 lakes that have shown changes in biodiversity from the pre-industrial period (ca. pre AD 1850) to the present. These data show that altitude, ca. 60 years of acidification impacts and fish stocking are the most important factors that affect their distribution and abundance. We review further case studies from two morphometrically and chemically different lakes (Tovel and Paione Superiore). Their lake sediment records span 400 and 150 years, respectively; multi-core, multi-proxy analyses show their pH, trophic and climatic evolution over time.

Introduction

Palaeolimnological research has shown that many high mountain lakes have experienced considerable biotic and sedimentary changes in recent decades (Lami et al., 2000; Battarbee et al., 2002a, b; Lotter & Birks, 2003). Despite a simplified food web structure, these ecosystems are often highly dynamic and interpretation of such changes is often problematic, particularly when knowledge about their limnology, biology and catchment processes is limited (Fott, 1994; Guilizzoni et al., 1996). In general, European alpine lakes are relatively well studied, particularly from a hydrochemistry viewpoint (Giussani et al., 1986). Most of these lakes are located above the treeline (Lotter et al., 2000a). In the Alps, this vegetation boundary consists of coniferous trees (*Pinus*, *Picea*, *Larix*). The alpine environment is impacted by humans, grazing and climate that have lowered its natural altitudinal limit by several hundred metres in the last few millennia (Tinner et al., 1996).

With early baseline studies on catchment-based limnology (Baldi, 1939), present-day research has now become primarily focused on atmospheric pollution and climate change effects on lake biota. In some cases local pollution sources are superimposed on long-range contamination. Since the end of 1980s, biological fossils have been used to study the pollution of lakes in the Italian Alps (Lami et al., 1994; Marchetto et al., 1994). As in many parts of the world, almost all of these studies have concentrated on lake acidification (timing and rate, e.g., P.I.R.L.A. Project; Charles et al., 1990; Marchetto et al., 1994), whereas only quite recently have other pollutants been considered: for example, the distribution and effects trace metals and xenobiotic substances (e.g., PAH, PCBs compounds) on whole lake ecosystems (Grimalt et al., 2001).

In this context, four EU funded projects were carried out from 1988 to 2003. In these projects lakes of the central-western Alps were often selected as key sites to provide a broader, regional, approach to pollution studies (e.g. Lami et al., 2000). Most of these alpine lakes are particularly well-suited to palaeolimnological studies because they are numerous (ca 6500; Dainelli, 1954), diverse, and experience low anthropogenic impact. Limnological and atmospheric precipitation studies and sediment core analyses have been performed on many lakes in the central-south Alps of Italy, Austria and Switzerland. Analysis of algae, fossil pigments and invertebrate remains in their sediments have addressed important questions about anthropogenic disturbance (Lotter et al., 1999; Guilizzoni & Lami, 2002; Smol, 2002) and models for quantitative reconstructions have been established using a range of biological remains (Marchetto & Lami, 1994). The quality of these inference models largely depended on a good knowledge of the autoecology and ecological *optima* for the individual species on which they were based, and on precise measurements of the environmental parameters, for example, phosphorus, pH and lake-water temperature.

To test various hypothesis about atmospheric pollution, climate changes and in-lake processes, sediment core analyses have included: physical (lithology, magnetic susceptibility, dry density, carbonaceous particles), chemical (Loss On Ignition, nutrients and $CaCO_3$ content) and biological (including fossil pigments) remains.

Here we present and discuss some of the most important Alpine palaeolimnological studies based on diatoms, chrysophytes, chironomids, Cladocera and pigments. Particular emphasis is given to unpublished data on fossil Cladocera remains in 29 high altitude lakes in Italy and Switzerland (study by M. Manca). Finally, we report two case studies showing evidence of anthropogenic and natural impacts on two well-investigated alpine lakes.

Environmental changes: lake acidification, climate change, and eutrophication as inferred from biological remains

Diatoms

Historically, the diatoms have been the most studied fossil organisms in palaeolimnology. In alpine lakes diatoms are widely distributed, abundant, and commonly well-preserved. Diatoms are good indicators of present and past water chemistry, and changes in their assemblages over time have been used to reconstruct long-term trends in pH, nutrients (lake trophy), hydrology, water level changes and climate (summarized in Wunsam et al., 1995; Stoermer & Smol, 1999; Smol & Cumming, 2000).

The first quantitative pH reconstruction in alpine lakes was carried out by Arzet (1987) using a diatom index. He studied 35 lakes in Germany, Austria, France, Slovakia and the Czech Republic. Of these, 6 lakes were located above 2000 m a.s.l. Diatom stratigraphies from Schwarzsee ob Sölden (Tyrol, Austria) showed a marked decline in the abundance of circumneutral and alkaliphylous diatom species and the occurrence of acidobiontic diatoms in the topmost 2–6 cm. This resulted in a marked decrease of inferred pH (from around 5.7–4.8 pH units). Applying the same method of diatom indices to Swiss alpine lakes, Niederhauser (1993) inferred past pH in Lengsees bei Bellwald (Wallis) and in Lake Zota (Canton Ticino). In both lakes recent acidification was also evident, indicating a pH decrease of around 0.7 units during the last century.

Since the late 1980's considerable progress has been made in the quantitative inference of environmental variables using weighted averaging (WA) regression techniques (ter Braak & van Dam, 1989, summary in Birks, 1995). Transfer functions have been established using modern reference data of limnological measurements and surface-sediment diatom abundances (Lotter et al., 1997, 1998). The first diatom calibration data set for WA pH reconstruction in Alpine lakes was developed by Marchetto & Schmidt (1993). It was subsequently applied, by Schmidt & Psenner (1992) and Psenner & Schmidt (1992), to two high mountain lakes in the South Tyrol (Italy) and by Marchetto et al. (1993) to a core from a small lake (Cristallina) in Canton Ticino, Switzerland. Both studies indicated recent lake acidification and a relationship between pH and atmospheric temperature during pre-industrial times (Fig. 1). A clear decoupling between temperature and pH during industrial times was, however, not evident in all central Alpine lakes, indicating complex mechanisms of pH change (Koinig et al., 1998). A

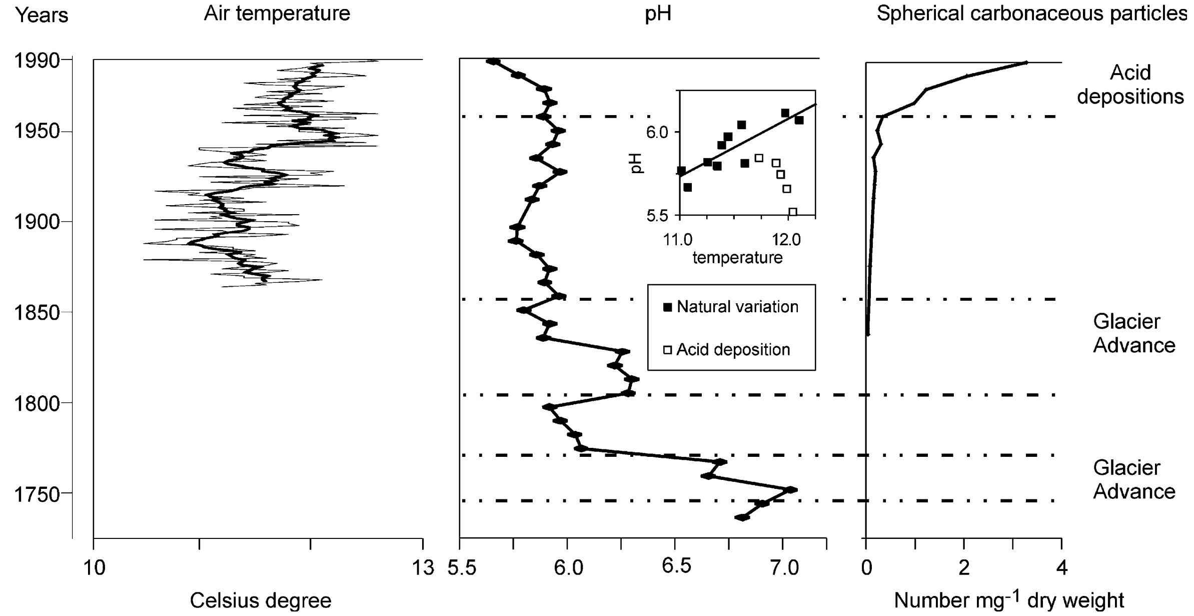

Figure 1. Diatom-inferred pH and carbonaceous particle distribution (number per mg dry wt.) in the sedimentary profile of Lake Cristallina (central Alps). Mean annual air temperature (7th order moving average) at the nearby meteorological station of Lugano and phases of glacier advance are also indicated. The scatter plot of inferred pH vs. mean temperature shows the recent decoupling between the two parameters that is a result of long-range industrial air pollution .

large European diatom surface sediment data set for weighting average pH reconstruction consisting of 118 lakes (41 in the Alps) was established during the AL:PE Acidification Program (Cameron et al., 1999) (see also the European Diatom Data Initiative, EDDI, web site http://www.craticula.ncl.ac.uk:8000/Eddi/jsp/index.jsp). The pH transfer function derived from this data set was applied to selected sites in the Alps. The results showed no significant correlation between atmospheric temperature records of the last 200 years and pH (Battarbee et al., 2002b). Another data set for pH reconstruction in central Alpine lakes was recently established by Schmidt et al. (2004a). Its application to a lake sediment core in the central Austrian Alps indicated an early Holocene long-term trend related to climate and the development of catchment vegetation. Calibration data from Swiss lakes (lake altitude range between 300 and 2400 m, summer temperature range from 7–20 °C) assembled by Lotter et al. (2000a) showed that diatom distribution were related to altitude. Since altitude is correlated with air temperature, diatom distribution might reflect temperature. The use of temperature to establish a transfer functions is, however, controversial. Weckström et al. (1997a) used water temperature to infer Holocene air temperature in Fennoscandian lakes (Korhola et al., 2000). Weckström (1997b) and Lotter et al. (1997) mentioned that statistically temperature was independent of other environmental variables. Anderson (2000), however, noted that temperature might be coupled with other important environmental variables effecting diatom distribution, such as pH (Psenner & Schmidt, 1992). Schmidt et al. (2004a) used thermistors for the first time in alpine lakes to study diatom/temperature relations. The results showed that summer water temperatures, although significant, had only a low ability to predict diatom distribution in the calibration lakes. Instead of summer water temperatures, Schmidt et al. (2004a) proposed that the date of autumn mixing is a more reliable climate indicator, since lake mixing is mainly affected by temperature. In contrast, the sensitivity of diatoms to temperature was found to be diverse (Schmidt et al., 2004b); for example, Fragilariaceae, which are frequent in alpine and arctic/subarctic environments, were more sensitive to ice-cover and summer water temperatures than other diatoms.

Phosphorus concentrations are commonly low in alpine lakes. Variations might be mainly due to human impact but also to climate. Two calibration data sets for total phosphorus (TP) have been established for the Alps; one of them mainly included lowland lakes (Wunsam & Schmidt, 1995); with only 2 lakes out of 86 located above treeline. This data set was applied to Längsee, Austria. The results showed (i) nutrient enrichment during occupation of the catchment during the Bronze Age, and (ii) catchment erosion during Late Glacial climate oscillations providing variations in in-washed nutrients (Schmidt et al., 2002). The second data set assembled by Lotter et al. (1998) included 68 small lakes located in calcareous catchments, mainly in Switzerland: 20 of the selected lakes were located above treeline. In comparisons of the predictive power of diatoms, chrysophyte resting stages, chironomids, and Cladocera for total phosphorus, diatoms were found to have the greatest predictive capability.

Chrysophytes

Chrysophyte scales and resting stages (cysts or stomatocysts) are often present in alpine lake sediments.

Siliceous scales were found in almost all the surface sediment samples of 27 lakes investigated in the Central Italian and Swiss Alps (Marchetto, 1991). However, there were large differences in scale concentrations (10^6–10^9 scales per gram dry weight). Analyses of five Italian lake sediment cores showed that pH could be inferred from the scales; two of them exhibiting a significant decrease of 0.5–0.7 pH units (Marchetto & Lami, 1994). In the near-neutral pH lakes the dominant species was *Mallomonas crassisquama* (Asmund) Fott, whereas in alkaline lakes (pH 7.9–8.0) the dominant species were *M. acaroids* var. *acaroids* Perty em. Ivanoff and *M. alpina* Pascher & Ruttner em. Asmund & Kristiansen. *M. alveolata* Dürrschmidt and *M. actinoloma* var. *maramuresensis* Péterfi & Momeu were the most common species in the acidic lakes (Fig. 2). A total of 18 taxa were identified (Marchetto & Lami, 1994), and, with the exception of one, the surface sediment assemblages were dominated by a single species ($>80\%$). Scales were, however, only preserved in the topmost sediment samples, dating back to around 70 years.

In contrast to the scales, chrysophyte cysts are commonly well preserved in alpine lake sediments and frequent enough for statistical analysis. Facher & Schmidt (1996) developed a chrysophte cyst-based calibration data set for pH from 50 lakes in central Europe, 29 of them were located above the timberline in the Alps (Italy, Switzerland and Austria). The prediction power of the pH model was similar to that known from diatoms.

A relation between stomatocyst assemblages and air temperatures spanning the last 200 years has also been found by Koinig et al., (2002) in a sediment core from Gossenköllesee (Austria). Kamenik et al. (2001) observed a strong seasonal distribution of chrysophyte stomatocysts in sediment traps suspended in Gossenköllesee. As with diatom-based studies the question is, whether (i) temperature is a predictor independent from other environmental variables, and (ii) how the stomatocysts can be used as climate indicators. Pla (1999, 2001) and Kamenik (2001) found that temperature had an independent influence explaining stomatocyst distribution in lakes of the Pyrenees and Alps. Kamenik & Schmidt (2005) have also shown that by combining thermistor measurements with stomatocyst sediment trap data, the prediction power of a temperature model (date of spring mixing) increased significantly.

Chironomids

During the last ca. 10 years models have also been developed for the quantitative reconstruction of climate-induced limnological changes using the head capsules of fossil chironomid larvae (Brooks & Birks, 2004). Some important studies have been carried out in Europe and North America to quantify climates during lateglacial times. In contrast, very few chironomid-based data exist from the Italian alpine region (Boggero et al., this volume), especially interpreting fossil remains in lake sediment cores.

Quantitative reconstructions of climate-induced limnological changes based on chironomid head capsules have recently been developed (Lotter et al., 1999). The quality of the quantitative inference models on which these are based depends on a good knowledge of the autoecology and ecological optima of the individual species. This knowledge is then used to constrain historical

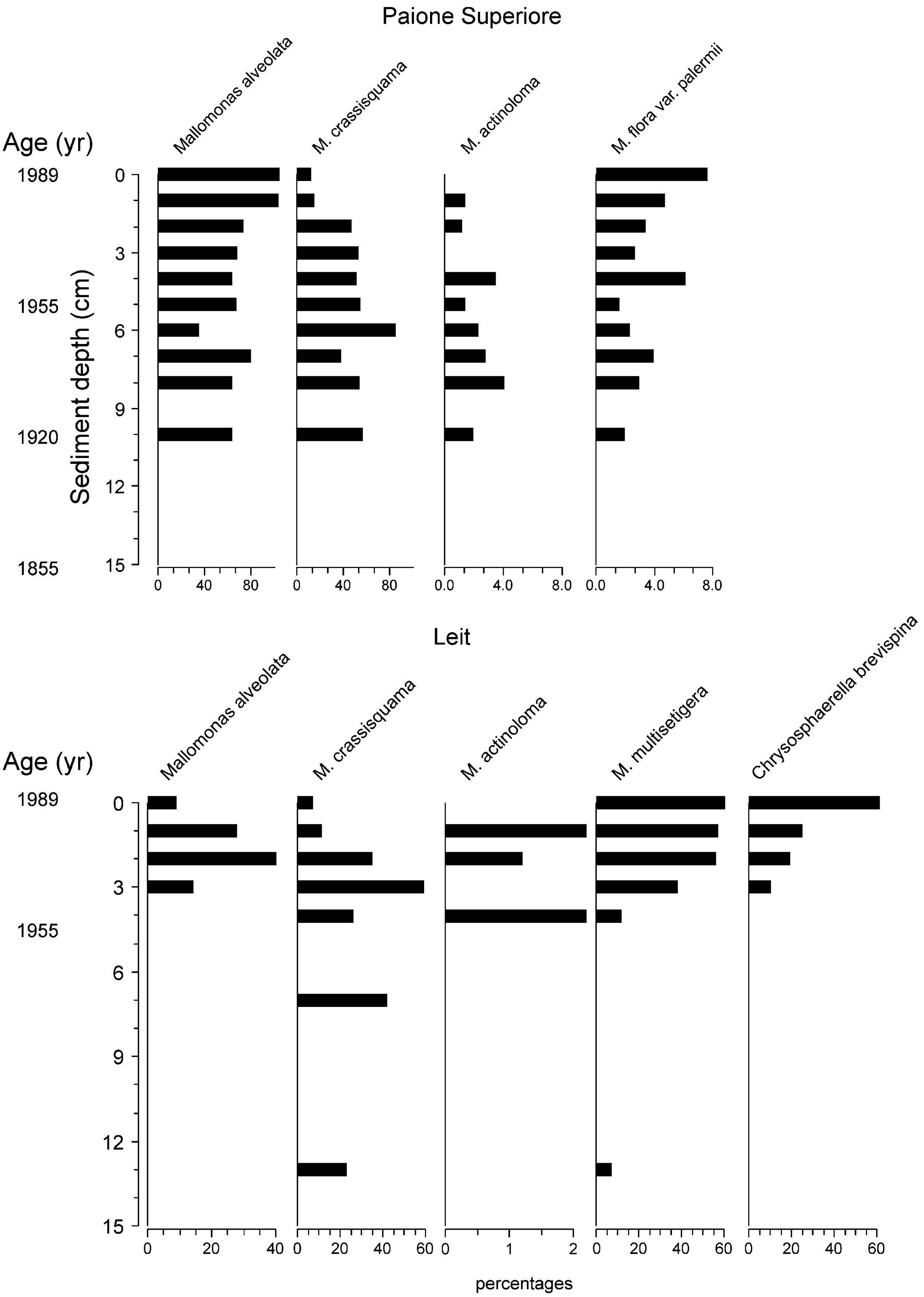

Figure 2. Fossil chrysophycean scale stratigraphies (relative frequency) in sediment cores from two Alpine lakes.

reconstructions of environmental variables (e.g. nutrients, temperature, pH).

Larvae of the aquatic non-biting midges (Diptera: Chironomidae) are abundant and sensitive indicators of lake-water temperature (Walker, 2001), and individual taxa are known to differ significantly in their temperature tolerances. Variations in water temperature have a direct effect on several biological activities such as pupation, emergence, growth, flight, feeding and hatching (Lindgaard, 1995).

The long resistance of larval heavily chitinized head capsules to degradation in lake sediments has led to their widespread use in palaeoecological studies. For example, in a core from Hagelseewli in the Swiss Alps the chironomid fauna is characterized (1) by low diversity, (2) by the total absence of taxa from the subfamily Tanypodinae and Diamesinae and Orthocladinae (Lotter et al., 2000b). This lake shows a low number of species and the dominance of *Micropsectra* and *Pseudodiamesa*. This low number of chironomids, in combination with the low number of Cladocera and studies of fossil pigments point to long periods of bottom-water anoxia resulting from long-lasting ice-cover that prevented mixing of the water column. The aquatic taxa in Hagelseewli are thus mainly indirectly influenced by climate change.

Chironomids are also sensitive to environmental changes caused by anthropogenic impacts such as eutrophication (Wiederholm, 1981) and acidification (Raddum & Fjellheim, 1984). Although several studies on Late Glacial-Holocene succession have allowed fine-scale reconstructions of fluctuations in temperature and precipitation regimes, detailed studies based on chironomid remains in the Alps are still lacking, and have not yet been used to address specific questions on the course, amplitude and origin of global changes (Massaferro & Brooks, 2002).

Cladocera

Cladocera assemblages in the lakes are especially sensitive to changes in primary productivity, pH and water transparency (Whiteside, 1969). In addition, the size structure and taxonomic composition of zooplanktonic Cladocera communities are particularly sensitive to changes in predation pressure (Kerfoot, 1974; Hobaek et al., 2002; Jeppesen et al., 2003a, 2003b) and alterations in the pelagic food web and can be induced by manipulation and whole lake experiments (Carpenter et al., 1986). Moreover, long-term changes in the biomass of crustacean zooplankton have been related to climate-driven factors (George & Harris, 1985). For example, many cladocerans appear to be related to a broad range of temperature changes and, in alpine and arctic lakes, to water depth (Lotter et al., 1997; Korhola, 1999). However, the response of cladocerans to mean seasonal and mean annual air temperature amongst the MOLAR lakes is quite weak or entirely lacking (Battarbee et al., 2002a; Manca & Armiraglio, 2002).

During a research project on 15 small alpine lakes in the Lake Maggiore catchment, the following crustacea were the most abundant in water samples (in decreasing order): *Cyclops abyssorum* (the ecomorph *C. tatricus* included), *Daphnia longispina*, and *Arctodiaptomus alpinus* (Manca & Armiraglio, 2002). In addition to these, 11 other species were found. The predator *Heterocope saliens* was found only in one lake (Muino Inferiore) (Manca & Armiraglio, 2002). All these species were also found in the surface sediments; the most abundant were, in order of abundance: *Alona affinis*, *Alona quadrangularis*, C*hydorus sphaericus* and *Acroperus harpae*. Whilst during the pre-1850 period, the two congeneric species *A. affinis* and *A. quadrangularis* had similar levels of abundance, in the present-day community the former dominates. In the recent period (top sediment), *Acroperus harpae* and *Chydorus sphaericus* are almost equally important, whereas in the 19th century, the latter was the third most abundant species. Numerical analysis of these abundance data suggests a relationship between environmental variables (pH, total phosphorus) and the cladoceran community structure. For example, in the more acidic lakes (pH of ca. 5.6–5.7) the community composition is represented by *Alona quadrangularis*, *A. rectangula* and *Chydorus sphaericus*. At a pH of <6.21 *Arctodiaptomus*, a taxa sensitive to acidification, was not found. In lakes with a pH of <6.3 diversity is lower than that of the pre-industrial period due to the disappearance of rare species. However, the presence or absence of a fish population seems to be the most important factor in structuring the zooplanktonic community in these small alpine lakes. In fact, *Daphnia* was lacking from sediments of the lakes where fish were regularly introduced. In general, only rotifers and *Cyclops* were found in lakes with fish.

This investigation has recently been supplemented by analyzing other 14 lakes in Ticino, Switzerland within the EU Project EMERGE (European Mountain lake Ecosystems: Regionalisation, diaGnostics & socio-economic Evaluation, EVK1-CT-1999-00032, http://www.mountain-lakes.org.). The results (never published before) for the pre- and after the industrialized period summarized for 29 lakes are shown in Figure 3.

The Project focused on understanding regional environmental (including human impacts) and biological features of a large number of lakes (ca. 300) distributed in 14 European lake districts in 15 European countries. It was based on an extensive approach, where the single sampling date at each lake is compensated by the large number of lakes sampled within each region and by the high number of samples collected from the water and sediment matrix.

Sampling was carried out between September and early October 2000, when the lakes are usually ice-free and Cladocera are well represented; despite this, in some cases, very low temperatures were measured and one lake (Lake Sfondato) was almost entirely ice-covered at the sampling date.

A short core was collected from each lake with a gravity corer; the recent Cladocera communities (ca. last 5 years) were reconstructed from an analysis of the top 0.5–1 cm sediment, while the

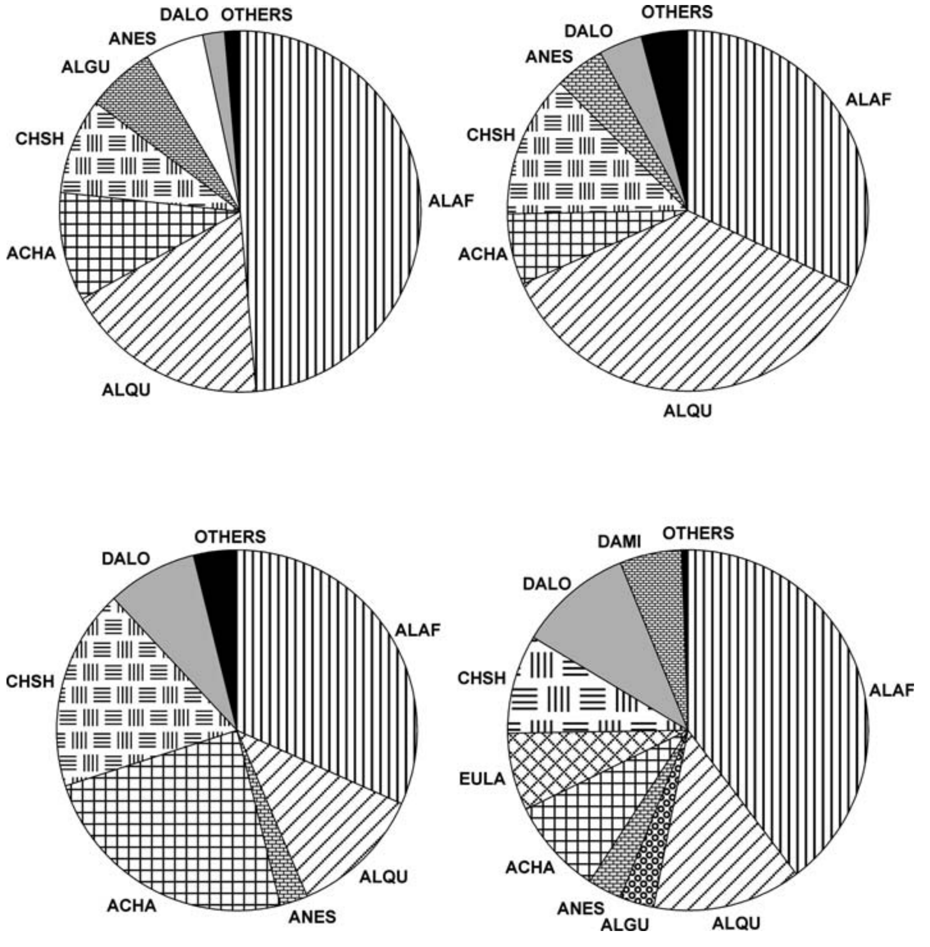

Figure 3. Cladocera communities reconstructed from sediments of the recent (left) and pre-industrial (right) periods in lakes in the Western Central Italian (upper panel) and Swiss (lower panel) Alps. For explanation of acronyms see Table 2. Species with abundance < 100 remains g d.w.$^{-1}$ are reported as "others".

15–17 cm levels referred to the pre-industrial period (EMERGE Protocol; EVK1-CT-1999-00032). Chronologies for some of the lakes were derived following protocols described in previous studies (e.g. Guilizzoni et al., 1992b). Cladocera sub-fossil remains were analyzed according to Frey (1958, 1986) and Manca & Comoli (2004). Species richness (taken as the number of taxa found) and the Shannon–Weaver diversity index were calculated for the past and present Cladocera assemblages.

In 25 (11 Swiss and 14 Italian) of the 29 lakes sampled the lowermost sediments were found to be representative of pre-industrial conditions (from carbonaceous particles analysis; Rose, 2001). The analysis was therefore restricted to those lakes (Table 1).

Lake altitudes range between 1855 (Alzasca) and 2580 m a.s.l. (Gardiscio); most lakes lie between 2000 and 2400 m a.s.l. Lake areas range between 0.10 (Muino) and 20.11 ha (Crosa) and catchment areas are between 9.14 (Muino) and 192.13 ha (Crosa). Most lakes have a surface area between 30 and 90 ha, with the exception of Lake Mognola, Switzerland, which is the largest one (>270 ha). Swiss lakes generally have a low lake-catchment ratio (<14), while the ratio of Italian ones is in most cases >40. Lake depths range between 6 and 68 m; the Swiss lakes are deeper than 16 m, the deepest being Lake Nero (68 m). pH ranges between 5.42 (Lake Gardiscio) and 8.03 (Lake Matogno); there is a slight dominance of acidic lakes (17/25), the Italian ones being in the lower (<6.20) and the higher >7.47 pH values.

Conductivity ranges between 7.37 and 80.4 μs cm^{-1}; six of the Italian lakes have a conductivity >20. Alkalinity ranges between 0 μeq l^{-1} (lakes Grande, Gardiscio and Sfondato) and 761 μeq l^{-1}. Six of the Swiss lakes are in the range 50–72 μeq l^{-1}, while half of the Italian ones are between 110 and 761 μeq l^{-1}, the others being <38 μeq l^{-1}. Most (48%) of the lakes have alkalinity <50 μeq l^{-1} and 72% <100 μeq l^{-1}. Other chemical data (e.g. Ca, Mg, SO_4) will be reported elsewhere.

Italian lakes have the lower and the higher N/NO_3 values (20 and 380 μg l^{-1}, in lakes Pojala and Paione Inferiore, respectively). Total phosphorus concentration, available only for the Italian lakes, is generally very low, between 1 μg l^{-1} (Lake Grande) and 7 μg l^{-1} (Lake Muino); however, Chl *a* concentration is between 0 (Lake Sfondato) and 6.83 μg l^{-1} (Lake Pojala). While present in all the Swiss lakes, with the exception of Gardiscio, fish appear to be regularly stocked only in 5 Italian lakes (Pojala, Boden Inferiore, Variola Superiore, Panelatte and Capezzone).

The species of Cladocera most represented in our cores are reported in Table 2. The most common species are *Alona affinis*, *A. quadrangularis*, *Chydorus sphaericus*, *Acroperus harpae* and *Alonella excisa*. *Daphnia*, mainly of the *longispina* type, was also widely distributed, while *D. middendorffiana* was only found in one Swiss lake. Rare species were mostly restricted to the bottom or top sediments of Swiss lakes.

Clear changes were observed in the recent communities of the lakes compared to those of the pre-industrial period, on both sides of Western-Central Alps (Fig. 3).

The present-day community of the Italian lakes is clearly dominated by *Alona affinis*, which was in the past equally represented with *A. quadrangularis*. In the pre-industrial period, species of the genus *Alonella* are less abundant, and there is a reduction in the presence of *Daphnia* and *Chydorus*, while *Acroperus harpae* almost doubles in relative abundance. The importance of rare species is also reduced.

The increase in *Acroperus* is more evident in the Swiss lakes, as in the recent period it becomes the second most important species after *Alona affinis*. The third most abundant species is *Chydorus sphaericus*, which doubles its relative abundance compared with the pre-industrial period.

In the Italian lakes, the presence of *Daphnia* is reduced after the onset of the industrial period: in addition to a decrease in the relative importance of *D. longispina*, there is a disappearance of *D. middendorffiana*. Similarly, *Eurycercus lamellatus*, which was an important species of the past communities, becomes rare.

Changes in species richness, diversity, and *eveness* in the different lakes of the Alps are reported in Figure 4. Lakes above the 1:1 line are those for which there was a decrease in species richness (Fig. 4-a), diversity (Fig. 4-b: Shannon–Weaver diversity index, H) or *eveness* (Fig. 4-c) from the pre-industrial to the most recent period.

Species richness clearly decreases in 12 of the 25 lakes taken into account, while it increases in 8 of

Table 1. Lakes in the Italian (lower case) and Swiss (upper case) Western Central Alps for which the recent and pre-industrial Cladocera communities were analyzed in the framework of the EMERGE Project. In addition to morphometrical, and selected hydrochemical data, a fish presence index (0–1) is reported

Lake	Alt (m a.s.l.)	Lake area (ha)	Catch area (ha)	Lake depth (m)	pH	Cond (μS cm^{-1})	Alk (μeq l^{-1})	N–NO$_3$ (μg l^{-1})	N–NH$_4$ (μg l^{-1})	TP (μg l^{-1})	DRSi (mg l^{-1})	DOC (μg l^{-1})	Chl *a* (μg l^{-1})	Fish
Grande	2269	0.75	89.27	6	5.76	7.37	0	215	0	1	0.58	0.40	0	0
Sfondato	2422	0.48	19.09	3	5.58	8.54	0	310	0	2	0.69	0.32	0	0
Campo	2293	0.75	69.36	7	7.47	49.3	375	228	0	2	1.38	0.23	0.06	0
Paione Inf	2002	0.87	121.26	14	6.64	13.2	38	380	8	2	0.8	0.27	0.27	0
Paione Sup	2269	0.65	50.94	12	6.06	9.21	3	353	25	6	0.43	0.67	0.26	0
Capezzone	2100	0.94	39.50	7	6.77	22.68	138	304	20	4	0.92	0.57	0.32	1
Variola Sup	2190	0.90	59.15	4	6.28	10.36	18	215	10	4	0.51	0.72	0.36	1
Variola Med	2123	0.69	88.30	4	6.19	9.87	17	169	3	2	0.57	0.68	0	0
Pojala	2305	5.70	107.65	16	7.17	33.34	250	20	2	6	0.5	0.70	6.83	1
Matogno	2087	3.03	136.92	15	8.03	80.4	761	147	28	4	0.85	0.64	0.43	0
Boden Inf	2334	5.88	81.17	7	7.9	56.9	519	81	5	2	0.73	0.36	0.38	1
Boden Sup	2343	2.83	26.65	6	7.8	48.4	412	189	3	2	0.8	0.47	0.99	0
Panelatte	2063	0.56	11.93	5	7.04	17.61	110	280	10	5	1.15	0.66	2.09	1
Muino Inf	1910	0.10	9.14	2	6.42	9.82	32	125	9	7	1.26	0.82	0.36	0
CROSA	2153	21.11	192.13	65	6.39	7.40	17	273	24		0.74			0.3
ANTABIA	2189	8.97	77.34	16	7.03	12.52	64	323	20		1.11			1
NERO	2387	8.31	74.02	68	7.21	14.30	60	159	2		0.59			1
FRODA	2363	2.32	58.28	17	6.83	12.46	50	215	0		0.65			1
SUPERIORE	2128	8.34	114.76	28.5	6.49	8.68	23	280	16		0.57			1
ALZASCA	1855	13.36	99.27	37	6.84	15.10	69	236	30		1.10			1
INFERIORE	2074	5.23	173.56	32	6.67	10.20	30	270	52		0.63			1
MOGNÒLA	2003	7.55	283.30	10.5	7.20	17.90	72	233	31		1.37			1
PORCHIERISC	2190	1.39	40.21	7	6.60	17.50	53	366	34		1.24			1
BARONE	2391	8.04	48.44	46	6.20	8.91	8	313	13		0.65			0.3
GARDISCIO	2580	1.28	11.06	10.4	5.42	7.74	0	204	25		0.38			0

Alt = Altitude; Catch = catchment; Cond = Conductivity at 20 °C; Alk = alkalinity; DRSi = dissolved reactive silica; DOC = dissolved organic carbon; Chl *a* = chlorophyll *a*.

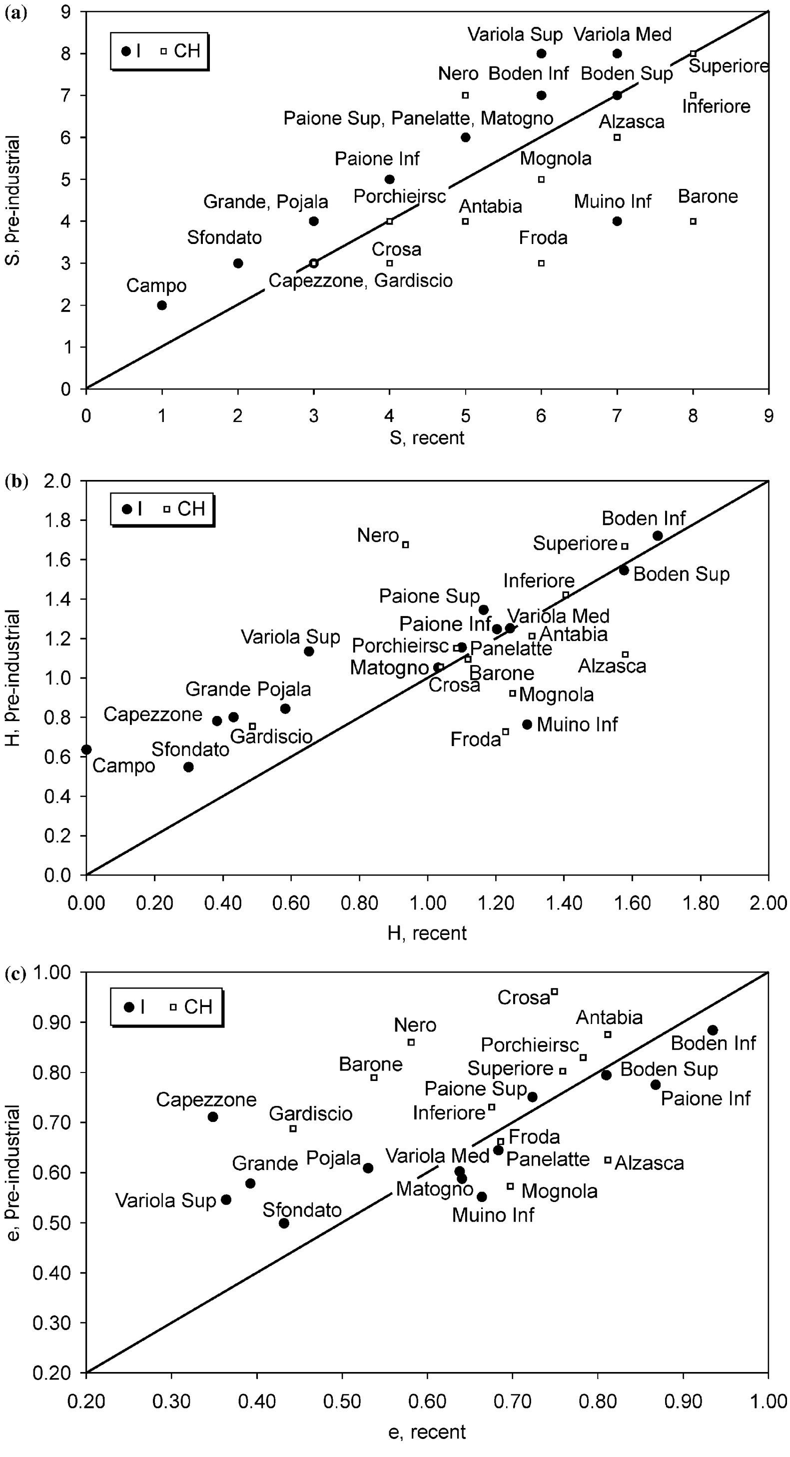

Figure 4. Comparison between past and present Cladocera communities in 25 Alpine lakes sampled within the EMERGE Project. From top to bottom, (a) species richness (S), (b) Shannon–Weaver diversity index (H); (c) *eveness*. The 1:1 line refers to no change between present and past (pre-industrial) communities.

Table 2. Acronyms, names and frequency of occurrence (F) in Italian and Swiss lakes (in parenthesis) of Cladocera taxa identified from subfossil remains in top and bottom samples of sediment cores from high mountain lakes. Common species (> 100 remains g d w^{-1} of the pooled data) (A) are distinguished from rare ones (B)

Acronym	Taxon	*TOP* *F*	*BOTTOM* *F*
A			
ALAF	*Alona affinis*	***11(11)***	***12 (8)***
ALQU	*Alona quadrangularis*	11 (5)	12 (7)
ALGU	*Alona guttata*	2 (1)	1 (1)
ANES	*Alonella excisa*	6 (4)	6 (4)
ACHA	*Acroperus harpae*	7 (9)	7 (6)
EULA	*Eurycercus lamellatus*	0 (0)	1 (3)
CHSH	*Chydorus sphaericus*	8 (10)	9 (8)
DALO	*Daphnia longispina*	7 (11)	10 (10)
DAMI	*Daphnia middendorffiana*	0 (0)	0 (1)
B			
SIVE	*Simocephalus vetulus*	1 (0)	1 (0)
LELE	*Leydigia leydigi*	0 (1)	0 (2)
ALTU	*Alona guttata tubercolata*	2 (0)	1 (0)
PLEDE	*Pleuroxus denticulatus*	0 (1)	0 (0)
ALEL	*Alonopsis elongata*	0 (1)	0 (0)
CARE	*Camptocercus rectirostris*	0 (2)	0 (0)
ALEX	*Alonella exigua*	0 (1)	0 (1)
ANSP	*Anchistropus* sp.	0 (0)	0 (1)
PLSP	*Pleuroxus* sp.	0 (1)	0 (1)
CHPI	*Chydorus piger*	0 (1)	0 (0)
CASP	*Camptocercus* sp.	0 (1)	0 (0)
KULA	*Kurzia latissima*	0 (0)	0 (1)

them, and remains almost unchanged in 5. Eleven of the 12 lakes in which the loss in species richness is observed are from the Italian side of the Alps, the only Swiss lake being Lake Nero, the deepest lake in which the difference ((N–NO_3 + N–NH_4)–TN) is highest. On the other hand, the three lakes in which the increase is most marked (lakes Froda, Muino and Barone), include the smallest Italian lake (Muino), and are all acidic and with alkalinity values < 60 μeq l^{-1}.

A loss in diversity (Shannon–Weaver diversity index, H, Fig 4-b) of the Cladocera community was observed in 10 lakes, 7 of which are lakes in the Italian Alps. Seven of them are acidic, and they include the most acidic ones (pH 5.42–6.06: Gardiscio, Sfondato and Grande; with zero alkalinity, Paione Superiore and Variola Medio) but also lakes with pH > 7 (Pojala, Nero and Campo) and a relatively high alkalinity lakes (between 60 μeq l^{-1} of Lake Nero and 375 μeq l^{-1} of Lake Campo). However, the highest change in diversity was observed in Lake Nero, the deepest lake in the Swiss Alps. All the lakes in which diversity decreased lie at altitudes ≥ 2100 m a.s.l., and were characterized by a relatively low level of diversity ($H < 1.00$); in contrast, increases in diversity were recorded in the Swiss lakes (3/4) located at relatively low altitudes (1855–2003, with the exception of Lake Froda, 2263 m a.s.l.) and the smallest Italian lake (Lake Muino Inf). In 11 cases diversity almost did not change during the past 150 years.

A detailed list of the changes in species in the eight lakes in which H mostly decreased is given in Table 3.

Changes in absolute abundance of taxa were expressed in 3 lakes as a dominance of *Alona quadrangularis* (lakes Grande, Sfondato and Variola Superiore), in 2 lakes (lakes Campo and

Table 3. Changes in absolute abundance of Cladocera taxa in lakes of the Western-Central Alps in which diversity (H) decreased or increased in the transition from the pre-industrial to the recent period. Acronyms as in Table 2

Lake	Increasing	Disappearing	Decreasing	New	Unchanged
H decreases					
Campo	ALAF	CHSH			
Sfondato		ALAF	CHSH, ALQU		
Capezzone	ALAF		DAND, ALQU		
Grande	ALRE, ALQU	DAND	CHSH		
Gardiscio		LELE	DALO	CHSH	ALAF
Pojala	ACHA,	EULA, ALGU		CHSH	ALQU
Variola sup	ALAF, CHSH, ACHA, ANES, SIVE	DAND, ALQU, ALRE	ALAF	ALTU	
Nero	ALAF, ACHA	DAMI, EULA, ANES	ALQU	DALO	CHSH
H increases					
Froda	ALAF,	CHSH	DALO	ALQU,ACHA,ALEL,ANES	
Muino Inf	ALAF,ALGU,CHSH			ALQU,ANES,CHPI	DALO
Mognola	ALAF, ACHA, ANES, ALO	ALQU		CHSH, CHPI	
Alzasca	DALO	ANES	ALAF,ALQU,CHSH,ALGU	LELE,ACHA	

Capezzone) as a dominance of *Alona affinis*, in one lake as a dominance of *Chydorus sphaericus* (Lake Gardiscio, in Switzerland), and in one lake as a dominance of *Acroperus harpae* (Lake Pojala). In Lake Nero, the lake with the richest and most diverse species assemblage, the community becomes dominated by *Alona affinis* and *Acroperus harpae*. *Daphnia* species (*D. middendorffiana*, *D. longispina* and a *Daphnia* undetermined) disappear from the community of 3 lakes, in one lake being replaced by another *Daphnia* species (*Daphnia longispina* in place of *Daphnia middendorffiana*, but with a remarkable decrease in abundance, in Lake Nero). All these lakes, with the exception of Variola Superiore and Nero, have relatively few species (2–5).

In contrast, the increases in diversity in lakes Froda, Muino Inf, Mognola and Alzasca are the result of a transition from a community dominated by *A. affinis* (Mognola, Froda, Alzasca) or *Chydorus sphaericus* (Muino Inf) to a community in which *Acroperus harpae* becomes important (Mognola and Froda), or *Chydorus* increases at the expense of *Alona quadrangularis* (Alzasca). Up to four "new" taxa appear in Lake Froda, and a general decrease in abundance characterizes the increase in diversity of Lake Alzasca, the lake with the highest diversity.

The equitability index (*eveness*, e, Fig. 4-c), which gives an idea of how far the diversity of the community is from the maximum attainable at a given number of species, also decreased in the recent period compared to the past (pre-industrial) community. The decrease was particularly evident for Variola Superiore, Grande, Capezzone (in Italy), Gardiscio, Barone, Nero and Crosa (in Switzerland); a less evident decrease was observed in lakes Sfondato, Pojala (on the Italian side), Inferiore, Superiore, Porchierisc and Antabia (on the Swiss side). An increase in *eveness* was found in lakes Muino and Paione Inferiore (Italy), as well as in Mognola and Alzasca (Switzerland) and, to a lower extent, in lakes Matogno, Variola Medio, Panelatte and the two Boden lakes in Italy, and Lake Froda in Switzerland.

Species richness and diversity is expected to vary as a function of environmental parameters, including lake area, and the abundance of neighboring-lakes (Dodson, 1992; Dodson et al., 2000; Shurin et al., 2000). For example, in a study of 128 lowland lakes sampled across five different regions in Europe, Cladocera species richness was related to water quality parameters, lake size, and the number of surrounding lakes, factors which were superimposed on a geographically structured background of variation in species richness (Hobaek et al., 2002). In another study, analyses of cladoceran remains in 293 surface sediment cores from 13 different remote mountain areas in

Europe (ranging from Greenland to Finland in the North and from Spain to Bulgaria in the South) showed that the number of taxa per lake decreased in a North–South direction, from 11–12 per lake in northern regions to approximately 4 in the southernmost regions (Brancelj et al., 2006). This decline was attributed to a concurrent increase in altitude from north to south, as species richness was more significantly related to altitude than latitude. A comparison of the top and bottom sections of the sediment cores revealed an identical number of taxa, whereas community assemblages varied significantly.

Compared with these extensive studies, the present one is more limited, in the sense that only a restricted range of environmental conditions is explored. The data used are representative of the Western Central Alps with the main characteristics of the lakes differing in terms of lake depth (Swiss lakes being in general deeper than the Italian ones) and altitude (Swiss lakes being lower than the Italian ones). A wider range of depths and altitudes was represented by the Italian lakes compared with the Swiss ones, which appeared to be mainly in the mid ranges of these parameters. This is probably the main reason that the results appear to be less clear than those obtained in a previous analysis in which only the Italian lakes were included (Manca & Armiraglio, 2002). However, some of the previously obtained results are still consistent with the results of this wider investigation: acidic lakes (<6.00 pH units) at higher altitudes (>2400 m a.s.l.) tend to be species poor and have a low species diversity; these low diversity lakes (diversity <1), are the lakes in which diversity further decreased after industrialization. Such a decrease is mostly expressed in the Italian lakes (only the extremely acidic Lake Gardiscio being affected in Switzerland): despite the data set being too restricted to allow a quantification of the effects of lake area or lake depth, Swiss lakes appeared to have a generally higher number of taxa than the Italian ones. Changes in diversity after industrialization resulted from a loss of rare species especially in Switzerland, whilst there was a tendency towards an increase in *Alona affinis* in the Italian lakes and of *Acroperus harpae* and *Chydorus sphaericus* in the Swiss lakes.

In the recent communities species richness, as well as diversity and *eveness*, tend to decrease with elevation, whilst in the communities of the pre-industrial period there seems to be no decreasing trend of species richness with increasing elevation; as diversity tends to decrease with elevation, while *eveness* tends to increase at increasing elevation (Fig. 4).

Alonella excisa is defined as a bottom-dweller, thriving on detritus and *Sphagnum* mosses (Nillsen & Sandoy, 1990). *Alona affinis* belongs to the "subarctic assemblage of cold-tolerant forms" (Korhola, 1999) and is reported as "a species typical of clear-waters", or "more abundant in relatively shallow sites with a high percentage of mires and TOC", or as a "phytophylous taxon" with a very wide ecological tolerance. *Acroperus harpae* and *Alona quadrangularis* are indicative of the littoral region, as they are mostly regarded as phytophylous, associated with macrophytes.

Chydorus sphaericus can be considered ecologically rather dualistic. On one hand, it is a common planktonic invertebrate of polluted sites, often becoming very abundant in situations of extreme eutrophication, whereas on the other hand, it can be very abundant in the littoral of small, vegetation-filled lakes and ponds (Korhola, 1996). Its increase with eutrophication in large, deep lakes, however, is at least partially due to the fact that it invades pelagic waters when filamentous algae become important in the open water, thus simulating a littoral habitat (Manca & Comoli, 1994).

The replacement of *D. middendorffiana* with *D. longispina* in Lake Nero is related to the introduction of fish. Despite having almost in all cases fish, the Swiss lakes still have *Daphnia*: probably because are generally deeper and thus offer more refuges for their populations.

On the other hand, the regular introduction of fish appeared to be responsible for the disappearance of *Daphnia* and the extreme impoverishment of zooplankton from many lakes of the Western Central Italian Alps (Cammarano & Manca, 1997), the disappearance dating back to the beginning of the 19th century, at the time of fish introduction. After a period of no fish introduction, mainly stopped because of its nonsense (given the absence of any food source the fish starved and died), lakes were re-colonized, probably through a passive transport of ephippia from lake to lake (Hairston, 1992; Manca & Armiraglio, 2002).

Fossil pigments

Pigments in lake sediments (Table 4) reflect environmental conditions in lakes and their catchments at the time of deposition. Their sedimentary composition and abundance can record historical changes in lake trophic status, anthropogenic and natural (climate) change, adding greatly to our understanding of the development of lakes. Such understanding is necessary for a number of purposes including the generation of palaeoenvironmental and palaeoclimate data which can be used for predictive models, and for enlightened lake management (Hodgson et al., 1998). Any interpretation of lake history based on pigment stratigraphy, is considerably facilitated by reference to contempory limnological and historical data. When such data are available it is possible to calibrate the pigment results, assess their performance as palaeolimnological indicators and thus to more accurately reconstruct ecosystem changes and food-web process (Leavitt & Findlay, 1994; Marchetto et al., 2004).

Since the early-1980s sedimentary plant pigments (algal and photosynthetic sulphur bacteria) have been widely used to reconstruct past algal community changes resulting from "cultural" eutrophication (Table 2; Züllig, 1981; Guilizzoni et al., 1983). Pigments have also been used in pH (Guilizzoni et al., 1992a) and climate reconstructions (Anderson, 2000). Changes in algal community composition may be caused either directly by natural (climate) and anthropogenic disturbances (e.g., nutrient enrichment and atmospherically delivered pollutants) or indirectly by in-lake responses. For example, the presence of high concentrations of carotenoids of purple-sulphur bacteria is used as proxy for intensity of lake stratification and anoxic conditions. Benthic UV radiation has also been inferred from fossil pigments (Leavitt et al., 1997).

The validity of using sedimentary pigments as an index of past events, or processes such as the trophic state and primary production rates, depends mainly on the preservation of these relatively labile organic compounds, the extent of differential degradation during and after sedimentation, and the extent of allochthonous sources of sedimentary pigment products. Physical, chemical and biological factors are responsible for the sedimentary pool of organic matter (see below), and these are well reviewed by Brown (1969) Swain (1985), Leavitt (1988, 1993) and Cuddington & Leavitt (1999).

Some years ago in a study on Alpine lakes Guilizzoni et al. (1992a) proposed a new proxy for lake pH reconstruction based on an easily measurable ratio of total plant pigments at two absorbance wavelengths (430 and 410 nm) in acetone extracts of lake sediments. A highly significant linear correlation ($p < 0.001$; $r = 0.71$) between 21 Alpine lake-water pH and the 430 nm:410 nm ratio indicated that acidity greatly influenced the pigment ratio. A stratigraphic analysis of a sediment core in an Alpine acid-sensitive lake in Italy showed a clear decreasing trend coincident with the increase in atmospheric pollution inferred by the carbonaceous particle profile. These data have been confirmed by comparing historical data on Italian thermal electricity production with other pH reconstructions based on diatoms and chrysophycean scale assemblages (Guilizzoni et al., 1996).

Factors affecting photosynthetic pigment distributions: a comparative study with other remote lakes in Europe

A recent study (Lami et al., 2005b) used a combination of lake survey and sedimentary data to evaluate the potential of various fossil indicators to reconstruct algal and bacterial responses to climatic changes and atmospheric pollution impacts. They explored the potential for using photosynthetic pigment remains in surface sediments (upper 0.5 cm) to describe the present-day community structure and population dynamics of primary producers. Their aim was to compare contemporary catchment and limnological data, sampled during simultaneous late-summer field work, with the surface sediment record from ca. 300 mountain lakes covering a latitude and longitudinal gradient across Europe. These data were collected in the frame work of the EU Project EMERGE that aimed to assess the status of remote mountain lake ecosystems throughout Europe following the requirements of the EU Water Framework Directive. To achieve this aim the authors focused on specific sedimentary carotenoids analyzed by HPLC rather than on chlorophylls since the former often have a higher biomarker value than chlorophyll derivatives (Leavitt & Hodgson,

Table 4. Pigments commonly found in lake sediments and the taxa from which they are derived (Guilizzoni & Lami, 2002)

Pigment	Taxa
Chlorophylls	
Chlorophyll *a*	Common to all plants
Chlorophyll *b*	Chlorophytes, Euglenophytes, Trachaeophytes
Chlorophyll *c*	Chrysophytes, Pyrrophytes
Chlorophyll derivatives	
Phaeophorbide *a*	Chlorophyll *a* derivative (grazing)
Phaeophytin *a*	Chlorophyll *a* derivative common to all plants
Phaeophytin *b*	Chlorophyll *b* derivative common to all plants
Phaeophytin *c*	Chlorophyll *c* derivative (Chrysophytes, Pyrrophytes)
Carotenes	
α-carotene	Cryptophytes, Chlorophytes, Trachaeophytes
β-carotene	Common to all plants, some bacteria
Xanthophylls	
Alloxanthin	Cryptophytes
Astaxanthin	Invertebrate herbivores, some chlorophytes
Canthaxanthin	Invertebrate herbivores, some filamentous cyanobacteria
Echinenone	Total cyanobacteria (formerly named blue-green algae)
Fucoxanthin	Siliceous algae
Lutein	Chlorophytes, Euglenophytes, Trachaeophytes
Myxoxanthophyll	Colonial and filamentous cyanobacteria
Oscillaxanthin	Oscillatoriaceae
Peridinin	Dinophyceae
Zeaxanthin	Cyanobacteria
Diadinoxanthin	Euglenophytes, Dinoflagellates
Diatoxanthin	Bacillariophyceae
Dinoxanthin	Pyrrophytes, Chrysophyceae
Myxol-2′-o-methyl-methylpentoside	*Oscillatoria limosa*
4-keto-myxol-2′-methylpentoside	*Anabaena flos-aquae*
Scytonemin	Lipid soluble carotenoid present in certain benthic cyanobacteria
Carotenoids of sulphur photosynthetic bacteria	
Isorenieratene	Green sulphur bacteria (*Chlorobium* sp.)
Okenone	Red sulphur bacteria (*Chromatium* sp.)
Licopene	*Rhodospirillum* sp.
Spheroidene, spheroidenone	*Rhodopseudomonas sphaeroides*
Rhodopinal	*Lamprocystis*, *Rhodospirillum tenuee*

2001). Among the ordination techniques available Redundancy Analysis (RDA) proved to be the most appropriate for this dataset. The environmental database contained variables with different ecological impact and therefore it was decided to split them into three main groups:

1. Proximal factors such as the main ions in water that have a direct impact on the algae. Within the proximal variables a first distinction was done and the following three sub-classes were established: chemical, trophic and physical. Then the variables which were significantly related with the pigments were subsequently merged to produce a single proximal data set.
2. Catchment, having more indirect effects on algal composition.
3. Location, as representative of the biogeographical component of the variability.

Numerical analysis compressed the data to a reduced number of components describing a substantial part of the variance in the original data matrix, while still being ecologically interpretable. RDA ordination suggests that the relative composition of carotenoids in surface sediments was indeed sensitive to change in lake or catchment processes as ca. 30% of the variance can be explained by these variables.

The main results suggest that among the proximal variables set three components can be ranked in the following order of importance: chemical (e.g. Ca, Mg), physical (altitude) and trophic variables (nitrogen, total organic carbon). The reduced role of trophic variables might be due to their rather shorter environmental gradient. Most of these remote, high altitude, high mountain lakes are typically oligotrophic. On the other hand, the final minimum adequate model and variance partitioning show that the main gradient is related to catchment geology and pollution (acidification). The gradient of basic ion concentrations, reflecting the geological composition of the catchment and nitrogen, explain most of the carotenoid variance. On this gradient carotenoids respond with a shift from phytoplankton dominated by cyanobacteria (echinenone, cantaxanthin and scytonemin, normally associated with benthic cyanobacteria) and photosynthetic sulphur bacteria (okenone) to a population dominated by cryptophytes (alloxanthin), dinoflagellates (diadinoxanthin) and diatoms (diatoxanthin). Based on the differences between fucoxanthin and diatoxanthin, a further distinction was evident between siliceous algae (fucoxanthin) that are more important in Norwegian and Scottish sites, and diatoms (diatoxanthin) that are more abundant in Pyrenees and Finnish lakes. A special case is represented by those lakes on calcareous rocks and experiencing prolonged profundal anoxia that were characterized by the presence of okenone form photosynthetic anaerobic bacteria.

In summary, the sedimentary pigment data in surface sediments proved to be a useful tool for lake classification, and relatively easy to measure. The differences among sites in the Lake District considered make it possible to partition them into two different eco-regions: Nordic lakes and mountain lakes in Continental Europe (Alps, Pyrenees, Tatras, Balkans). In contrast, Greenland was quite different from all the other lake districts, due to the peculiarity of these lakes (SO_4-rich and deep anoxic; Lami et al., 2005b).

Two case studies for the application of a multi-proxy approach

Lake Tovel

Lake Tovel is located in the Adamello-Brenta Natural Park (Italian Alps; 1178 m a.s.l) on carbonate bedrock (Dolomite). It probably originated from the melting of dead ice after the end of the last glaciation and reached its present dimensions and depth in AD 1597–98 when landslide material occluded the paleo-outlet (Kulbe et al., 2005). The resulting large slump was dated exactly by dendrochronology by Oetheimer (1992). Lake Tovel is an oligotrophic lake (surface area = 0.39 km^2, max. depth = 39 m) with a dimictic mixolimnion, which is characterized by marked water-level fluctuations. This lake was limnologically well-studied during the early 1930s (Merciai, 1930) because of its tourist attraction. Summer blooms of the dinoflagellate *Glenodinium sanguineum* March., which accumulated the carotenoid astaxanthin, caused the red colour of the lake. Since this phenomenon was not observed from 1964 onwards a multidisciplinary limnological project started in 2001 (BEST - Blooms & Environment: Science for Tovel/SALTO: Reddening tide lacking), including a palaeolimnological survey, was carried out. In particular the study included geochemistry and seismic (Kulbe et al., 2005; Cantonati et al., 2003), plant pigments, diatoms, chrysophyte cysts, Cladocera and chironomids (Lami et al., 2005a).

Based on the information stored in the fossil pigments and chironomids (Lami et al., 1991; Guilizzoni et al., 1992c) it was hypothesized that nutrients might principally have controlled changes in algal composition and carotenogenesis during the reddening period (Lami & Guilizzoni, 1991); Nutrient-deficiency generally results in the synthesis of carotenoids, and in particular astaxanthin is formed in response to P limitation (Manny, 1969; Watson & Osborne, 1979).

A following study on sedimentology and geochemistry hypothesized that the disappearance of the lake‘s reddening might be due to increased local rainfall (Fuganti & Morteani, 1999). Analyses of major and trace elements in the lake sediments which were compared with the water indicated a natural source.

A recent detailed palaeolimnological study of the sediments accumulated during the last 400 years did not resolve the problem of the disappearance of reddening (Rolih, 2004; Kulbe et al., 2005; Lami et al., 2005a). Two piston cores and 27 gravity cores were used to reconstruct the sedimentation history of Lake Tovel (Kulbe et al., 2005). A seismic survey and the sediment cores showed 2.50 m thick landslide sediments in the north of the lake and less than 50 cm in the southern part. From the 27 gravity cores two were sampled in more detail. The minerogenic components of the sediment are dominated by dolomite with low amounts of calcite, quartz and (biogenic) silica. Thin sections indicated that laminae do not represent varves. Due to the landslide the annual sediment accumulation varied distinctly across the lake.

The mean total organic matter content is ca., 7% d.w. with peaks (ca. 15%) at the surface and at the beginning of the 18th century (Fig. 5). In general, TOC:TN ratios indicate only a limited input of allochthonous organic carbon. Total nitrogen has increased during the last 40 years. There could be several reasons for this increase: (i) atmospheric pollution (Guilizzoni et al., 1996; EMEP, 1997; (ii) catchment sources. Is it known that an excess of nitrogen affected the production of the red carotenoids astaxanthin in the dinoflagellate blooms (e.g.; but no evidence was found in this respect for the algal species living in Lake Tovel (M. Cantonati, pers. com.)

A slight increase in lake trophy as inferred from total phosphorus reconstructed by diatom remains was also evident from 1965 onwards (Angeli, personal communication).

Concentration of Cladocera remains and the number of taxa were generally low; this result was largely expected, being Lake Tovel a typical rotifer and copepod lake in spring-summer and in winter respectively. Zooplanktonic taxa were no more found from ca. 39 cm to the upper section of the core, only reappearing in the top 2.5 cm sections. Here the assemblages were similar to the first decades of 1600s when the lake was slightly eutrophic.

β-carotene is an indicator of algal abundance whereas many single carotenoids can be used as a signature for specific algal taxa (Fig. 5). Fucoxanthin (a very labile carotenoid of diatoms) is present in almost all sections indicating good pigment preservation. Specific pigments in the core show large fluctuations with low concentration values alternating with pronounced peaks. Other pigments in the core indicate marked algal community switches throughout the past centuries. For example those carotenoids more resistant to decomposition such as echinenone, produced by cyanobacteria (cyanophytes), lutein/zeaxanthin, characteristic pigments of green plants, scytonemin (a UV protective pigment of cyanobacteria) are usually well represented throughout the core. Astaxanthin, the carotenoid belonging to the dynoflagellates is also abundant during the past 4 centuries and not specifically related to any environmental variables. By the comparison of our results with the long-term meteorological data we can exclude a climatic affect on the disappearance of the reddening phenomenon.

Photosynthetic purple anaerobic bacteria, as inferred by their specific carotenoid okenone are a major component of the microflora of this meromictic lake. This pigment indicates anoxic conditions and four periods of high content are shown (Fig. 5). Okenone is much more abundant during cold periods of the Little Ice Age. In contrast, in the 20th century, temperature and climate reconstructions show a clear warming (Lami et al., 2005a) and the anaerobic bacteria are reduced. Thus, tracking their abundance through out the lake history provides information about the intensity of lake stratification, which is itself related to climate.

Lake Paione Superiore

Lake Paione Superiore is a small lake (max depth 11.7 m) located above the timberline (2269 m a.s.l) in the central-western Alps; carbonate buffering is poor as the watershed bedrock consists of clear-banded orthogneisses and grey gneisses with potassium feldspar and epidote. The first limnological study of Lago Paione Superiore was published in 1947 (Tonolli, 1947). Since this time further limnological studies have been carried out by Mosello et al. (1993), Callieri et al. (1999),

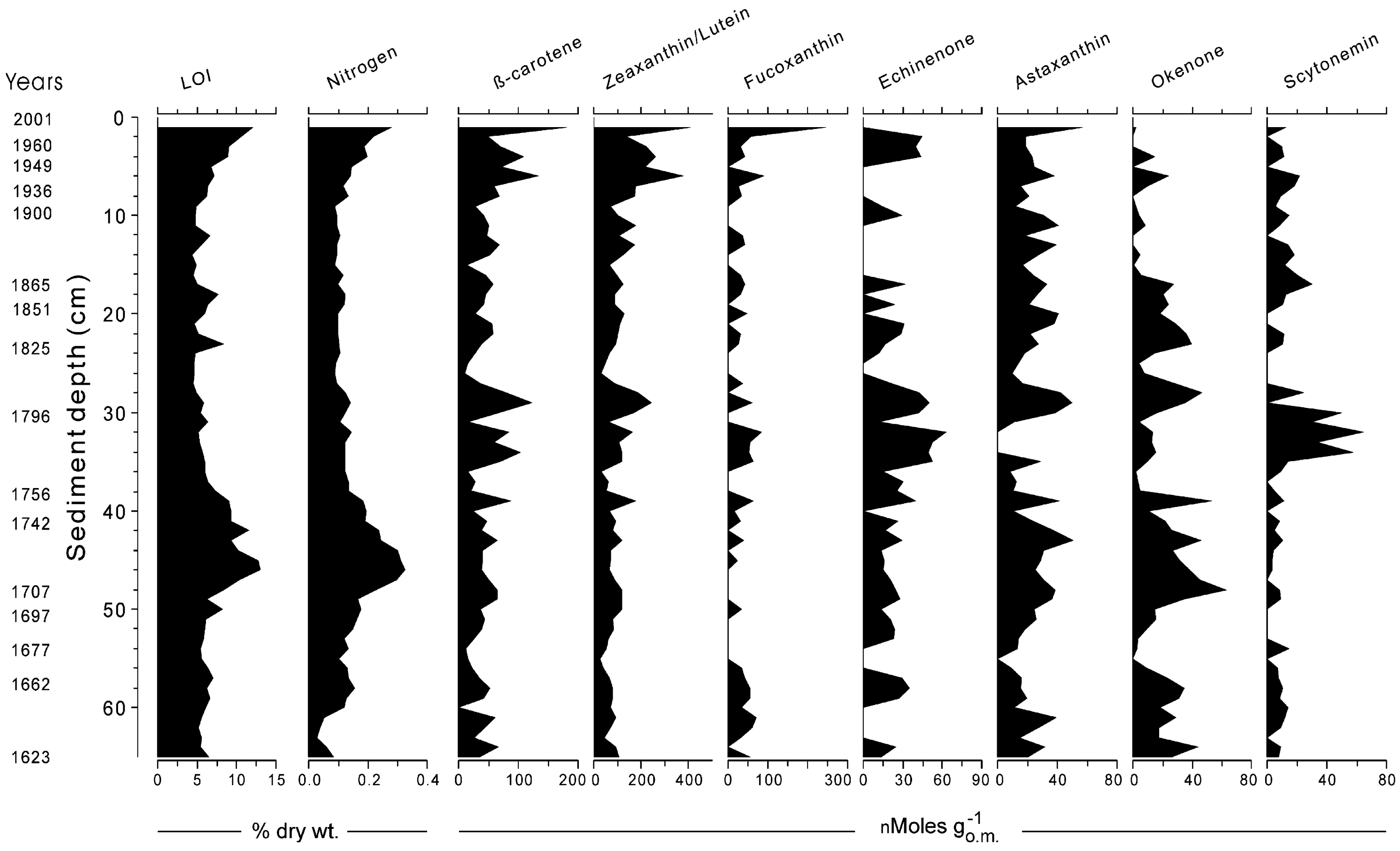

Figure 5. Lake Tovel, core TOV 01/5. Selected geochemical (Loss on ignition, LOI; nitrogen) and specific carotenoids of algal and photosynthetic sulphur bacteria populations (okenone).

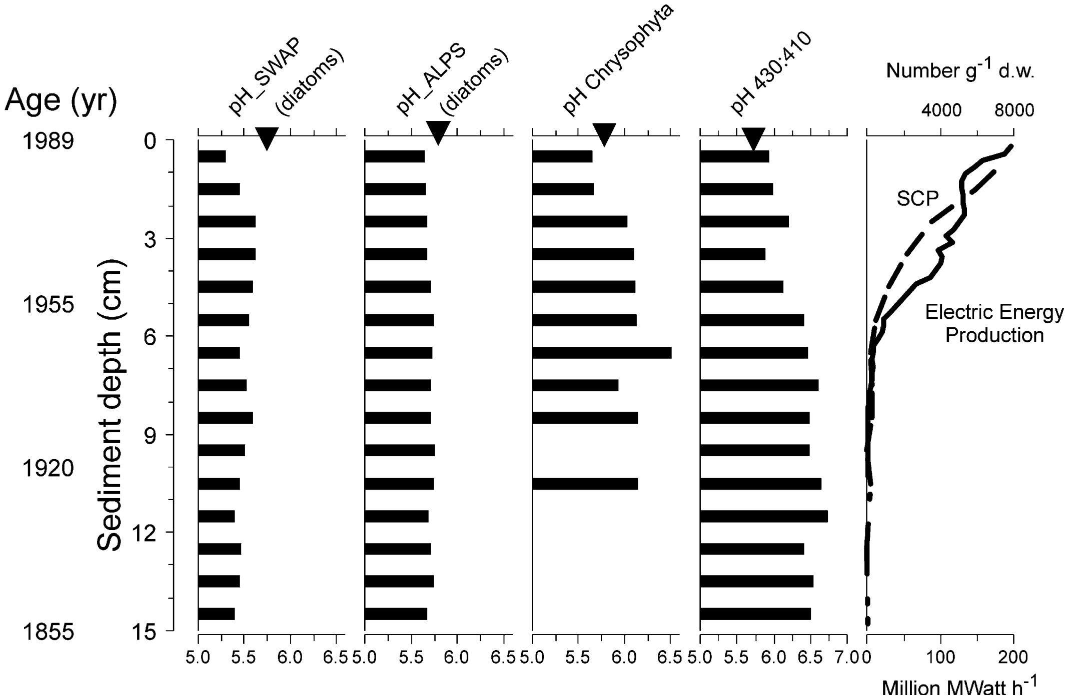

Figure 6. Fossil diatom-inferred pH using two models (SWAP, and ALPS, see text), chrysophyte scales and pigment ratio-inferred pH in a sediment core of Lake Paione Superiore. Thermal electric production for Italy and carbonaceous particles (SCP) curves are also indicated.

Pugnetti & Bettinetti (1999), Manca & Comoli (1999, and literature therein), recently summarized by Marchetto et al. (2004).

Multi-proxy studies (nutrients, carbonaceous particles, diatoms, chrysophyte stomatocysts, pigments, and chironomids (Fig. 6) were performed of sediment cores from the last ca. 100 years (Guilizzoni et al., 1996).

Two diatom calibration data sets (SWAP, Stevenson et al., 1991 and ALPS, Marchetto & Schmidt, 1993) were applied to infer pH. The inference using the SWAP model was 0.4 pH units lower than the measured pH. The ALPS model better approximated the modern pH, indicating a slightly decreasing trend in pH from the mid 1950 onwards (Fig. 6). The pH changes in the pigment ratio (Guilizzoni et al., 1992a) and the pH inferred from fossil chrysophyte scales indicated a clear significant correlation with the concentration of spherical carbonaceous particles (SCP). From these results we concluded that the onset of atmospheric pollution was between 1950 and 1955 AD (radiometric techniques were used to date the sediment). The lake became acidified approximately 10 years later (ca. 1965). In addition to lake acidification, a slight increase in lake trophy since the early 1960's was indicated by the pigments. This increase in total algal pigments corresponds with increased total nitrogen and biogenic silica.

The increase in total nitrogen might be due to the general increases in nitrogen pollution in Europe. Since originally the lake was nitrogen and phosphorus limited (Mosello et al., 1993), the increase in nitrate and ammonium could have produced a slight eutrophication in the lake. Analyses on snow-core samples demonstrated that the watershed of this lake receives high loads of SO_4, NO_3 and NH_4 (Mosello & Tartari, 1987).

The coupling between air temperature and pH and its decoupling during industrial times as was postulated by Psenner & Schmidt (1992) and Marchetto et al. (1993) is also indicated in the sediment core from Lake Paione Superiore. A chemical surveys of mountain lakes in the Alps (Boggero et al., 1993; Marchetto et al., 1995) have shown, however, complex interactions between climate (altitude dependent air temperature) and catchment variables, such as vegetation cover of the watersheds controlling rock weathering, and consequently the acid/base balance (Engstrom et al., 2000; Schmidt et al., 2004).

Paione Superiore is the highest lake of a three lakes in a cascade ecosystem. For its Cladocera community, it was noted that after a period of three years of no fish introduction, re-colonization of the lower lake occurred by transport of ephippia from the upper lake. *Daphnia* in these lakes is a cyclical parthenogenetic species, able to produce ephippia at the end of the growing season, hence the re-colonization was related to the hatching of the ephippial eggs. In this case the sediments acted as an "egg bank" (Hairston, 1992).

Bosmina species are rare in lakes above 1800 m altitude, whereas in most cases *Daphnia* is the only planktonic taxon that is represented in the surface sediments (Lotter et al., 2000b). Commonly a single species of chydorids were found in many high altitude lakes, i.e. *Alona quadrangularis*, *A. rectangula*, *Acroperus harpae*, and most frequently *C. sphaericus*. Of course, the occurrence of taxa does not necessary reflect the geographical, physiographic location, or human impacts, but also specific local site features such as shading and consequently low summer water temperature.

Conclusions

Although not exhaustive, it is clear from this overview that detailed palaeolimnological studies of Italian lakes located on the down slope of the Alps are quite rare and almost restricted to a few case studies (Lake Tovel and Paione Superiore). These lakes were probably the first ones in which a multi-proxy, multi-cores palaeolimnological analyses were performed in the early 1990s.

Other high altitude lakes were studied in a series of EU programmes that started at the end of 1980s and lasted for all of the 1990s. Particularly well-studied from a palaeolimnological perspective were the Paioni cascade lakes (central-western Alps). The acidification history, i.e. onset of acidic deposition, natural process vs. anthropogenic disturbance, pre- and post-chemical changes and watershed processes are documented in a number of papers summarized in Marchetto et al. (2004). In Lake Paione Superiore, the highest of these cascade lakes, a slight eutrophication in recent years was detected, driven by a nitrogen increase in the lake water, probably originating from atmospheric pollution.

Although restricted to relatively few studies, palaeoecological analyses of lake sediment cores along the down slope of the Alps have provided important insights into, and understanding of, trends and causes of processes such as acidification, trophic evolution and climate changes. Much of these results cannot be attained by any other method. All the studies were mainly based on fossil plant pigments, diatoms, chrysophytes and Cladocera analysis. In a few palaeolimnological studies chironomid remains were also analyzed.

The onset of acidification occurred between 1940 and 1950. However, air pollution, as inferred by carbonaceous particles accumulated in the lake sediments, showed the onset of deposition at the beginning of the 20th century and a rapid increase in concentration from 1950 and 1960. The recent reduction in atmospheric sulphur has lead to a slight recovery in alkalinity in a few lakes. The biological remains investigated have changed markedly, some beginning at periods when inferred pH was between 5.3 and 5.8.

The primary cause of the past 50 years of acidification is clearly a result of the increased deposition of strong acids derived from the combustion of fossil fuels. However, acidification of some Alpine lakes was shown before anthropogenic impacts resulting from natural processes such as temperature variations (Psenner & Schmidt, 1992; Marchetto et al., 1993).

Nitrogen deposition in these seemingly pristine natural areas has resulted in subtle but detectable limnological changes that could represent the beginning of a stronger response to N enrichment.

However, the most comprehensive study on the Alpine lakes, although not strictly a palaeolimnological study, was that performed under the European EMERGE Programme (2000–2003): in this programme sediment analyses (chemical and biological remains) were made on recent and pre-industrial sediment layers: the results from the Alps Lake District were compared with other similar environments throughout Europe.

As well-established for some biological remains (e.g. diatoms and chironomids), a statistical analysis was applied to the sedimentary carotenoids and environmental variables (Lami et al., 2005b). The study used a combination of lake survey and palaeoecological reconstructions to evaluate the potential of fossil carotenoids indicators of algal and bacterial responses to climatic changes and atmospheric pollution. Pigment concentrations were quantified in detail in the surface sediments of about 300 lakes to determine how pigment abundance and composition varied as a function of the physical and chemical characteristics of mountain and high latitude lakes (Lami et al., 2005b). One aim is that a transfer function will be derived in order to quantitatively reconstruct past primary productivity and nutrients. This approach is, however, still under development as there are many factors that can confuse the patterns. Using these methods, statistically significant relationships have been found between some carotenoids (e.g. diatoxanthin, alloxanthin, echinenone) and lake water pH (and related ions), nitrogen and altitude (temperature). At present these are not strong enough to make an inference model.

However, pigment training sets could consider another level of approach. It would perhaps more useful to plan a transect survey across a lake that can reveal great changes in pigment composition which are related mainly to depth (D. Hodgson, personal communication). In some cases a training set of samples from the same lake may be more powerful. Generally, we think that both within-lake and regional pigment training sets can be used semi-quantitatively but may not produce strong inference models. To improve this, what is needed are robust criteria for selecting a sub-set of lakes to maximize the environmental gradient of interest (e.g., depth, pH, conductivity) before testing the relationships (Lami et al., 2005b).

Finally, it is important to emphasize that a number of research activities on lakes in the Swiss, French and Austrian Alps have been carried out by other palaeolimnological and palaeoecological groups. These have traced in great detail the Holocene palaeoenvironmental history and climate changes in this alpine region through the analysis of pollen, geochemistry and $\delta^{18}O$ signals and from speleotherm calcite (e.g. Lotter et al., 2000b; Frisia & Fairchild, 2001; Tinner & Ammann, 2001; Lotter et al., 2002; Schmidt et al., 2004). The time-window considered and the specific aims of these studies are however beyond the scope of this special issue.

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