ABSTRACT: A comprehensive study of the sediment profile of L. Viitna Linajärv, a small closed drainage lake located in northern Estonia (59°27´N, 25°01´E), was conducted to assess the impact of water-level changes on the carbon accumulation dynamics in the lake during the Holocene. The variations of the P content, C/N ratio, fossil pigments and diatom communities indicate essential changes in the lake ecosystem history during the Holocene. The results show that on millennial time-scale (10³ years) fluctuations of the lake level, concurrent shore erosion and coprecipitation of dissolved organic matter with allochthonous mineral particles were the driving factors in the lake history. Net organic carbon accumulation was ~30 g m⁻² yr⁻¹ at the beginning of the Holocene (ca 9000 BP), then decreased to 10 g m⁻² yr⁻¹ (5000–2000 BP) and increased in the upper layers (since 1000 BP) up to 60 g m⁻² yr⁻¹.

KEY WORDS: lake-level changes, carbon accumulation, fossil diatoms, sediment lithology, lake eutrophication, Estonia

1. INTRODUCTION

During the past few decades, increasing attention has been paid to the response of ecosystems to climate change (Mann et al. 1998, Battarbee et al. 2001). Short-term manipulative experiments and modelling have shown that there are many closely related regional and local factors that can significantly affect each other and so mitigate or accelerate effects of the primary climate impulses (Leavitt 1993, Hassan et al. 1997, Lami et al. 2000). Numerous studies show that anthropogenic and natural factors including water-table changes, eolian activity (Virkkanen 2000), as well as forest fires (Punning et al. 1997) can cause rapid changes in the sediment composition and rate of organic carbon accumulation. The fluctuations of water level alter the lake morphology and change the in-lake location of the sedimentation zones (erosion, transportation, accumulation; Håkansson 1977) thereby directly influencing sedimentation rate and resuspension.

Currently, there is tremendous scientific interest in compiling the budget of the global biological carbon cycle (Lincoln 2005). It has been demonstrated that lake ecosystems appear to have an important role in this process (Einsle et al. 2001). Dean and Gorham (1998) estimated global carbon sequestration by lakes on average between 5 g C m⁻² yr⁻¹ (large lakes) and 72 g C m⁻² yr⁻¹ (small lakes), which is...
about half of the carbon sequestrated by peatlands.

This study was performed on Lake Viitna Linajärv (hereafter Lake Linajärv), which has been earlier thoroughly studied for reconstruction of lake-level changes (Punning et al. 2003). The maximum levels and highest amplitudes of lake-level fluctuations were reached in the first half of the Holocene. So the water depth of the lake may have reached 8 m 9500–9000 BP and up to 9 m 8000 BP. Then the level stabilised and the water depth decreased continuously along with the filling of the lake basin with sediments. Some visible small-scale water lowering events occurred around 7400 BP and 5300 BP. The water depth in the lake was lowest (2–3 m) about 1000 BP and since that time has slightly increased.

The importance of the water depth, basin slopes and distance to the shore for lithology of sediments was demonstrated by the statistical treatment of the mineral and organic matter concentration data from surface sediment cores within the lake, and their comprehensive analysis (Punning et al. 2004). A strong correlation between particulate organic and mineral matter in sediment fluxes indicates flocculent settling of the mineral particles (Terasmaa and Punning 2006).

According to the results of pollen analysis (Punning et al. 2003) birch forest dominated at the beginning of the lacustrine sedimentation (ca 9600 BP). Around 9200 BP, elm and alder found favourable conditions for growth in the vicinity of the lake. From 8000 BP expansion and dominance of mixed deciduous forests began, showing a continuous warming in climatic conditions. Around 5000 BP, spruce invaded and at first there existed mixed forest of spruce and broad-leaved trees. In further forest development spruce began to supplant the other tree species. The decrease of broad-leaved forest accelerated during the onset of climate deterioration and the associated increase in soil leaching and degradation. From 3000 BP pine forest started to dominate. The first strong evidence of permanent cultivation activities was found around 1000 BP when the pollen of rye appeared in the pollen diagram (Punning et al. 2003).

In this paper we present a diatom record for Lake Linajärv and integrate it with lithological and paleobotanical data about the lake-level fluctuations. The aim of the research was to find out how the variability and changes in the lake level, concurrent shore erosion and lake trophic status are linked to the changes in the sedimentation regime and cycling of carbon in the lake.

2. STUDY AREA, MATERIAL AND METHODS

Lake Linajärv, situated in northern Estonia (59°27’ N, 26°00’ E) (Fig. 1a), is a closed-drainage seepage lake with a small
catchment underlain by lacustrine- and fluvial-glacial deposits. On the poor sandy soils of the watershed *Pinus sylvestris* L. dominates with other species, such as *Picea abies* (L.) H. Karst and *Betula pendula* Roth in moister places. Steep-sloped eskers surround the lake from west and south. On the east a terraced fluvioglacial plain borders the lake and in the north is a small paludified area. Lake Linajärv is a dimictic, eutrophic lake with an area of 3.8 ha elongated from north to south; its mean depth is 1.8 m and maximum depth, near the southern shore, is 4.8 m (Fig. 1b, c). Limnological studies showed a marked increase in the chlorophyll *a* (*Chl a*) concentration in the water during the last years (up to 45 μg l⁻¹); total phosphorus concentration varied from 30 to 40 μg l⁻¹ and Secchi depth from 0.5 to 3.0 m during the stratification period (usually from May up to September) (Punning and Leeben 2003).

Sediment coring in Lake Linajärv was performed from the ice. The core was taken from the deepest part of the lake (core Li1) (Fig. 1c). Due to the unconsolidated nature of sediments a modified Livingstone-Valentyne piston corer was used to obtain an up to 60 cm long upper sediment core, and a freeze corer was applied to take a 110 cm long surface sediment core. The short core was divided into 1 cm sections in the field and packed in PVC boxes. The frozen core was sliced into sub-samples in the laboratory. The lower part of sediments from 170 cm down to the mineral bottom at a depth of 960 cm was sampled with a Russian type peat sampler. The lithology of the core was recorded in the field. The long sediment core was divided into 50 cm long surface sediment core. The short core was divided into 1 cm sections in the field and packed in PVC boxes. The frozen core was sliced into sub-samples in the laboratory. The lower part of sediments from 170 cm down to the mineral bottom at a depth of 960 cm was sampled with a Russian type peat sampler. The lithology of the core was recorded in the field. The long sediment core was divided into 50 cm long pieces, wrapped in plastic and stored in cold and dark. The subsampling of long cores was made in the laboratory prior to analysis.

All cores were analysed for lithological characteristics (water, organic, mineral matter and carbonate content) using standard methods (Dean 1999). Total carbon (TC) and nitrogen (TN) were measured at Tallinn University of Technology with an Elementar AnalyserSystem GmbH VarioEL and calculated as percentages of dry matter (DM). The content of organic carbon (OC) was calculated as the difference between TC and inorganic carbon as described by Dean (1999). Considering that the C/N ratio is approximately 6 in planktonic matter and above 30 as estimated by us in plants growing in the littoral zone or transported into the lake from the catchment, the simple formula for the estimation of the share of planktonic matter in the sediments derived by Punning and Tõugu (2000) was used. The content of chlorophyll derived pigments (CD) was measured spectrophotometrically using the methods described by Bengtsson and Enell (1986). Pigment concentrations were expressed as spectrophotometric units per gram of organic matter, one unit being equivalent to an absorbency of 0.1 in a 1 cm quartz cuvette. The phosphorus (TP) content of the sediment samples was determined in 0.5 M HCl digestion of the combusted (550°C) sample following the scheme of Hieltjes and Lijklema (1980).

The core was dated by terrestrial plant remains using the accelerator mass spectrometry (AMS) method at the Ångström Laboratory, Uppsala University (Sweden). The annual carbon and mineral matter accumulation rate was calculated on the basis of the obtained time-scale and the records of the dry matter and carbon content.


For pollen analysis, samples were boiled in 10% KOH and treated with the standard method of acetylsis (Moore and Webb 1978). In general, at least 500 arboreal pollen (AP) grains were identified and counted under the microscope. Pollen percentages were calculated using the sum of terrestrial pollen grains (sum of AP and non-arboreal pollen (NAP)). The frequencies of Polypodiaceae and *Sphagnum* spores were presented as a percentage of terrestrial pollen and Pteridophyta and Bryophyta spore sum. The pollen diagrams were made using the TILIA software (Grimm 1990).
3. RESULTS

3.1. Diatoms

The fossil diatom record in core Li1 (Fig. 1c) shows three major zones (Fig. 2), which coincides well with the lithology of the core. So below the depth of 500 cm there are consolidated dark brown gyttja with minerogenic interlayers. Upwards (up to 300 cm) follows dark compact gyttja and then very soft and unconsolidated brown detritus gyttja.

Taxa characteristic of planktonic forms of oligotrophic diatom assemblages, such as Cyclotella radiosa (Grun) Lemmerman and C. ocellata Pantocsek, are prevailing in Zone I (from basal layers up to the depth of 489 cm). Planktonic species characteristic of mesotrophic and eutrophic waters, such as Asterionella formosa Hasall, Stephanodiscus astraea (Ehrenberg) Grun. and Synedra acus Kütz., occur at moderate frequencies.

In the interval 490–179 cm, in Zone II (Fig. 2) the frequency of diatom valves in the sediment sequence was variable. The preservation of fossil diatom remains was poor, many valves were badly eroded and diatom abundance was low due to diatom dissolution. All the specimens contained mostly broken central areas and ends of valves that belong to the littoral benthic species Pinnularia viridis (Nitzsch) Ehr. and Stauroneis anceps Ehr. occurring in low frequencies. The planktonic diatoms were absent and epiphytic forms Achnanthes minutissima Kütz. and Gomphonema parvulum (Kütz.) Grun. occurred in low numbers.

The dominant taxa are benthic and epiphytic (Pinnularia viridis, Achnanthes minutissima, Fragilaria construens (Her.) Grun) in Zone III, which starts from 178 cm (Fig. 2). The uppermost part of the sediment sequence (accumulated during the last centuries) shows an expansion of the planktonic species Tabellaria flocculosa (Roth.) Kütz., Synedra acus and the epiphytic species Achnanthes minutissima, Fragilaria construens, Gomphonema parvulum and Nitzschia spp. Most of these live in eutrophic waters and/or

Fig. 2. Relative frequencies (%) of dominant diatom species and summary graph of planktonic, benthic and epiphytic forms of diatoms.
are associated with substrate, e.g. sands, stony deposits or aquatic macrophytes (Håkansson and Regnell 1993, Håkansson et al. 1998).

3.2. Pollen

In the pollen diagram (Fig. 3) the NAP is present in low numbers with low species richness. A slight increase in NAP (mainly Poaceae and Artemisia) in the basal layers of the core (940–920 cm) was connected with tundra-like open vegetation (Kof f and Kangur 2003) at that time. Another increase in NAP was detected in the sediment layers accumulated during the last millennium.

The spores of Polypodiaceae are present in higher percentages on the diagram between the depths 650 and 450 cm (approximately 8000–4000 BP). In the composition of NAP noticeable changes appear in the amount of Ericaceae and Calluna pollen (Fig. 3). The increase in Sphagnum spores began at a depth of 230 cm (800 BP) and is most probably connected with the paludification of the northern lakeshore and the formation of the Sphagnum peat layer there (Punning et al. 2003).

3.3. Lithology and sedimentation

The concentration of chlorophyll derivatives (CD) per gram of organic matter has its maximum values (up to 40 μg) in layers from 420 cm to 200 cm (4000–800 BP) (Fig. 4). The TP concentration is highest (4–6 mg g⁻¹ DM) in mineral rich sediments from basal layers up to the depth of about 550 cm, decreasing upwards (in gyttja) on average 1–2 mg g⁻¹. The carbonates are represented only in the deeper layers (from 800 cm to 560 cm) where their concentration reaches 5%.

The organic carbon concentration in core Li1 varies largely, being 10% in basal layers and reaching up to 40% in gyttja (from the depth of 520 cm) accumulated ca 6000 BP and even 48% in layers accumulated ca 2000 BP (Fig. 4). The OC/N ratio has the

![Graph](image)

Fig. 3. Pollen diagram of selected taxa from core Li1 (See Fig. 1). The frequency of Polypodiaceae and Sphagnum spores was presented as a percentage of terrestrial pollen and Pteridophyta and Bryophyta spore sum.
lowest values (highest proportion of primary produced organic matter in the lake) in the layers accumulated about 7800 BP (640 cm) and during the past 400–500 years (Fig. 4). Annual accumulation of organic carbon and allochthonous mineral matter is highest in basal layers reaching respectively 20–30 and 100 g m\(^{-2}\) yr\(^{-1}\) at the beginning of lake sediment accumulation (9000–8000 BP) (Fig. 5a). Upwards the accumulation rate decreases continuously and reaches its lowest values (ca 10 g m\(^{-2}\) yr\(^{-1}\)) at a depth of 320 cm (ca 2000 BP). Then an increase with sharp fluctuations follows, with maximum accumulation values (up to 60 g m\(^{-2}\) yr\(^{-1}\)) reached at a depth of 120 cm (400 BP). Carbon accu-
Holocene pattern of organic carbon accumulation in a lake

The rise in the OC at a depth of 640 cm (formed 7800 BP), where the OC/N ratio was the lowest (11.8; Fig. 4), confirms a rise in the rate of primary production in the lake. This agrees with pollen data, where an increase of *Tilia*, *Corylus* and *Quercus* suggests an expansion and dominance of mixed deciduous forest from 8000 BP onwards and shows a continuous warming in climate (Fig. 3). Eutrophication was also significantly accelerated by the erosional input of phosphorus in the course of loading from the catchment during the transgression. The decomposed peat layers in the peat section in the northernmost tip of the lake (see Fig. 1c, profile AB), dated at 7400 BP (Punning et al. 2003), suggest a lower lake level with a possible water column depth of 6–7 m. Also the increase of benthic diatom taxa and poor preservation of their frustules refer to shallow basin sedimentation. The increase of spores of Polypondiaceae (Fig. 3) supports the assumption of the regression of the lake level, which created suitable habitats for ferns. Since that time the intensity of the rate of mineral matter accumulation has decreased (Fig. 5). The decrease of phosphorus concentration in sediments and the slight increase of fossil pigment content as well as the disappearance of carbonates indicate that the hypolimnion (in any case the near-bottom area) became permanently anoxic (Fig. 4).

From a depth of 490 cm upward a sharp decrease in the diatom abundance and preservation occurs (Fig. 2). This was probably connected with the decreasing water depth, which was accompanied by substantial increases in the sedimentary pigment and organic C content (Fig. 4). During the water-level fluctuations erosion of organic rich sediments from the littoral zone and their sedimentation to the profundal area took place. This interval (ca 4000 BP to 1000 BP) is characterised on the diatom diagram mainly by the benthic diatom taxa *Pinnularia viridis* and *Stauroneis anceps*. The decrease of the water depth was accompanied by substantial increases in the sedimentary pigment and organic C content.

The upper 300 cm of sediments consists of colloidal homogeneous detritus gyttja, whose water content is over 95%.

4. DISCUSSION

The obtained data about the diatom distribution are consistent with our earlier conclusion (Punning et al. 2003) that Lake Linajärv has undergone major changes in level and trophic status during the Holocene. The following discussion considers how the variability and changes in the lake level, concurrent with shore erosion and trophic status are linked to the variability and changes in the cycling of carbon in the lake.

During the initial stages of the lacustrine sedimentation 10000–9000 BP intensive erosion from the slopes covered by sparse vegetation (Punning et al. 2003) took place. The lake was largely fed by groundwater, as shown by the presence of Fe and Mn hydroxides (coloured interlayers) and carbonates in the sediments. The lamination and presence of Fe and Mn in sediments indicates that seasonally the lake had oxic conditions and retention of inorganic P from sediments was hindered (Shapiro et al. 1971, Engstrom et al. 1985). Diatom assemblages in these sediments consisted mainly of planktonic species, speaking about a relatively deep water (Fig. 3). Using the approach of Lotter (1988) on Lake Rotsee (Switzerland) for the interpretation of the diatom data, we assumed that 9500 BP the depth of the water column in Lake Linajärv might have been up to 9 m. This is in good accordance with our earlier calculations (Punning et al. 2003). Already by 8500 BP an eutrophic diatom flora (*Synedra acus, Asterionella formosa*) dominated in the lake (Fig. 2). The sporadic presence of *Achnanthes minutissima, Gomphonema parvulum* and *Nitzschia* spp. refers also to eutrophic waters, and their increase might also be associated with the expansion of aquatic macrophytes (Håkansson and Regnell 1993, Håkansson et al. 1998).

The curve of the mineral matter influx (Fig. 5) has two periods of relatively high influx—in the Early Holocene (9000–7500 BP) and the Late Holocene (ca 1000–400 BP).

The rise in the OC at a depth of 640 cm (formed 7800 BP), where the OC/N ratio was the lowest (11.8; Fig. 4), confirms a rise in the rate of primary production in the lake. This agrees with pollen data, where an increase of *Tilia*, *Corylus* and *Quercus* suggests an expansion and dominance of mixed deciduous forest from 8000 BP onwards and shows a continuous warming in climate (Fig. 3). Eutrophication was also significantly accelerated by the erosional input of phosphorus in the course of loading from the catchment during the transgression. The decomposed peat layers in the peat section in the northernmost tip of the lake (see Fig. 1c, profile AB), dated at 7400 BP (Punning et al. 2003), suggest a lower lake level with a possible water column depth of 6–7 m. Also the increase of benthic diatom taxa and poor preservation of their frustules refer to shallow basin sedimentation. The increase of spores of Polypondiaceae (Fig. 3) supports the assumption of the regression of the lake level, which created suitable habitats for ferns. Since that time the intensity of the rate of mineral matter accumulation has decreased (Fig. 5). The decrease of phosphorus concentration in sediments and the slight increase of fossil pigment content as well as the disappearance of carbonates indicate that the hypolimnion (in any case the near-bottom area) became permanently anoxic (Fig. 4).

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The upper 300 cm of sediments consists of colloidal homogeneous detritus gyttja, whose water content is over 95%.
At a depth of 210–225 cm well-preserved interlayers of moss (Warnstorfa fluitans (Hedw.) Loeske) remains are found. Beginning from this depth upwards a sharp increase in the influx of mineral matter began accompanied by increasing organic matter influx reaching values up to 60 mg m\(^2\) yr\(^{-1}\) (Fig. 5a). The higher sedimentation rate and oxygen shortage led to an increase in fossil CD in sediments in layers accumulated 2000–1000 BP (Fig. 4). All data show that a sharp decrease of water level took place and the mineral matter came mainly from lake sediments accumulated earlier during high water levels. High values of the OC/N ratio (Fig. 4) indicate a relatively high proportion of non-planktonic carbon, which originates mainly from allochthonous organic matter and redeposited sediments eroded in the near-shore area. Scarcity and bad preservation of diatom frustules are evidence of heavy erosion. Also the content of herbaceous pollen increases, indicating both an opening in the forest cover and increasing landscape diversity (Fig. 3).

The water depth in the lake stabilised ca 1000 BP. Since that time an expansion of the meso-eutrophic planktonic species Tabellaria flocculosa and epiphytic species, such as Achnanthes minutissima, Fragilaria construens, Gomphonema parvulum and Nitzschia spp. starts from a depth of 150 cm (Fig. 2). As our earlier studies (Punning et al. 2004) revealed, the historically documented water-level lowering caused an expansion of littoral vegetation, increased the share of organic matter in sediments and thus caused a decrease of the mineral/organic matter ratio. The regular monitoring conducted since 1970 shows that at least during the past decades Lake Linajärv has been eutrophic with a relatively high concentration of nutrients and low Secchi transparency (Punning and Leeben 2003).

Our multi-proxy data demonstrate that the depth of the water column, which is affected by prevailing hydro-climatic conditions, is an extremely important factor having an essential impact on the biogeochemical cycling in small lakes (area 2–6 ha). The variability and changes in the lake level and trophic status, which are linked to the variability and changes in the cycling of carbon in the lakes, plays an important role in the sink of greenhouse gases in sediments. The sediment record from Lake Linajärv shows that among all phenomena accompanying climate change and biogeochemical cycling, carbon accumulation seems to be especially sensitive to lake-level fluctuations. Earlier investigations (Battarbee 2000) demonstrated that the depth of the water column controls many chemical and biological processes, such as primary production, nutrient cycling rate, hypolimnetic O\(_2\) consumption and lake ecology. Battarbee et al. (2001) in their study of the sediments of remote Scottish mountain lakes prove that there are quasi-periodic cycles in organic matter accumulation. They conclude that these are caused by changes in the lake productivity driven by climate variability.

On the basis of the time-scale and the records of the carbon content it is possible to calculate total yearly carbon accumulation in sediments during the Holocene in Lake Linajärv (Fig. 5a). During the initial stage of the lake (9600–9000 BP) the concentration of carbon in the sediment was low (Fig. 4) but the high rate of sedimentation caused high accumulation of OC of mainly allochthonous origin. The influx of OC was up to 30 g m\(^{-2}\) yr\(^{-1}\). Using an equation derived earlier (Punning and Tõugu 2000), we found that the average share of carbon of planktonic origin in the total OC in Lake Linajärv sediments may have been up to 60%.

After 8000 BP, when significant changes occurred in the biogeochemical cycling in connection with an amelioration in climatic conditions and the surface area of the lake had increased, the influx of mineral matter decreased notably and the accumulation of OC stabilised by 8000–4500 BP at ca 20 g m\(^{-2}\) yr\(^{-1}\) (Fig. 5a). At least 70–80% of this amount is of planktonic origin as follows from the OC/N ratio. The minimum values of accumulated carbon (10 g m\(^{-2}\) yr\(^{-1}\)) occurred at a depth of 350 cm around 2600–2000 BP. Beginning from the depth of 220 cm the accumulation of organic carbon has increased, being up to 50–60 g m\(^{-2}\) yr\(^{-1}\) approximately 500 BP, and the share of organic compounds made up more than 80% of the total weight of sediment. The increase in the
mineral matter accumulation is a response to water level fluctuations, which caused extensive erosion and redeposition of sediments from shallower zones. The close link between the rates of organic and mineral matter accumulation might be explained by co-precipitation of sinking organic and mineral matter. A strong correlation between organic and mineral matter in the settling matter during the summer stratification indicates flocculent settling of mineral particles (Terasmaa and Punkka 2006). This explanation, though very preliminary, makes it possible to clarify the rapid fluctuations in the organic matter accumulation in Lake Linajärv during the last millennia. The colloidal consistency of the upper part (ca 250 cm) of sediments and high content of autochthonous organic matter in it might be explained by the increase of primary production and low water level in the lake. The increase of CD content in consequent sediment layers also speaks about changes in the intensity of primary production and degradation conditions of pigments before final burial.

5. CONCLUSIONS

The comprehensive paleoecological studies of Lake Linajärv sediment cores show that against the climate driven long-term trend in the development of the lake ecosystem, shorter-term processes occur that cause significant changes in the trophic status of the lake and the accumulation regime of organic and mineral matter. The obtained results showed that the fluctuations of the lake level and water depth were the leading factors determining the lithological composition of sediments and habitats of diatom assemblages in the lake. Fluctuating water level was also the most important factor controlling the development of the lake ecosystem at a medium (10^2–10^3 years) time-scale. The higher water levels of Lake Linajärv were accompanied by essential increases in the accumulation rates of mineral and allochthonous organic matter. Diatom assemblages of that time are characterised by dominance of planktonic taxa. In the course of the water-level stabilisation the share of benthic diatoms increased and the accumulation rates of mineral and organic matter (10 g m^{-2} yr^{-1}) had their minimum values. The uppermost part of the sediment sequence (accumulated during the last centuries) shows an expansion of the planktonic species characterising eutrophic waters. During this interval an essential increase of the accumulation rate of both mineral and organic (up to 60 mg m^{-2} yr^{-1}, mostly autochthonous) matter took place in Lake Linajärv.

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6. REFERENCES


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