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ORIGINAL PAPER

Human impacts and eutrophication patterns during the past ~200 years at Lago Grande di Avigliana (N. Italy)

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Abstract A short sediment core from Lago Grande di Avigliana (Piedmont, Italy), the second most eutrophied lake in Italy, was analysed for pollen and diatoms to reconstruct land-use changes and to estimate baseline conditions for total phosphorus (TP) in the water column. Varve counts on sediment thin-sections and ^{210}Pb, ^{226}Ra, and ^{137}Cs dating provided a reliable chronology for the past ~200 years. The main pollen-inferred land-use changes showed a sharp decrease of hemp retting around AD 1900, as well as a gradual change to less intensive agriculture and increasing abundance of exotic plants since AD ~1970. Diatom-inferred TP reconstructions indicated stable TP concentrations until AD ~1950, revealing baseline mesotrophic conditions (TP <25 μg l^{-1}). After AD ~1950, TP values increased distinctly and continuously, culminating in the late 1960s with concentrations of 150 μg l^{-1}. Subsequently, diatoms implied a linear decrease of TP, with an inferred value of 40 μg l^{-1} in the surface sediment sample. Comparison with instrumental TP measurements from the water column since AD 1980 showed a rapid recovery and allowed a direct validation of the diatom TP inference. However, although the TP concentration has decreased considerably, baseline conditions have not yet been reached. When compared to the limnological effects of sewage discharges on inferred-TP concentration, our results indicated that agricultural land use played a minor role in the lake's eutrophication.

Keywords Land-use changes · Varves · Eutrophication · Pollen analysis · Diatom analysis · Validation · Italy

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Introduction

Over the past centuries, land use has profoundly affected ecosystems. The impact of agricultural land use or of urbanisation on lake-water quality is increasingly evidenced by palaeoecological studies covering historical time-scales exceeding the time period of monitoring (e.g., Lotter et al. 1997; Bradbury et al. 2004). At present much attention is paid by nature conservation agencies to protect and restore ecosystems (e.g., the European Water Framework Directive, European Union 2000). If a polluted and/or disturbed lake or any other ecosystem is to be restored, a management target is needed to define natural background conditions (Lotter and Psenner 2004). Such a target can often be provided by long-term palaeoecological studies of sediment archives (e.g., Nhapi et al. 2004; Miettinen et al. 2005; Reid 2005; Sondergaard et al. 2005).

This study presents results from a high-resolution palaeoecological investigation of annually laminated sediments from Lago Grande di Avigliana (Northern Italy), which was classified as the second most eutrophied lake in Italy (n=147 lakes, Gaggino et al. 1985). Despite more or less continuous seasonal chemical and biological records since 1980, no data are available on the pre-industrial conditions of the lake. Thus, an important question concerns the extent to which human impact on the terrestrial and aquatic ecosystem has changed over time.

The main aims of the present study were therefore: (i) to make an assessment of changes in the terrestrial and the aquatic environment during the past ~200 years, including the period of strongest anthropogenic eutrophication; (ii) to define pre-industrial conditions for lake-water nutrients; and (iii) eventually to verify whether the restoration procedures have been effective enough to reach pre-industrial conditions.

To achieve these aims, we used biotic (pollen and diatoms) and abiotic (loss-on-ignition) proxies. The pollen record is a classical palaeoecological tool to infer changes in vegetation and human impact on the terrestrial environment (Behre 1981; Bennett and Willis 2001). Diatoms are sensitive to changes in the environmental conditions (e.g., pH, total phosphorus) and can be used to provide quantitative estimates of nutrient concentrations (e.g., total phosphorus, TP) in lakes (Anderson et al. 1993; Lotter 1998; Lotter et al. 1998). Finally, loss on ignition provides a qualitative estimate of sediment components (organic matter, carbonates, and residual silicates, Heiri et al. 2001).

Materials and methods

Lago Grande di Avigliana (353 m asl; 45°03′54″ N, 07°23′12″ E) is a hard-water lake located in the lower part of the Val di Susa (north-western Italy; Fig. 1). The lake is part of a complex hydrological system consisting of four aligned basins, the two outer ones being overgrown during the early to middle Holocene (Schneider 1985). It receives its water from Lago Piccolo di Avigliana. The lake characteristics are summarized in Table 1. At present the region has a characteristically temperate mid-latitude climate without any dry season. Precipitation is about 800 mm year^{-1} with maxima occurring in spring and autumn (Biancotti et al. 1998). The tree and shrub vegetation in the flat and humid areas of the lowlands is at present dominated by *Alnus glutinosa*, *Ulmus minor*, *Quercus robur*, *Robinia pseudacacia*, and *Salix alba*. On the hills *Q. pubescens* occurs together with other drought-adapted species (e.g., *Opuntia vulgaris*, and *Celtis australis*) on south-exposed slopes, while cooler and moister slopes are dominated mainly by *Q. robur* and *Castanea sativa*. Above ~600 m, *Fagus sylvatica* and *Abies alba* occur where chestnut trees are absent (Tosco 1975).

The core (AVG 07/02) was collected from the centre of the lake (Fig. 1) in September 2002 using a freeze corer (Renberg 1981), as to preserve the fragile water–sediment interface. The frozen core was transported to the lab in a freeze-box, cleaned, photographed, and sub-sampled in 1 cm steps with a band saw at 4°C room temperature. After measuring their volume, frozen sub samples were freeze-dried and a weight corresponding to 1 cm^3 was processed for pollen, diatom, and loss-on-ignition analyses and for isotope measurements.

Loss on ignition was measured every centimetre at 550°C and 950°C to estimate the amount of organic matter, carbonate content, and silicate content (expressed in % of total dry weight) of the sediment. Samples were treated following Heiri et al. (2001). Thin-sections were prepared following the shock-freeze and freeze-dry technique (Merkt 1971; Lotter and Lemcke 1999).

The chronology is based on isotope measurements (^{210}Pb, ^{226}Ra, and ^{137}Cs) of freeze-dried sediment samples (Fig. 3a and 3b) and independent varve counts on thin sections (Fig. 3c). Isotope measurements were carried out in spring 2003. We used the model of Constant Rate of Supply (CRS model) for the ^{210}Pb-inferred depth-age model. Varve counts were made under a stereomicroscope with polarized

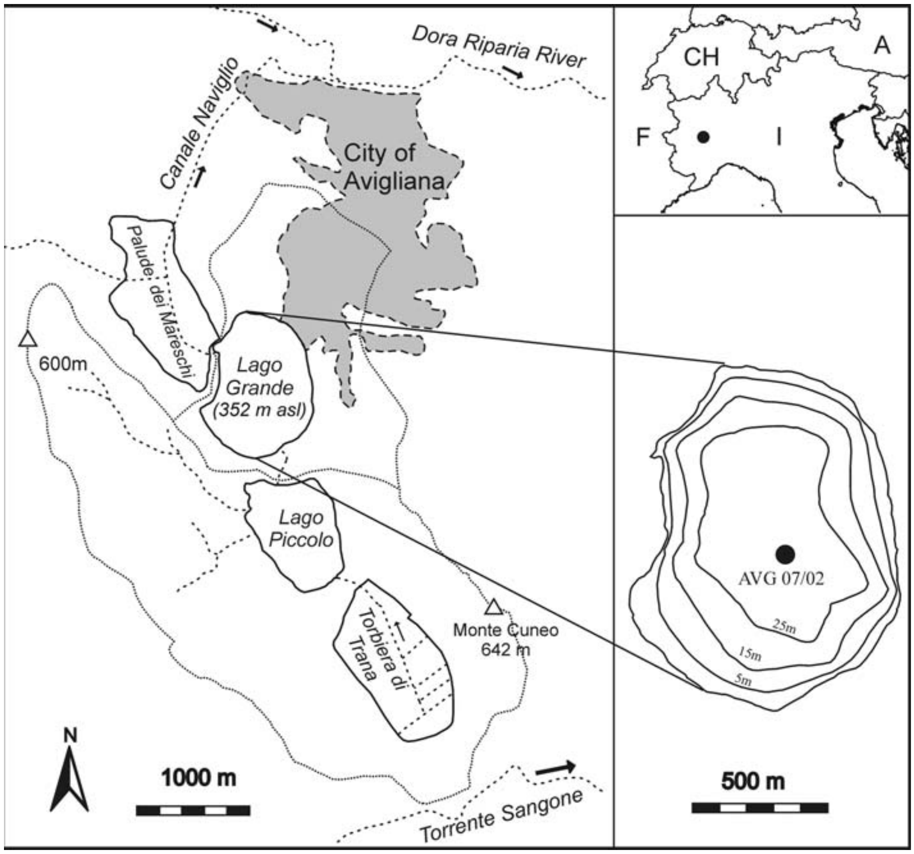

Fig. 1 Location of Lago Grande di Avigliana (grey shading: urban area) and bathymetric map of the lake basin (from Badino et al. 2001; modified) with coring location marked by the solid circle

Table 1 Morphometric, physical and hydrochemical features of Lago Grande di Avigliana (after Gaggino and Cappelletti 1984)

Elevation (m asl)	352
Lake surface (km^2)	0.83
Catchment area (km^2)	10.7
Length of shore line (km)	3.6
Maximum depth (m)	26
Mean depth (m)	19.5
Maximum length (km)	1.2
Maximum width (km)	0.8
Lake volume (10^6 m^3)	16.2
Theor. Renew. Time (years)	2.3
Winter-ice cover	irregular
pH	7.6
Min–Max TP (μg P l^{-1})	53–704
Alkalinity (meq l^{-1})	2.54
Conductivity (μS cm^{-1})	260

light, by counting the spring/summer carbonate layers in increments of 10 mm.

Preparation for pollen analysis included physical (sieving, decanting) and chemical (HCl, KOH, HF, acetolysis) treatments, staining with Fuchsin, and mounting on microscopic slides with glycerol, following Lotter (1988). At least 400 pollen grains were counted at 400× magnification and identified using determination keys (Punt 1976; Moore and Webb 1978; Punt and Clarke 1980, 1981, 1984; Punt et al. 1988; Punt and Blackmore 1991) and the pollen atlas of Reille (1992, 1995). The abundance of tree, shrub, and herb pollen was calculated as the sum of terrestrial pollen, excluding pollen and spores of ferns and aquatics. As hemp plants were soaked in the lake for retting prior to further processing (Badino et al. 2001), the *Cannabis/Humulus* pollen type was excluded from the pollen sum because changes in its abundance are not thought to be related to its abundance in the vegetation.

Diatom preparation followed standard procedures, involving treatment with H_2O_2 (30%) and HCl (10%), followed by heating for >7 h at 70°C (Renberg 1990; Battarbee et al. 2001). After rinsing the samples with distilled water, they were dried onto cover slips and permanently mounted using Naphrax®. Enumeration of diatoms (~400 frustules per sample) was done using a Leica DMR microscope at 1000× magnification with phase contrast optics. Diatom taxonomy follows largely Krammer and Lange-Bertalot (1986, 1988, 1991a, b).

Pollen and diatom diagrams were zoned by optimal partitioning using sum-of-squares criteria (Birks and Gordon 1985). The number of significant zones was assessed by comparison with the broken-stick model (Bennett 1996).

For the TP reconstruction, subfossil diatom taxa occurring at least in one sample with abundance >1% were selected. The selected diatom taxa ($n = 27$) represented at least 94% of the subfossil diatom assemblages and were all represented in the modern diatom calibration set. The TP reconstruction was performed using the Swiss diatom calibration set including 72 modern samples, covering an epilimnetic spring TP range from 5 to 520 $\mu g\ l^{-1}$ (Lotter et al. 1998). Following Lotter et al. (1998), we used a two component WA-PLS model, characterised by a jack-knifed r^2 of 0.79 and a root-mean-square-error-of-prediction (RMSEP) of 0.19 $\log_{10}\mu g$ TP l^{-1}. Prior to calibration and reconstruction, diatom data were square-root- and TP data log-transformed. Additional details on calibration set properties and transfer function development are available in Lotter et al. (1998), for general information on numerical methods see ter Braak and Juggins (1993), ter Braak et al. (1993) and Birks (1995, 1998).

Management history of Lago Grande di Avigliana

In 1985, Lago Grande di Avigliana was classified as the second most eutrophied lake (among 147 examined lakes) in Italy (Gaggino et al. 1985). TP concentrations were ca. 220–230 $\mu g\ l^{-1}$. The principal cause leading to the eutrophication was the presence of water collectors which discharged part of the sewage from the drain network of the city of Avigliana (Gaggino et al. 1985; Calderoni and Marchetto 1998). In contrast, between 1876 and ~1950 AD, water quality of the lake was good and inhabitants used it as drinking water (Badino et al. 2001). Therefore, parts of the drain network were deflected into the Doria Riparia River starting from ~1980 AD in order to avoid the drain of polluted water into Lago Grande di Avigliana. However, the network was definitely deflected only in 1994 AD, when the construction of a circular sewage collector was accomplished.

Starting from 1923 AD, the ''Consorzio Irrigatorio delle Gerbole di Rivalta e Paesi Limitrofi'' pumped approximately 4 millions m^3 water $year^{-1}$ to irrigate the surrounding agricultural fields (500 ha). Water was extracted starting in June until autumn and transferred to the Lago Piccolo di Avigliana (Fig. 1). However, due to the eutrophication of Lago Grande di Avigliana, this resulted in the eutrophication of the upstream Lago Piccolo di Avigliana, too. Therefore, starting in 1994 AD, water was extracted from Lago Grande di Avigliana from a hypolimnetic station (20 m water depth) and transferred directly into the sewage-system of the Consorzio. In this way nutrient-rich water was extracted from the hypolimnion of the lake and used to fertilize the fields. According to water-quality monitoring studies, the lakes' water quality was partially re-established in 1999 AD (Badino et al. 2001).

Results and discussion

Loss on ignition

The main sediment mass consists of the non-ignited sediment fraction (mainly silicate minerals) (Fig. 2). Carbonate content and organic matter vary generally between 10% and 20% of dry weight. Two notable interruptions are evidenced by increases in the ignition residue at 41.5–46.5 cm and at 33.5–35.5 cm depth, which match two visually identified turbidities. In addition, a major reduction of the ignition residue is recorded at ~30 cm depth, likely indicating reduced minerogenic input from the catchment due to a decrease in erosion. In the topmost 6 cm (i.e., from ~1975 to the present), a gradual decrease of the ignition residue accompanied by increase of organic matter indicates a modest increase of productivity in the lake.

Sediment chronology

The chronology is based on isotope measurements (^{210}Pb, ^{226}Ra, and ^{137}Cs) (Fig. 3a, b) and on independent varve counts on thin sections. The inferred

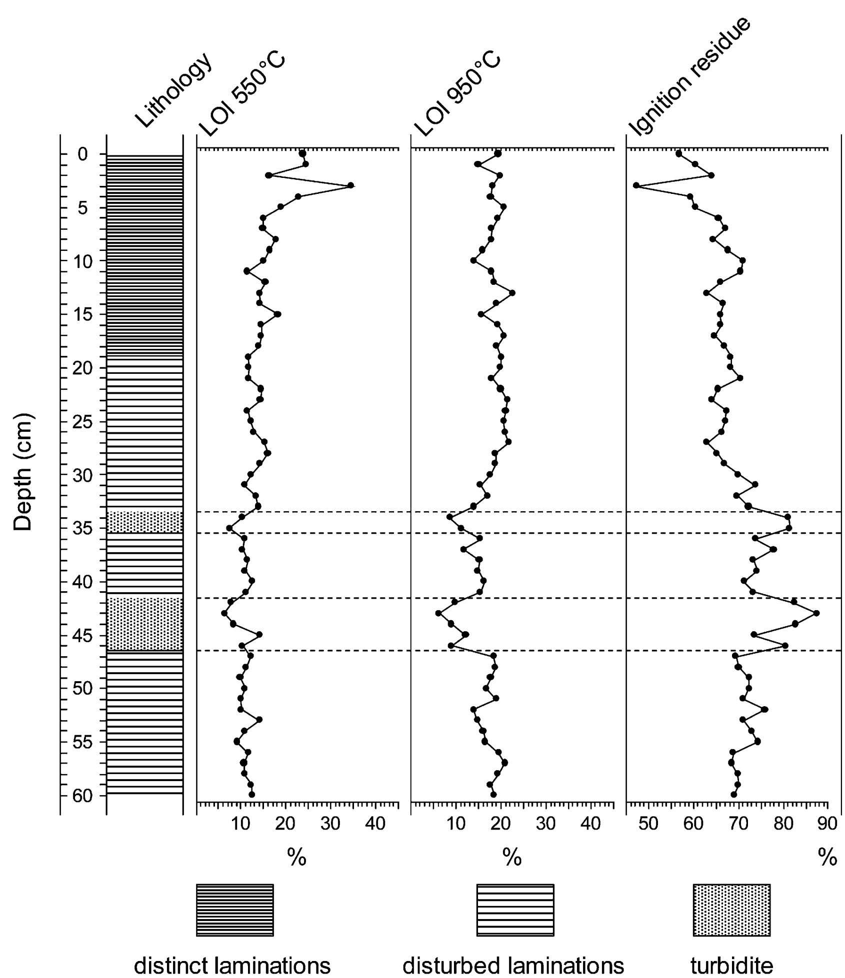

Fig. 2 Loss on ignition (values in % of dry weight) of core AVG 07/02

depth-age model (Fig. 3c) is referred to corrected depths obtained after the elimination of the turbidities located at 41.5–46.5 cm and at 33.5–35.5 cm depth (Fig. 2). Distinct ^{137}Cs peaks mark the 1986 Chernobyl event (at 3 cm depth) and the fallout peak from the atmospheric nuclear weapons tests in 1963 (at 11 cm depth). The inferred accumulation rate between the two ^{137}Cs peaks (at 1963 and at 1986) is approximately 3.47 mm year^{-1}. Total ^{210}Pb activity plotted on a logarithmic scale versus depth shows constant values similar to supported ^{210}Pb below ~22 cm, eventually dating ~1850 AD at that depth. The mean inferred accumulation rate between 22 cm and 10 cm depth is ca. 0.97 mm year^{-1}, while a higher rate (2.27 mm year^{-1}) was obtained for sediments between 10 cm and 0 cm. The isotope-inferred models and the varve count agree well between 0 cm and 14 cm, while below that depth ^{210}Pb-inferred ages appear older than varve counts. However, the sediment composition as inferred from loss-on-ignition measurements does not indicate a substantial change at 14 cm depth. Therefore, the varve-inferred accumulation rate was extrapolated downcore. The validation with pollen-inferred time markers (e.g., *Cannabis sativa* pollen declines and *Ambrosia* pollen) indicates that the extrapolated model eventually overestimates the sediment age by maximum ~20 years (Fig. 3c).

Pollen stratigraphy and inferred land-use

Overall, 120 different pollen-types were identified in sediment samples of Lago Grande di Avigliana (Fig. 4). Due to the distance to littoral vegetation, pollen of aquatic plants was extremely rare. Four statistically significant pollen assemblage zones were

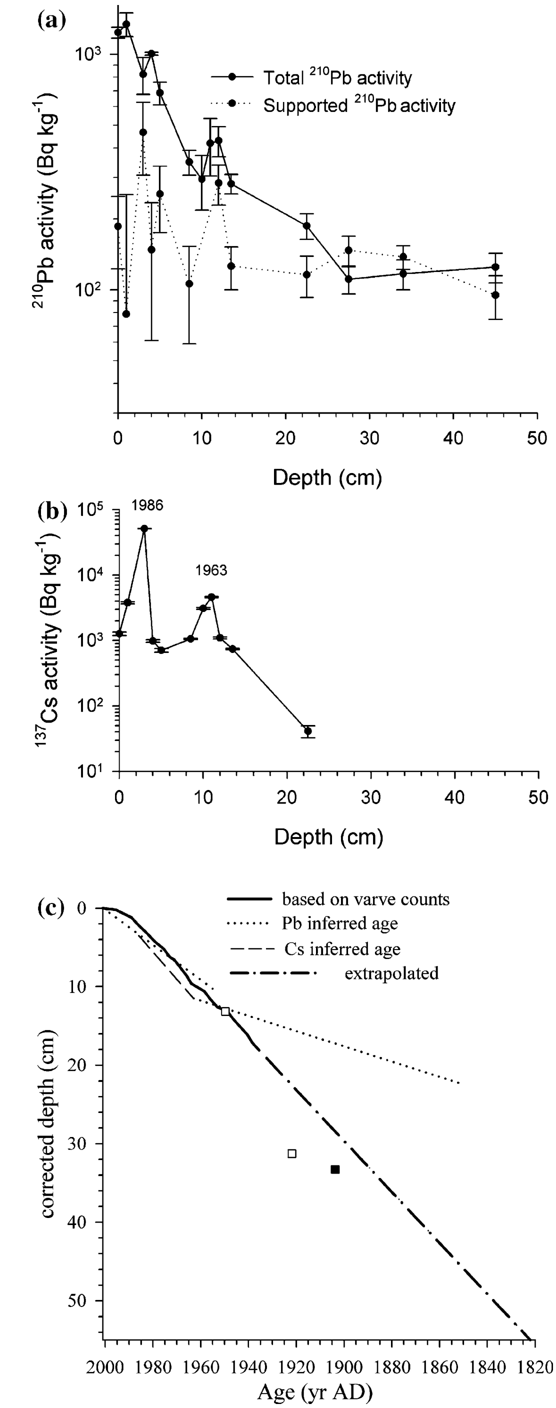

Fig. 3 (**a**) Total and supported ^{210}Pb activity, (**b**) ^{137}Cs activity, and (**c**) depth-age model based on isotopes and on varve counts in sediment thin sections (see legend). □ = expected age for changes in *Cannabis* pollen abundance; ■ = expected age for *Ambrosia* pollen first appearance

distinguished. These separate the gradual vegetation changes that lead from a landscape marked by farming and forest management activities to a landscape characterized by less disturbed forests and lakeshores as well as by introduced ornamental plants.

As inferred from high herb pollen values and by *Juglans*, *Castanea*, *Cerealia*, and *Secale* pollen, agriculture was intensive and the landscape was fairly open from 1830 to 1880 AD (AVG-P1; 53–35.5 cm depth). The tree pollen sum never exceeded 50% and anthropogenic indicators (e.g., *Plantago lanceolata*, *Rumex*, and *Urtica*) were continuously present. The presence of dry pastures is inferred from high abundances of *Juniperus* (Behre 1981). High amounts of *Cannabis/Humulus* pollen, as shown in this record, are often the result of hemp retting in lakes, a procedure necessary for the treatment of this cultivated plant prior to further processing (Bradshaw et al. 1981; Mercuri et al. 2002). *Cannabis sativa* cultivation and textile industries were abundant in northern Piedmont (Canavese) in the 19th century. Hemp cultivation declined in Italy starting from ~1925, and after ~1950 it further declined because of competition with synthetic fibres (Dionisi 1951). Since 1971 its cultivation is forbidden by law in Italy.

The sudden increase of Gramineae pollen marks the onset of zone AVG-P2 (35.5–18.5 cm depth; 1880–1935 AD). A further slight opening of the landscape is inferred from generally lower tree pollen values than in zone AVG-P1. This decrease was mainly due to lower percentage values of *Juglans*, which might indicate the abandonment of the walnut plantations. Gradually increasing values of *Fraxinus excelsior* may attest to its expansion in the catchment. Higher values of *Populus* pollen were possibly caused by its expansion in the more humid areas of the catchment, while the increase of *Plantago lanceolata* could indicate the persistence of disturbance. *Platanus* pollen is discontinuously present proving the presence of ornamental vegetation (Pignatti 1982). A strong reduction of hemp retting at ~1900 AD is inferred from the sharp decrease of *Cannabis/Humulus* pollen.

At ~32 cm depth (i.e., ~1890 AD) the first pollen occurrences of *Ambrosia* were detected. In Piedmont two North American species of this genus, *Ambrosia*

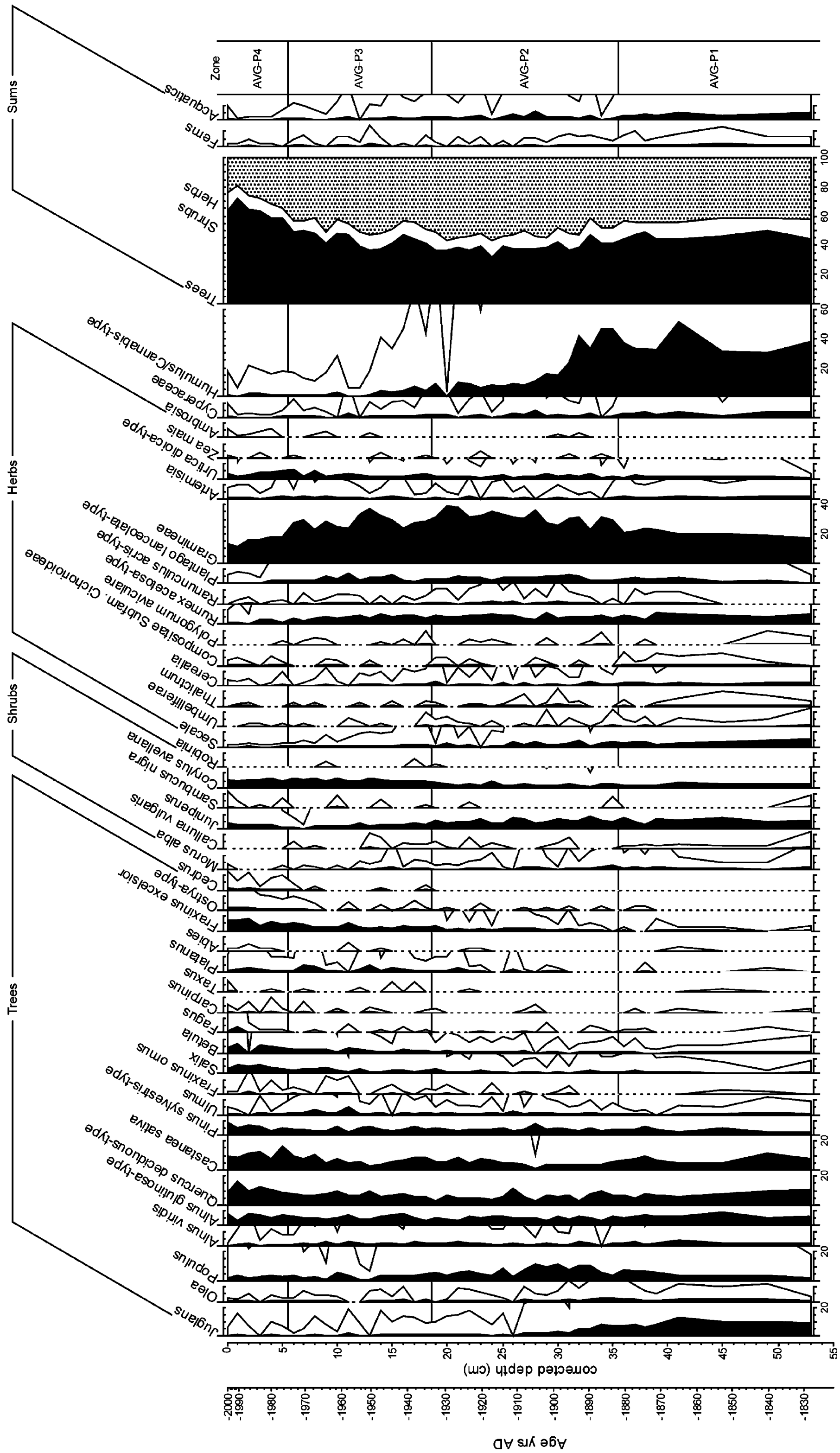

Fig. 4 Pollen stratigraphy of Lago Grande di Avigliana, core AVG 07/02. Pollen taxa are sorted by weighted average on depth and by groups

artemisiifolia and *A. trifida*, occur at present on ruderal and fallow land. According to direct observations, *A. artemisiifolia* expanded in Piedmont starting at least in 1902 (Pignatti 1982). This is distinctly earlier than north of the Alps (e.g., van der Knaap et al. 2000).

Starting from 1935 AD (AVG-P3; 18.5–5.5 cm depth), the Gramineae pollen curve gradually decreases and the arboreal pollen curve increases from ~40% to 50%. In addition *Secale* pollen decreased after around 1960, and therefore a decrease in agricultural land is inferred. *Corylus* pollen increased starting from ~20 cm depth, parallel to the decrease of *Juniperus*, indicating a gradual recolonisation of abandoned and ruderal patches by woody pioneers. If the expansion of pollen-unproductive urban areas did not significantly affect the pollen-inferred landscape, it implies that the landscape was gradually becoming less open than before. At the transition to zone AVG-P4 (5.5–0 cm depth; 1975–2001 AD), herbaceous pollen further decreased, while tree pollen (*Fagus*, *Ostrya*, *Quercus*, *Salix*, *Cedrus* and *Castanea*) increased. In addition, lower percentages of *Plantago lanceolata* and *Artemisia* imply that ruderal vegetation was less abundant than before. In the vegetation map of the area around the lake (Tosco 1975), *Ostrya* is not mentioned, possibly indicating its scarce presence. Low percentages of this pollen type in our record may however imply its presence in the surroundings at that time. According to Mondino et al. (1981) *Ostrya carpinifolia* was expanding in abandoned chestnut woodland and pastoral areas in Piedmont. In fact, agricultural activities in the area around Turin strongly declined between 1950 and 1970 AD because workers were more attracted by the local car industry.

Diatom stratigraphy and inferred TP changes

Overall, 85 different diatom taxa were identified and enumerated from the sediment core of the deepest part of Lago Grande di Avigliana. As could be expected, the diatom assemblages are dominated by planktonic taxa and show a typical succession found in many anthropogenically eutrophied lakes (e.g., Lotter 2001). The diatom stratigraphy was subdivided into two significant zones (Fig. 5). In the first zone (AVG-D1; 60–12 cm depth), the mesotrophic *Cyclotella cyclopuncta* prevailed, showing relative abundances between 40% and 80%. In addition, *Cyclotella comensis* and *Fragilaria crotonensis* were the most prominent species, both showing an increasing abundance towards the end of the zone

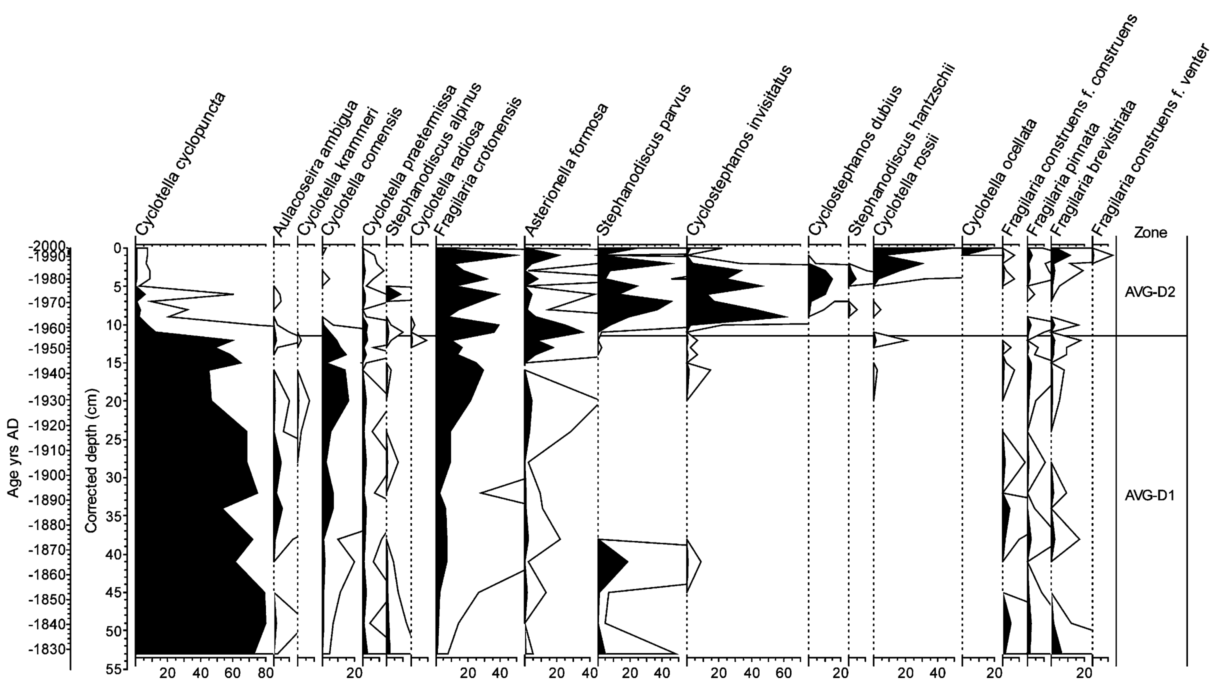

Fig. 5 Diatom stratigraphy of Lago Grande di Avigliana, core AVG 07/02. Diatom taxa are sorted by weighted average on depth

(Fig. 5). The shift from AVG-D1 to AVG-D2 (12–0 cm) is characterised by a sharp and dramatic decrease of *Cyclotella cyclopuncta*, dropping to values below 10%. The small planktonic diatom taxon was replaced by other planktonic taxa preferring eutrophic conditions such as *Asterionella formosa*, *Cyclostephanos invisitatus*, *C. dubius* and *Stephanodiscus parvus* (Lotter et al. 1998). Even though AVG-D2 is identified as one single zone, a distinct structure is apparent. During the initial phase, taxa tolerating high Si:P ratio (van Donk and Kilham 1990; Lotter 1998) such as *Asterionella formosa* and, to a certain extent, *Fragilaria crotonensis*, are attaining relatively high abundances. Subsequently, taxa competitive at low Si:P ratio such as *Stephanodiscus* and *Cyclostephanos* replace *Asterionella formosa* and partly *Fragilaria crotonensis*, which shows high variability during AVG-D2. The last part within the zone is characterised by a reversal of the eutrophication trend, as *Stephanodiscus* and *Cyclostephanos* are replaced by *Asterionella formosa*, as well as *Cyclotella rossii* and *C. ocellata*, two taxa preferring mesotrophic to eutrophic conditions (Lotter et al. 1998) that were not present at all in the first part of the stratigraphy (AVG-D1; Fig. 5).

The diatom-inferred TP-reconstructions suggest stable TP concentrations until 1950, indicating mesotrophic conditions (TP <25 µg l^{-1}) (Fig. 6). After 1950, a distinct and continuous increase of TP concentrations is inferred, culminating in the late 1960s at 150 µg l^{-1}. Subsequently, diatoms imply a linearly decreasing TP trend. Surprisingly the inferred value of 40 µg l^{-1} in the surface sample (Fig. 6) is considerably lower than the measured value of 81 µg l^{-1} in 2003 AD (Table 2).

Some TP measurements from the water column from Lago Grande di Avigliana exist (Badino et al. 1979, 2001; de Bernardi et al. 1984; Gaggino et al.

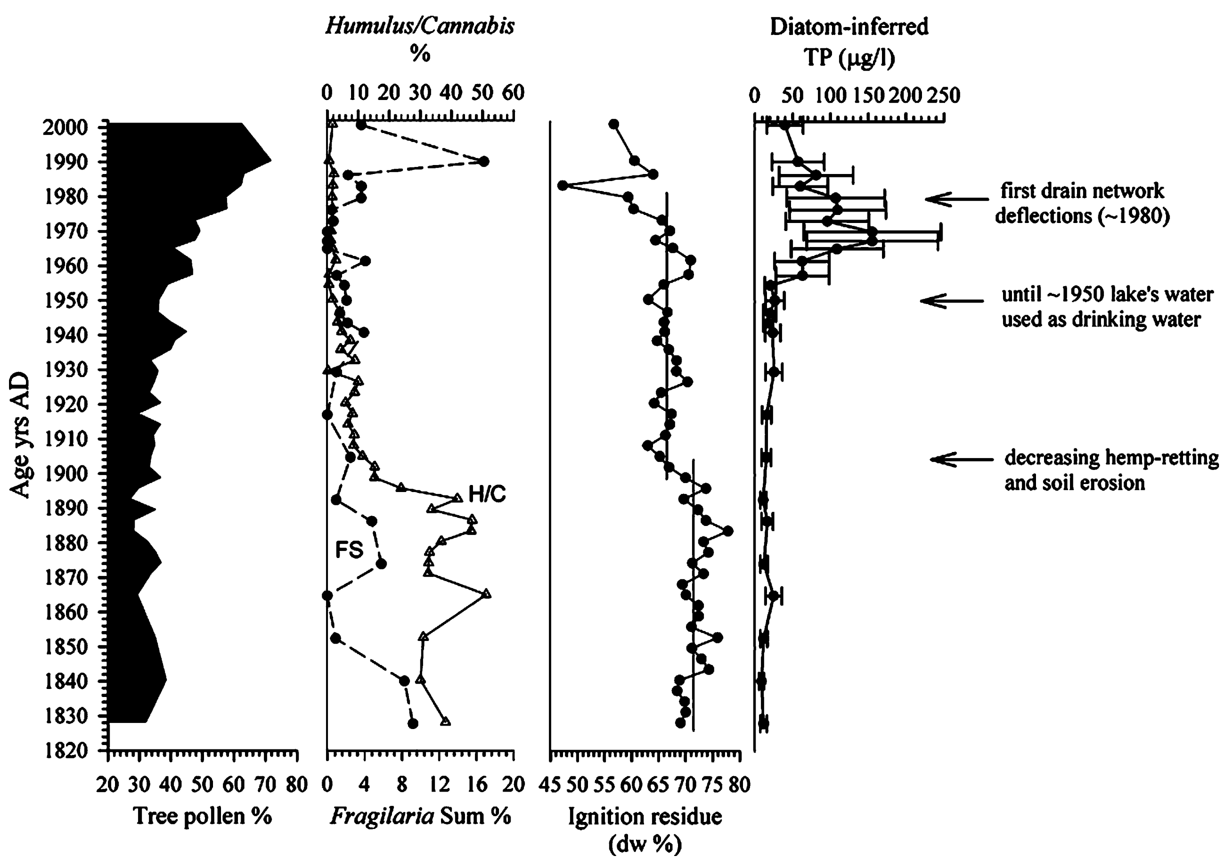

Fig. 6 From left to right: changes in forested area (tree pollen %); *Cannabis* retting and *Fragilaria* Sum (%); erosion activity (Ignition residue dw%); and total diatom-inferred TP at Lago Grande di Avigliana

1985; Defilippi 1998) (Table 2), which allow a comparison of the diatom-inferred TP values. Unfortunately, the data are, except for the past decade, sparse and heterogeneous concerning the date of sampling and the sampled water depth, hampering a direct comparison. However, two main features comparing diatom-inferences with measured TP data are visible. First, the measured TP values during the past decade support the diatom-inferred decreasing TP-concentration. Second, the diatom-inferred TP values are in general considerably lower than the measured data. Similarly, the same transfer function based on the Swiss calibration set underestimated the TP values of Baldeggersee (Switzerland), which was assigned to the relatively low mean TP concentration (31 μg l^{-1}) of the calibration set lakes, resulting in an underestimation of high TP values (Lotter 1998). In contrast, several studies have shown an overestimation of diatom-inferred TP concentrations compared to measured data (e.g., Anderson and Rippey 1994; Bennion et al. 1995) at the lower end of the TP gradient. Obviously, an appropriate gradient length of the calibration set is crucial to obtain quantitatively correct reconstruction values. For comparison, we have also applied a transfer function based on the calibration set of Wunsam and Schmidt (1995), including 86 lakes from the Alps and pre-alpine regions in Northern Italy, Austria and Germany. The reconstruction shows in general the same trends as our reconstruction, but the absolute values are considerably lower (data not shown). This is probably due to the low mean TP concentration of the calibration set (23 μg l^{-1}). It seems that the trends of a reconstruction are less affected by the properties of the calibration set than its magnitude.

Table 2 Average TP during lake circulation at Lago Grande di Avigliana

Year AD	Depth (m)	TP (μg l^{-1})
14/01/2003[a]	mean (0–25 m; *n*=9)	81
19/02/2002[a]	mean (0–25 m; *n*=10)	77
22/02/2001[a]	mean (0–25 m; *n*=10)	105
1999[b]	?	150
05/05/1998[b]	mean (0–25 m; *n*=9)	118
22/02/1994[c]	mean (0–25 m; *n*=6)	161
27/01/1993[c]	mean (0–25 m; *n*=6)	200
1984[d]	?	225
26/03/1980[e]	mean (0–25 m; *n*=6)	248
03/1979[f]	mean (1–15 m; *n*=5)	353[g]
03/1974[f]	mean (1–15 m; n=5)	290[g]

Data sources: [a]Dati Regione Piemonte; [b]Defilippi (quoted in Badino et al. 2001); [c]Badino et al. (2001); [d]Gaggino et al. (1985); [e]De Bernardi et al. (1984); [f]Badino et al. (1979); [g]Total orthophosphate

In addition to calibration-set properties and model-inherent WA-PLS problems, some reservations apply as well to measured monitoring data. The TP concentration is highly variable throughout the season and related to timing and degree of thermal stratification (e.g., Wetzel 2001). Therefore, some measured values may not reflect the accurate season and habitat for particular diatom species, particularly when considering the differences between spring- and autumn-blooming taxa. Furthermore, the diatom record in the central area represents an integrated record, reflecting often more than one year and also input from littoral parts of the lake.

Conclusions

We conclude that:

(i) the diatom-inferred TP reconstruction indicates that the current TP concentration is still slightly higher than prior to 1950. If the mean of the inferred TP values prior to 1950 is taken as a baseline measure (~17 μg l^{-1}), this implies that the maximum values reached in the 1960s (150 μg l^{-1} or higher) were up to nine times higher, while at present inferred TP is ca. 2 times higher (~40 μg l^{-1}), indicating a rapid recovery of the lake's TP concentration. Hence we conclude that conservation measures (i.e., drain network deflection of sewage discharge) had a positive effect on the TP concentration of Lago Grande di Avigliana. However, pre-1950 baseline conditions have not yet been restored. The lake's diatom assemblage did not return to its previous composition, possibly owing to the incomplete recovery.

(ii) The comparison with historical TP measurements had two main outcomes. First, the measured data during the past decade support the diatom-inferred decreasing TP-concentration by showing similar trends. Second, the diatom-inferred TP values are in general lower than the measured data. This might be due either to the calibration-set properties and model-inherent WA-PLS features or to the high variability of TP concentration throughout the season.

(iii) As inferred from our palaeolimnological record, hemp retting was strongly reduced around 1920 AD and was definitely abandoned ~1950. Since the abundances of *Humulus/Cannabis* pollen and of inferred-TP concentration are independent, it appears that nutrient input through retting did not affect the lake TP concentration as much as the discharge of the sewage from the drain network (Fig. 6). However, retting likely had an influence on the abundance of the epiphytic *Fragilaria*, which have probably grown on the hemp fibres during the retting (Fig. 6). Higher ignition residue values prior to ~1900 AD might have been caused by sustained soil erosion.

(iv) The change of *Secale* and tree pollen abundance (Figs. 4 and 6) indicates a gradual increase of forested areas on abandoned farm/agricultural land starting from ~1960 AD. Agricultural activities in the area around Turin strongly declined between 1950 and 1970 AD because workers were more attracted by the local car industry. When compared to the limnological effects of sewage discharges on inferred-TP concentration, our results indicate that agricultural land use played a minor role.

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