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Anthropogenically induced changes in the sedimentation processes in the littoral zone of Lake Verevi, South Estonia

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Abstract. Studies of four sediment cores from the littoral zone of a small Lake Verevi with a well-established history of lake hydrochemistry and hydrobiology were conducted. Observational data describe essential changes in the composition of macrophytes and the trophic state of the lake during the last century. Lithological composition (organic, siliciclastic, and carbonaceous matter) in the four sediment profiles taken within a distance of 20 m showed good lithostratigraphical correspondence but differences (up to two times) in the mass accumulation rates of various compounds. Most of the organic matter (75–85%) in the sediment originates from phytoplankton as demonstrated by low organic carbon/nitrogen ratios. Accumulation of organic matter is not directly related to changes in lake trophicity and primary production but rather seems to be dependent on the accumulation of siliciclastic matter, which engages the organic matter in the settling processes. This is supported by the extremely high correlations between the mass accumulation rates of siliciclastic and organic matter ($R^2 > 0.8$). Although the greatest changes in the lake environment took place after 1970 due to severe human impact on the lake, most of the changes in the sediment records started earlier. Precipitation of $CaCO_3$ began already in the 1930s due to natural eutrophication processes and reached its highest values in the 1970s, which can be related to the anthropogenic impact. Also the share of carbon from algae, indicating a rise in the trophic status, started to increase in the 1930s. Macrofossil records reveal that also major changes in the vegetation may have started earlier than historically recorded. The rise in the trophic status of the lake had no direct effect on the accumulation of organic matter.

Key words: lake sediments, eutrophication, macrophytes, sedimentation, organic matter, siliciclastic matter, carbonates.

INTRODUCTION

The palaeolimnological approach is widely used for reconstructing past environmental conditions (Last & Smol, 2001). In order to understand how the palaeoinformation in the sedimentary records reflects past changes in the lake environment, it is necessary to study how historically recorded changes in the lake environment are represented in the topmost sediments. By combining observational and palaeolimnological data sets it is possible to identify short-term processes at decadal scale mainly associated with pollution pressures from human activity (Punning et al., 2004; Davidson et al., 2005). The information obtained from the littoral zone is especially important for the reconstruction of changes in the use of the lake or the surrounding land (Gaillard & Digerfeldt, 1991; Hannon & Gaillard, 1997).

The main consequence of human activity during the last century is eutrophication of lakes due to excess input of nutrients (P, N) originating from agricultural fertilizers and urban wastewaters. Although eutrophication is mainly related to the human activity during the last century, there are also records from the 12th century revealing similar changes (Ekdahl et al., 2004). Usually eutrophication processes are represented in the sedimentary records as an increase in the mass accumulation rates (MAR) of organic matter, lowering of carbon/nitrogen (C/N) ratio, and also as precipitation of calcium carbonates (Ekdahl et al., 2004; Meyers, 2006; Vreca & Muri, 2006; Xue et al., 2007).

Depending on the lake morphometry, catchment topography, and in-lake processes, these interactions are not always straightforward. To distinguish the origin of organic matter in the sediments, C/N ratios have often been used because it is known that algae have lower C/N ratios than vascular plants (Ho & Meyers, 1994; Meyers, 1994). Therefore we would expect to have lower C/N values in the sediments during times of higher eutrophication due to algal blooms, but an increase in the input of allochthonous organic matter from the catchment and higher aquatic plants could mask this. Besides, the accumulation of organic matter does not depend only on its production but also on its decomposition and preservation. Primary production and decomposition of organic matter are in turn directly related to the precipitation of carbonates, as the removal of CO_2 from the water column during photosynthesis affects the water pH and may enhance precipitation of carbonates, and on the other hand, decomposition of organic matter may lead to anoxic conditions in the sediment surface causing carbonates to dissolve (Dean, 1999). In order to separate the cause from the effect in these kind of studies, a multiproxy aproach is needed, and the changes in the lake environment have to be of large scale and historically well recorded.

This paper presents high-resolution lithological and geochemical records of four undisturbed and well-dated sediment cores taken from the littoral zone of a small Lake Verevi in Estonia. The main aim is to reconstruct the changes in the sedimentation environment by using the observational data of the lake hydrochemistry and hydrobiology, including macrophyte mapping. Lake Verevi was selected because it has a relatively flat catchment area and abundant littoral vegetation restricting input of allochthonous material; besides, good monitoring data describing some major changes in the lake environment are available for the last 100 years. The objectives of this research were to study how the historically recorded changes in the lake trophic status and vegetation are recorded in the sediments, how they affected sedimentation processes, and how well they are temporally correlated.

STUDY SITE

Lake Verevi is situated in South Estonia, within the borders of the town of Elva (Fig. 1a). It is a small lake (12.6 ha) with a maximum length of 950 m and width of 320 m. Its average depth is 3.6 m and maximum depth 11 m (Ott et al., 2005).

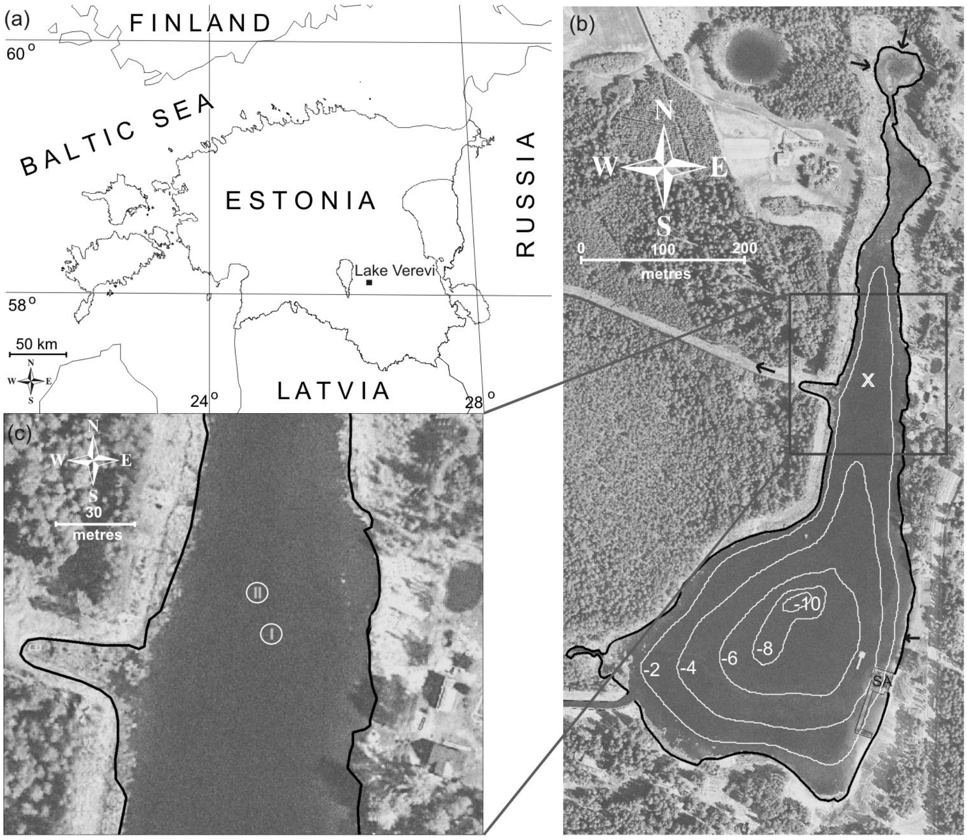

Fig. 1. Location of Lake Verevi (a), its bathymetry and location of sampling area marked with X (b), and location of sampling areas I and II in the northern area of the lake (c).

The eastern shore is shaded from the winds and the area to the west is covered with quagmires and swamps. The outflow of the lake is located on the western shore (Fig. 1b). The lake water is alkaline (pH 8.3) with water transparency of 2.1 m. Average amounts of nutrients differed strongly between surface and bottom layers during the period of 1929–2001 (980 mg m^{-3} of total N and 55 mg m^{-3} of total P in the surface layers and 6322 mg m^{-3} of total N and 830 mg m^{-3} of total P in the bottom layers) (Ott et al., 2005). During winter the lake is covered with ice for 5 months. Lake Verevi is elongated in the north–south direction and can be divided into two parts: the deeper and wider southern part and the narrow northern part (Fig. 1b). The study area in the narrow northern part (Fig. 1c) is shallow (up to 2 m) with flat bottom morphology and is protected from the wave action as well as inputs from the catchments by a dense macrophyte cover.

Macrovegetation in Lake Verevi was monitored in 1957, during 1984–1988, and from 1998 to 2003 (Mäemets & Freiberg, 2005). According to these studies, macrophytes occupied 35–50% of the lake's area between 1957 and 2003. In

1957 macrophyte assemblages in the northern part of the lake were characterized by dominance of charophytes and presence of *Ranunculus circinatus* Sibth., *Utricularia vulgaris* L., *Elodea canadensis* Michx., *Potamogeton praelongus* Wulfen, and *Myriophyllum verticillatum* L. Among the floating-leaved plants *Nuphar lutea* (L.) Sm. was dominating at that time (Mäemets, 1991). During the last few decades significant changes have occurred in the composition of the submerged species. A detailed map of the macrophyte cover from 1988 (Mäemets, 1991) shows that in the northern part of Lake Verevi charophytes were replaced by *Ceratophyllum demersum* L. in the 1980s. Some Characeae were still present together with *Utricularia vulgaris* and *Potamogeton praelongus*. The occurrence of *Nuphar lutea* and *Potamogeton natans* L. had increased.

Our study area (Fig. 1c) was situated in the zone where *Ceratophyllum demersum*, *Ranunculus circinatus*, and *Potamogeton friesii* Rupr. were dominant in 2001 (Mäemets & Freiberg, 2005). During fieldwork in 2006 and 2007 patchiness of aquatic vegetation was observed, and also *Nuphar lutea* and *Chara* spp. were growing in the study area.

The ecological status of the lake was close to natural (moderately eutrophic) from the 1920s until the end of the 1950s. The first swimming pool was built in 1929, but it is calculated that the impact of swimmers on the nutrient loading is negligible (1.5% of P and 0.6% of N out of annual loading) (Ott et al., 2005). During the 1970s and 1990s, the lake was contaminated by irregular discharge of urban wastewaters and it became hypertrophic. In 1978 oxidation ponds were constructed west of the lake, beside the inflow from where sewage water flowed into the lake a number of times during the flood periods in springs. Oxidation ponds were isolated in 2002 (Ott et al., 2005). In the summer of 1998, the water table was lowered 0.7 m in order to clean the lake floor in the swimming area. During the summer months of 1998 the shallow northern end of the lake and the whole transition zone between the emergent and the submerged vegetation were denuded. After the restoration of the water level in the summer of 1999, the submerged plants reached the depth of 2.0 m and in 2000, 2.5 m (Mäemets & Freiberg, 2005).

METHODS

Sampling

The sediments were studied in the northern shallow part of the lake (Fig. 1c) in two neighbouring areas (at a distance of about 20 m) with various aquatic vegetation. The water depth of all sites varied from 1.9 to 2.0 m and the distances between the single cores within different sampling areas were about 1–2 m. Sediment cores V1 and V3 (area I, Fig. 1c) were retrieved in October 2006 and cores V4 and V5 (area II, Fig. 1c) in August 2007 using a modified Livingstone–Vallentyne piston corer (Vallentyne, 1955). The sediment cores were immediately sectioned into 2-cm slices in the field, and stored in polyethylene boxes in a refrigerator at +5 °C prior to analysis. The characteristic data of sediment cores are given in Table 1.

Table 1. Main data on the studied cores and sediment accumulation values

Characteristic	Core V1	Core V3	Core V4	Core V5
Coring date	20.10.2006	20.10.2006	27.08.2007	27.08.2007
Core length, cm (No. of samples)	24 (12)	26 (13)	64 (32)	62 (31)
^{210}Pb age of bottom layers, AD	–	–	1900	–
Mean linear accumulation rate, mm yr^{-1}	2.5	2.7	5.6	6.2
Mean dry matter mass accumulation rate, mg cm^{-2} yr^{-1}	18	20	46	54
Performed analysis	**Core V1**	**Core V3**	**Core V4**	**Core V5**
^{210}Pb			+	
Lithology	+	+	+	+
Macrofossils		+		+
C, N		+		+
Grain size		+		+

Analysis

Lithological, macrofossil, grain-size, elemental (C, N), and ^{210}Pb analyses of the samples were performed. As the water content of the sediment was high and the volume of single samples was limited, analyses were made from different cores (Table 1).

The lithological characteristics of the samples were measured using standard approaches (Boyle, 2001; Heiri et al., 2001). To determine the mass of dry matter (DM), the samples were dried to constant weight at 105 °C. The total organic matter content was measured by loss-on-ignition at 550 °C (LOI_{550}) and expressed as percentages of DM. The content of carbonates (in the form of $CaCO_3$) was calculated from the loss after burning the LOI_{550} residue at 950 °C for 150 min.

Sediment particle size was determined by wet sieving using four metallic woven mesh sieves in a Vibratory Sieve Shaker ‘Analysette 3’ PRO. Particle size was determined from the amount of the sediment that remained on each sieve partitioning of the fractions >0.25 mm, 0.25–0.1 mm, 0.1–0.036 mm, and <0.036 mm. For each fraction the standard LOI method was applied in order to get the amount of organic, siliciclastic, and carbonaceous components.

For macrofossil analyses (sample volume 70 cm^3) the residues on a sieve of mesh aperture 0.25 mm were dispersed in water, and macroscopic remains were picked and counted under stereomicroscope.

The radiometric dating of core V4 was performed using the ^{210}Pb method by direct gamma assay with an EG&G Ortec HPGe GWL series well-type coaxial low background germanium detector (Appleby et al., 1986). The upper 59 cm of core V4 was dated, and the age–depth curve was calculated using the CIC model (Table 2). Mass accumulation rates of organic, siliciclastic, and carbonaceous matter were calculated for all four cores based on the age–depth curves and LOI data.

Table 2. ^{210}Pb data, age of analysed layers, and sedimentation rate for core V4

Depth, cm	^{210}Pb, Bq/kg	Date, AD	Age, yrs	SE, yrs	Sedimentation rate	
					mg cm^{-2} yr^{-1}	cm yr^{-1}
0.0	210.0	2007	0		0.0	
1.0	201.1	2006	1	1	54.1	0.67
7.0	185.0	1997	10	6	54.1	0.55
11.0	139.8	1989	18	6	54.1	0.44
15.0	107.6	1981	26	5	57.3	0.49
21.0	59.1	1969	38	7	44.6	0.43
27.0	62.9	1956	51	6	37.4	0.40
33.0	24.3	1944	63	10	46.9	0.54
39.0	15.9	1934	73	16	40.2	0.51
45.0	21.5	1923	84	11	43.9	0.62
51.0	11.1	1910	97	16	43.9	0.79
59.0	6.1	1895	112	22	43.9	0.86

The contents of total organic carbon (TOC) and nitrogen were measured in HCl pre-treated samples in the University of Tartu with a Perkin-Elmer 2400 Series II CHNS/O Elemental Analyzer and calculated as percentages of DM. The origin of organic matter in sediments was traced by C/N ratio values. The share of planktonic matter in the organic matter was estimated by using a simple equation for the mixing of the two components (Punning & Tõugu, 2000), considering that the C/N values in planktonic matter (algae) are approximately 6 and 20 or higher in aquatic macrophytes (Ho & Meyers, 1994; Meyers, 1994).

RESULTS

Lithology and chronology

The sediments in all the studied cores consisted of dark-brown unconsolidated, highly porous, homogeneous gyttja. Changes in the water content were similar in all four cores (Fig. 2a) and all cores had characteristic maximal and minimal peaks. As Menounos (1997) showed, the water content of lake sediments provides informative data for environmental reconstruction and is valuable information for correlating individual cores from a lake. By using the ^{210}Pb data (Table 2) from the reference core (V4, Fig. 2a), age–depth curves could be compiled for all cores. Deepest sediment layers were dated to approximately AD 1900. Also changes in the $CaCO_3$ and organic matter content (Fig. 2c), which coincided well with the changes in the water content, were taken into account for the compilation of age–depth curves, adding reliability to the compiled curves (Fig. 2b). As the sediment records for cores V1 and V3 lacked identifiable peaks in the deepest end, we cannot be absolutely confident about the last correlations dating these sediments back to 1910. Therefore in Fig. 2a these correlations are marked with question marks. Temporal correlation between cores and sites is also confirmed by similar changes in the accumulation rates of *Chara* spp. oospores (Fig. 2d).

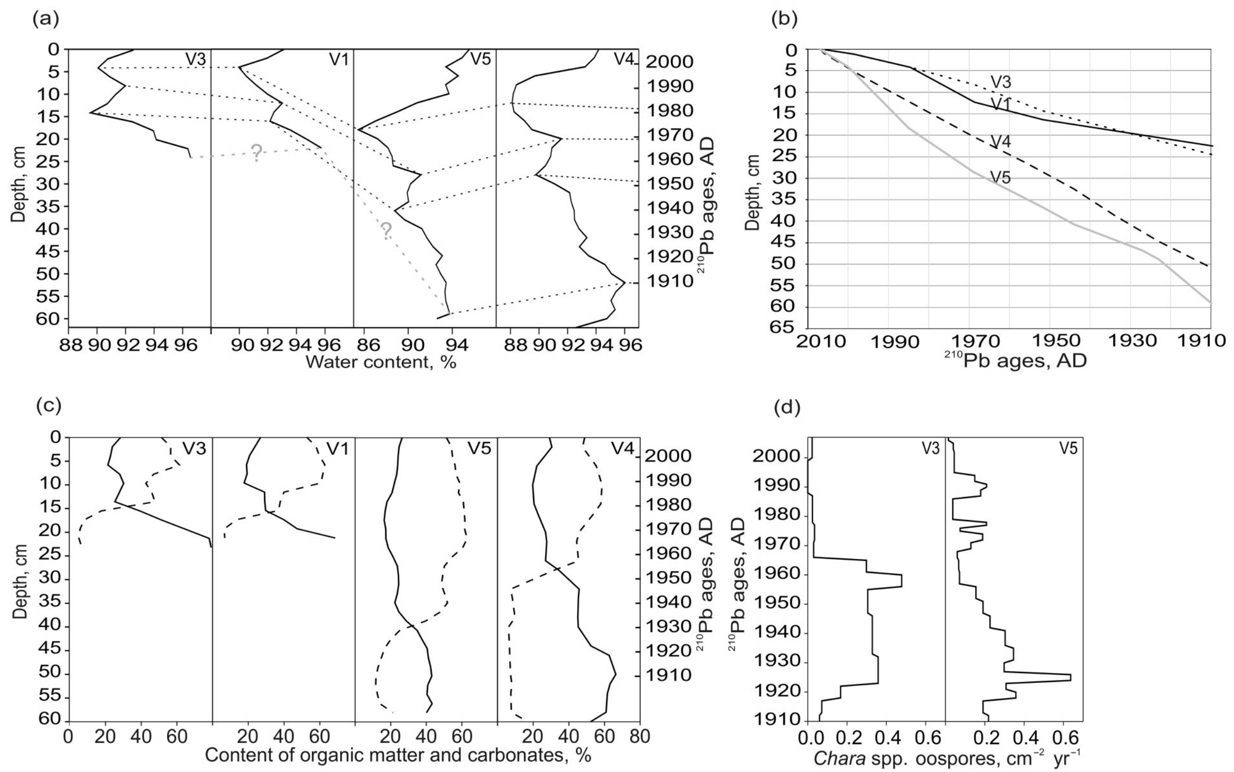

Fig. 2. Water content records for cores V1, V3, V4, and V5 (a). Core V4 was dated by ^{210}Pb (date on the right scale); cross-correlation on the basis of water content records is provided. Age–depth scales (b) showing the linearity in the accumulation and essential differences in the accumulation rates in area I (cores V1, V3) and area II (cores V4, V5). Organic matter content (solid line) and carbonate content (dashed line) (c) were taken into account in the age–depth correlations between cores. Correlations were also supported by accumulation rates of *Chara* spp. oospores (d).

Mass accumulation rates

It was possible to follow temporal changes in the lithological composition of all cores on the basis of the obtained age–depth scales. The variation of the MAR of total organic matter, siliciclastic matter, and carbonates showed different patterns in the different study areas (Fig. 3), and was much lower for all components in cores V1 and V3 (area I) compared to cores V4 and V5 (area II). In 1910–2007 the average MAR varied in the two areas from 5 to 15 mg cm^{-2} yr^{-1} for organic matter, from 8 to 25 mg cm^{-2} yr^{-1} for carbonates, and from 5 to 15 mg cm^{-2} yr^{-1} for siliciclastic matter. The average MAR values of total dry matter for the period 1910–2007 varied from 18 (area I) to 54 (area II) mg cm^{-2} yr^{-1} (Table 1).

Although average MARs have quite different values in areas I and II, major changes in the MARs of different components show some similarities. Four periods, characterized by different conditions in the sedimentation environment, can be distinguished in the sequestration of total organic matter and siliciclastic matter in Lake Verevi since 1910 (Fig. 3a, b). The first period (from 1910 up to the 1920s) is characterized by high MARs of organic matter in all four cores (always lower in area I) and low MARs of siliciclastic matter (except core V5). From the 1920s to the 1950s the MAR of organic matter dropped and stayed low in all cores except core V4, where the MAR did not drop until the 1940s. The MARs of siliciclastic matter stayed stable in cores V1 and V3 (area I), but increased

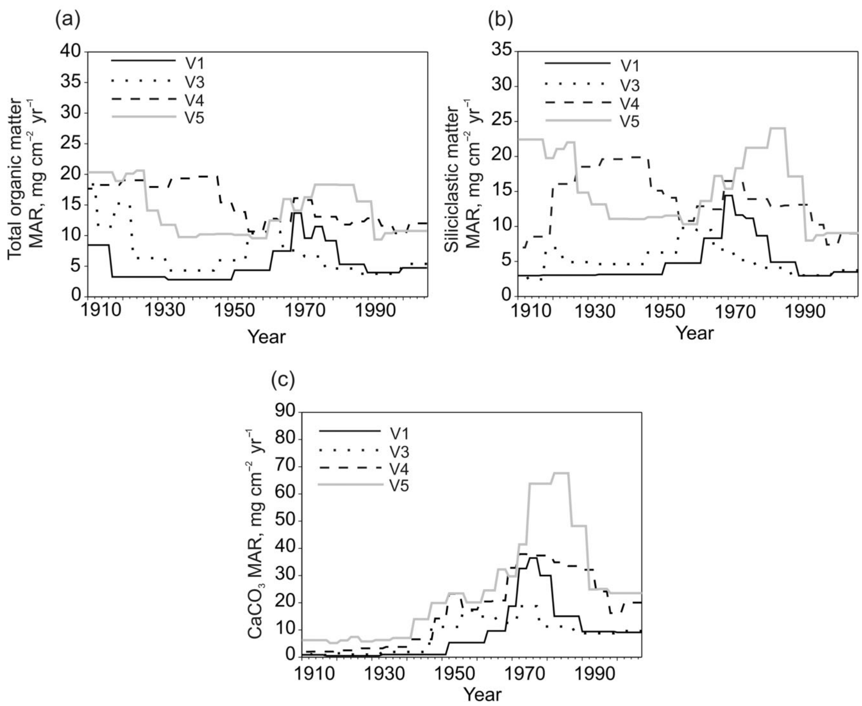

Fig. 3. Dynamics of mass accumulation rates (mg cm^{-2} yr^{-1}) of total organic matter (a), siliciclastic matter (b), and $CaCO_3$ (c) in four sediment cores.

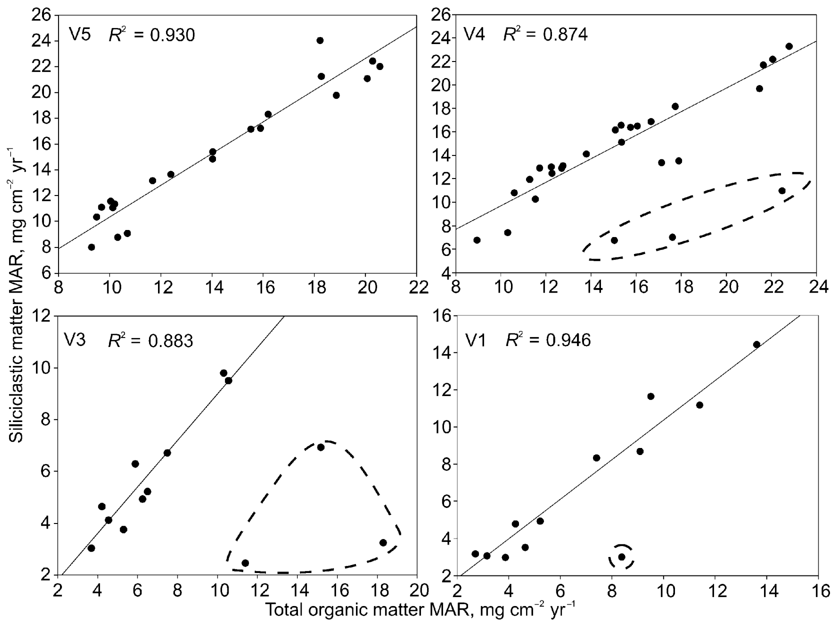

Fig. 4. Accumulation rates of organic and siliciclastic matter in all four cores. Trendlines and correlations for cores V1, V3, and V4 were calculated excluding data points before the 1920s (surrounded with dashed lines).

in core V4 and dropped in core V5 (area II). The third period (started from the 1950s) is characterized by an increase in the MARs of organic and siliciclastic matter in all four cores, followed by a period of a slight decrease in the MAR of both components. Changes in the last two periods have some time gap between the two areas, starting earlier in area I. Similarities in the changes of the MARs of organic and siliciclastic matter are expressed by extremely high correlation values in all four cores (Fig. 4). In core V5 high correlations exist throughout the core, starting already from 1910, but in cores V1, V3, and V4 high correlations start from somewhere in the 1920s, as at the beginning of the 20th century there are some high MAR values of organic matter not followed by siliciclastic matter.

The variations in carbonate MARs show the greatest lithological changes among the studied cores of Lake Verevi and can be separated into three major periods (Fig. 3c). The mean $CaCO_3$ MAR during the first period (from 1910 to 1940) was stable and low, being below 10 mg cm^{-2} yr^{-1} in all cores. From the 1940s the MARs of $CaCO_3$ started to increase in all cores, reaching their highest values during 1970–1980 (maximum 67 mg cm^{-2} yr^{-1} in core V5) and decreasing later on.

Lithology of different size fractions

The distribution of dry matter by size fractions was as follows: 51% of the total dry matter was in the < 0.036 mm fraction, 39% in the 0.036 mm fraction, 8% in the 0.1 mm fraction, and only 2% in the 0.25 mm fraction (Table 3). Organic

Table 3. Mass accumulation rates of organic, siliciclastic, carbonaceous, and total dry matter in four size fractions during 1910–2007, and their percental differentiation

	Size fraction, mm				Total
	0.25	0.1	0.036	<0.036	
Organic matter, mg cm^{-2}	32	144	508	426	1110
% of total	2.9	13.0	45.8	38.4	
Siliciclastic matter, mg cm^{-2}	11	95	451	620	1178
% of total	1.0	8.1	38.3	52.7	
$CaCO_3$, mg cm^{-2}	41	93	635	1045	1814
% of total	2.3	5.1	35.0	57.6	
Total dry matter, mg cm^{-2}	85	332	1594	2091	4102
% of total	2.1	8.1	38.9	51.0	

matter was mainly (84%) associated with the 0.036 mm and smaller than 0.036 mm fractions, and the rest was associated with the coarser fractions (0.25 mm and 0.1 mm). Also siliciclastic matter and carbonates belonged predominantly to two finer fractions (93% of the carbonates and 91% of the siliciclastic matter).

Carbon/nitrogen ratio

The C/N values varied in different size fractions from 8 to 14 (Fig. 5). The values were higher (10–14) during 1910–1920 in all size fractions and decreased later on, stabilizing somewhere between the 1960s and the 1970s (values from 8 to 11).

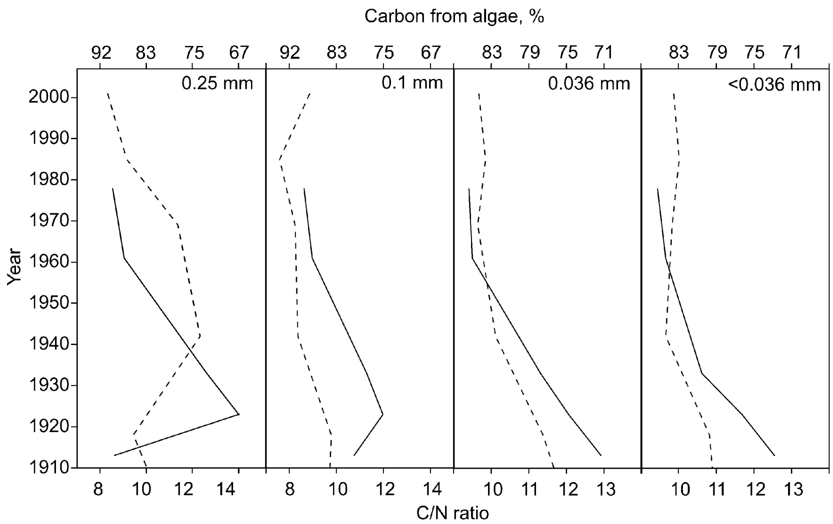

Fig. 5. Records of the C/N ratios for cores V3 (solid lines) and V5 (dashed lines). The lower scales show the C/N values and the upper scales the percentage of carbon from algae calculated as described by Punning & Tõugu (2000).

During the earlier period the ratios were always highest in core V3 (area I) and had similar values after the 1960s. The overall changes were similar in all three finer fractions of both cores, only the 0.25 mm fraction acted differently.

The C/N values suggest that the main source of organic matter in the studied cores was algae, especially in the sediments accumulated after the 1960s. The proportion of organic matter from decomposed aquatic macrophytes was low, reaching 25% in sediments accumulated in both study areas in 1910–1950 and 15% in sediments accumulated since the 1950s (Fig. 5).

Macrofossils

Sediment cores V5 and V3 were poor both in the number of species and the amount of macrofossils. Only oospores of *Chara* spp. were found in rather large numbers in both cores, being most abundant between the 1920s and the 1950s (Fig. 2d). In core V5 fragments of *Nymphaea alba* L. appeared from the 1970s, but the species was absent throughout core V3. The finding of *Najas* spp. seeds in core V3 is noteworthy as this species is never mentioned in the macrophyte mappings. *Najas* spp. seeds were most abundant between 1920 and 1930, with up to 11 seeds in one sample.

DISCUSSION

Sedimentation of organic matter

The low number of macrofossils and small amount of organic matter in the 0.25 mm size fraction (Table 3) show that a very small amount of the abundant macrophytes had reached the sediment and most of them had decomposed in the ‘standing dead’ state (cf. Kuehn et al., 1999), indicating fast decomposition processes. Also the C/N ratio supports this, as the bulk of the organic matter in the sediment originates from algae while the share of higher plants is low (Fig. 5). We may also presume that allochthonous organic matter is almost absent due to the sheltered nature of the study area and that most of the organic matter in the sediments of Lake Verevi comes from aquatic macrophytes and algae.

Although the origin of organic matter in sediments is known, the mechanism behind the sedimentation and preservation processes of organic matter is unclear. Most extraordinary finding is the extremely high correlations between the accumulation of organic and siliciclastic matter in all four cores (Fig. 4). A possible explanation is that the organic matter in the water column reaches the sediment mainly with settling siliciclastic matter by forming conglomerates. It is well known that fine-grained suspended particles have tendencies of repackaging into large aggregate particles called flocs (Van Rijn, 1993; Roberts et al., 1998; Kim et al., 2005). During this process, most of the particulate organic matter as well as various micro- and macrocomponents will be closely associated with suspended mineral particles. As the decomposition processes in this shallow area of the lake are quick and profound, organic matter originating from algae need not reach the sediment on its own and decomposes in the water column.

The amount of preserved organic matter has not always been related to the amount of siliciclastic matter. For example, at the beginning of the 20th century high accumulation of organic matter (Fig. 3a) was not followed by a large amount of siliciclastic matter (Fig. 3b). The same period is characterized also by rather high C/N ratios, which means that a larger part of carbon originated from aquatic plants (Fig. 5). High correlation between organic and siliciclastic matter dates from around the 1920s, temporally exceeding historically recorded human-induced eutrophication processes. Although an increase in the trophic status is usually followed by an increase in the accumulation of organic matter (Vreca & Muri, 2006; Xue et al., 2007), in Lake Verevi it is not so. The accumulation of organic matter was high already at the beginning of the 20th century and although there has been an increase in the trophic status, no extremely high rates in the accumulation of organic matter were recorded. In most cores MARs increase from the 1960s to 1990 (Fig. 3a), but they also coincide with the accumulation of siliciclastic matter (Fig. 3b), and decrease after 1980–1990 even though there is no record of changes in the trophic status during the last decades and the lake is still hypertrophic. Therefore the changes in the accumulation of organic matter were not directly triggered by changes in the trophic status and primary production but depended rather on the amount of settling siliciclastic matter.

Also differences in the MARs of organic matter between the two adjacent sites can be explained by the amount of settling siliciclastic matter. However, the reason for differences in the MARs of siliciclastic matter between the two sites is not so clear. One explanation for this could be the changes in macrovegetation, for it is widely accepted that water movement affects sediment dynamics in and around submersed macrophyte beds (Madsen et al., 2001), maximal values of suspended matter sedimentation can be found near the edge of macrophyte stands (Horppila & Nurminen, 2001), and that sediment composition, MAR, aquatic macrophyte productivity, and species composition are closely related (Barko et al., 1991). Although major changes in the vegetation and sedimentation dynamics (Fig. 3) in Lake Verevi coincide quite well, these presumptions are yet preliminary as we only have data from two sites and therefore further studies are needed to test this hypothesis.

Changes in trophic status

The results from our analyses reveal that there were some major changes in the sedimentation regime as well as in the ecological status of Lake Verevi during the last 100 years. Most of these changes can be linked to the rise in the lake's trophic status.

The increase in the share of carbon from algae (Fig. 5) is in a reasonably good temporal correlation with the historically recorded increase in the trophic status (Ott et al., 2005). The connection between the increasing trophic status and low

C/N ratios in shallow lakes is widely known (Ekdahl et al., 2004; Vreca & Muri, 2006; Xue et al., 2007). Also our earlier results of systematic studies of surface sediments of many Estonian lakes (Punning et al., 2004, 2005) show that the mean values of C/N ratios in sediments depend on the trophic status of the lake, increasing from eutrophic (about 10–11) to dystrophic (more than 20). Based on the sedimentary records, the share of algae started to increase already before historically recorded human-induced eutrophication processes, as C/N ratios started to decline already in the 1930s and reached minimal values in the 1960s (Fig. 5). The reason for this could be natural eutrophication before intense anthropogenic influence, as the lake was described as moderately eutrophic already in the 1930s (Mäemets & Freiberg, 2005). One driver for natural eutrophication can be the change in the climate as the rise in annual temperatures can also increase the primary production and internal phosphorus loading (Moser et al., 2002).

Changes in the trophic status are preserved in the sediments of Lake Verevi also as $CaCO_3$ records. Lake Verevi has always been a hard-water lake, but the rise in the pH due to the eutrophication processes may have triggered the $CaCO_3$ precipitation (Dean, 1999). However, this mechasim is not always that simple, for there is a drop in carbonate MARs after the 1980s, but there are no records of any decline in the trophic status and primary production. An explanation for this could be that even though primary production has been high, there have also been high decomposition rates, for organic matter has not managed to settle due to the lack of settling siliciclastic matter (both MARs dropped from the 1970s to the 1980s; Fig. 3). As the decomposition of organic matter causes anoxic conditions and therefore dissolubility of carbonates (Dean, 1999), we can assume that even if the carbonates were formed during vegetation seasons, they were quickly dissolved due to the unfavourable conditions that followed. Similarly to the C/N ratio, the increase in the precipitation of carbonates precedes the historically recorded human-induced changes in the trophic status starting already in the 1930s. Still, precipitation of carbonates reached the highest values in the 1970s when strong human impact on the lake started.

The accumulation rates of *Chara* spp. oospores (Fig. 2d) indicate that also major changes in the vegetation cover may have occurred earlier than recorded in macrophyte mappings. Oospore counts start to decline already in the 1960s, preceding historically recorded changes and anthropogenic eutrophication almost by two decades. The reason for these differences can possibly be the gap in the macrophyte monitoring during that period. It must be also considered that to some extent the differences may be due to the standard error (±7 years) in ^{210}Pb datings.

CONCLUSIONS

The obtained data from Lake Verevi show that in the studied sheltered littoral area, where the sediment profiles consist of authigenic carbonates, siliciclastic suspended matter from the open area of the lake, and autochthonous organic matter, the sedimentation rates differ up to two times between adjacent sites in a relatively flat-bottomed area. Most of the total organic matter (75–85%) in the sediments consists of decomposition products of algae, and the degradation of abundant macrophytes in the shallow well-oxygenated littoral is quick and complete. Impacts of human-induced eutrophication processes are not preserved in the sediments as well as expected and do not quite well coincide temporally with palaeodata. Precipitation of $CaCO_3$ and an increase in the share of carbon from algae started in the 1930s and can be related to natural eutrophication processes. Also major changes in the macrovegetation (replacement of Charophytes with *Ceratophyllum demersum*) started earlier than historically monitored and cannot be directly linked to the human-induced rapid eutrophication, which started in the 1970s. Mass accumulation rates of organic matter do not increase substantially with eutrophication processes but are instead strongly related to the MAR of siliciclastic matter as shown by the extremely high correlations. It seems that organic matter in the water column reaches the sediment mostly with settling siliciclastic matter by forming conglomerates.

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REFERENCES

Appleby, P. G., Nolan, P. J., Gifford, D. W., Godfrey, M. J., Oldfield, F., Anderson, N. J. & Battarbee, R. W. 1986. ^{210}Pb dating by low background gamma counting. *Hydrobiologia*, **141**, 21–27.

Barko, J. W., Gunnison, D. & Carpenter, S. R. 1991. Sediment interactions with submersed macrophyte growth and community dynamics. *Aquat. Bot.*, **41**, 41–65.

Boyle, J. F. 2001. Inorganic geochemical methods in paleolimnology. In *Tracking Environmental Change Using Lake Sediments. Vol. 2. Physical and Geochemical Methods* (Last, W. M. & Smol, J. P., eds), pp. 83–142. Kluwer Academic Publishers, Dordrecht.

Davidson, T. A., Sayer, C. D., Bennion, H., David, C., Rose, N. & Wade, M. P. 2005. A 250 year comparison of historical, macrofossil and pollen records of aquatic plants in a shallow lake. *Freshwater Biol.*, **50**, 1671–1684.

Dean, W. E. 1999. The carbon cycle and biogeochemical dynamics in lake sediments. *J. Paleolimnol.*, **21**, 375–393.

Ekdahl, E. J., Teranes, J. L., Guilderson, T. P., Turton, C. L., McAndrews, J. H., Wittkop, C. A. & Stoermer, E. F. 2004. Prehistorical record of cultural eutrophication from Crawford Lake, Canada. *Geology*, **32**, 745–748.

Gaillard, M.-J. & Digerfeldt, G. 1991. Palaeohydrological studies and their contribution to palaeoecological and palaeoclimatic reconstructions. *Ecol. Bull.*, **41**, 275–282.

Hannon, G. E. & Gaillard, M.-J. 1997. The plant macrofossil record of past lake-level changes. *J. Paleolimnol.*, **18**, 15–28.

Heiri, O., Lotter, A. F. & Lemcke, M.-J. 2001. Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results. *J. Paleolimnol.*, **25**, 101–110.

Ho, E. S. & Meyers, P. A. 1994. Variability of early diagenesis in lake sediments: evidence from the sedimentary geolipid record in an isolated tarn. *Chem. Geol.*, **112**, 309–324.

Horppila, J. & Nurminen, L. 2001. The effect of an emergent macrophyte (*Typha angustifolia*) on sediment resuspension in a shallow north temperate lake. *Freshwater Biol.*, **48**, 1447–1455.

Kim, J.-W., Furukawa, Y., Dong, H. & Newell, S. 2005. The effect of microbial Fe(III) reduction on smectite flocculation. *Clays Clay. Miner.*, **53**, 572–579.

Kuehn, K. A., Gessner, M., Wetzel, R. & Suberkropp, K. 1999. Decomposition and CO_2 evolution from standing litter of the emergent macrophyte *Erianthus giganteus*. *Microb. Ecol.*, **38**, 50–57.

Last, W. M. & Smol, J. P. (eds). 2001. *Tracking Environmental Change Using Lake Sediments. Volume 2: Physical and Geochemical Methods*. Kluwer Academic Publishers, Dordrecht.

Madsen, J. D., Chambers, P. A., James, W. F., Koch, E. W. & Westlake, D. F. 2001. The interactions between water movement, sediment dynamics and submersed macrophytes. *Hydrobiologia*, **444**, 71–84.

Mäemets, A. 1991. Suurtaimestik. In *Verevi järve seisund. Hüdrobioloogilised Uurimused 17* (Timm, H., ed.), pp 95–109. Estonian Academy of Sciences, Institute of Zoology and Botany, Tartu.

Mäemets, H. & Freiberg, L. 2005. Long- and short-term changes of the macrophyte vegetation in strongly stratified hypertrophic Lake Verevi. *Hydrobiologia*, **547**, 175–184.

Menounos, B. 1997. The water content of lake sediments and its relationship to other physical parameters: an alpine case study. *Holocene*, **7**, 207–212.

Meyers, P. A. 1994. Preservation of elemental and isotopic source identification of sedimentary organic matter. *Chem. Geol.*, **114**, 289–302.

Meyers, P. A. 2006. An overview of sediment organic matter records of human eutrophication in the Laurentian Great Lakes region. *Water Air Soil Pollut. Focus*, **6**, 453–463.

Moser, K. A., Smol, J. P., MacDonald, G. M. & Larsen, C. P. S. 2002. 19th century eutrophication of a remote boreal lake: a consequence of climate warming? *J. Paleolimnol.*, **28**, 269–281.

Ott, I., Kõiv, T., Nõges, P., Kisand, A., Järvalt, A. & Kirt, E. 2005. General description of partly meromictic hypertrophic Lake Verevi, its ecological status, changes during the past eight decades, and restoration problems. *Hydrobiologia*, **547**, 1–20.

Punning, J.-M. & Tõugu, K. 2000. C/N ratio and fossil pigments in sediments of some Estonian lakes: an evidence of human impact and Holocene environmental change. *Environ. Monit. Assess.*, **64**, 549–567.

Punning, J.-M., Koff, T., Sakson, M. & Terasmaa, J. 2004. Human impact on the ecosystem of Lake Ruusmäe (Southern Estonia) traced in its sediments. *Pol. J. Ecol.*, **52**, 285–299.

Punning, J.-M., Koff, T., Kadastik, E. & Mikomägi, A. 2005. Holocene lake level fluctuations recorded in the sediment composition of Lake Juusa, southeastern Estonia. *J. Paleolimnol.*, **34**, 377–390.

Roberts, J., Jepsen, R., Gotthard, D. & Lick, W. 1998. Effects of particle size and bulk density on erosion of quartz particles. *J. Hydraul. Eng.-ASCE*, **124**, 1261–1267.

Vallentyne, J. R. 1955. A modification of the Livingstone piston sampler for lake deposits. *Ecology*, **36**, 139–141.

Van Rijn, L. 1993. *Principles of Sediment Transport in Rivers, Estuaries, and Coastal Seas*. Aqua, Amsterdam.

Vreca, P. & Muri, G. 2006. Changes in accumulation of organic matter and stable carbon and nitrogen isotopes in sediments of two Slovenian mountain lakes (Lake Ledvica and Lake Planina), induced by eutrophication changes. *Limnol. Oceanogr.*, **51**, 781–790.

Xue, B., Yao, S. & Xia, W. 2007. Environmental changes in Lake Taihu during the past century as recorded in sediment cores. *Hydrobiologia*, **581**, 117–123.

Inimtegevusest tulenevad muutused settimisprotsessides Verevi järve litoraalses osas

Egert Vandel ja Tiiu Koff

Eelmise sajandi 1970. aastatel tugeva inimmõju all olnud Verevi järve põhjapoolsest litoraalsest osast võeti neli setteläbilõiget. Setteproovidest määrati litoloogiline koostis ja süsiniku ning lämmastiku suhe ja tehti sette fraktsioon- ning makrojäänuste analüüs. Setteläbilõike vanuse saamiseks kasutati ^{210}Pb-meetodit. Settes leiduv orgaaniline aine pärineb valdavalt (75–85%) vetikatest ja selle akumulatsioon on tugevalt seotud mineraalse aine akumulatsiooniga ($R^2 > 0,8$). Setteläbilõigete litoloogias on sarnased muutused, kuid lähestikku asuvate (vahemaa 20 m) punktide sette akumulatsiooni kiirustes esineb kuni kahekordne erinevus. Analüüside tulemused näitasid, et muutused settimisprotsessides on alanud varem kui ajalooliselt kirjeldatud inimmõju järvele. Karbonaatide sadenemine ja süsiniku ning lämmastiku suhte langus algas juba 1930. aastatel ja on tingitud looduslikust toitelisuse tõusust järves. Samuti on muutused suurtaimestikus alanud varem kui seireandmetes kirjeldatud.