

LATE HOLOCENE WATER-LEVEL CHANGES IN LAKE ISO LEHMÄLAMPI, SOUTHERN FINLAND, REFLECTED IN SUBFOSSIL CLADOCERANS AND CHIRONOMIDS¹

Liisa Nevalainen, Tomi P. Luoto, Kaarina Sarmaja-Korjonen

Department of Geology, P.O. Box 64, FIN-00014 University of Helsinki, Finland;
e-mail: liisa.nevalainen@helsinki.fi, tomi.luoto@helsinki.fi, kaarina.sarmaja-korjonen@helsinki.fi

Abstract

Analyses of subfossil cladocerans (Crustacea: Cladocera) and chironomids (Diptera: Chironomidae) were applied to examine water-level changes in a small and oligotrophic lake in southern Finland over the past 2000 years. Major changes in the invertebrate communities occurred ca. 400 AD onwards when the littoral cladoceran *Alonella nana* started to replace the planktonic *Eubosmina* as the dominant species and chironomids *Psectrocladius sordidellus* group and *Zalutschia zalutschicola* increased. These changes were most likely due to a decreasing water level and an enlarging proportion of the littoral area, providing suitable vegetative habitats, e.g. aquatic bryophytes (mosses), for these taxa. The lowering water level reached its minimum just before the Medieval Warm Period, ca. 800–1000 AD, after which the lake level rose again and remained high until modern times. A prominent change in the chironomid assemblages occurred during the 20th century when *Ablabesmyia monilis* and *Chironomus anthracinus* type increased, presumably due to changes in water chemistry, caused by anthropogenic load of pollutants.

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Key words: Chironomidae, Cladocera, climate, Finland, late Holocene, lake-level changes

INTRODUCTION

Development of climate has been one of the main topics lately in the Holocene research. In addition to temperatures, also effective moisture (precipitation – evapotranspiration) has varied during the Holocene and has been reflected in lake levels (Harrison, Digerfeldt 1993, Harrison *et al.* 1993, Guiot *et al.* 1993, Yu, Harrison 1995). Past lake-level fluctuations have been studied by e.g. detecting changes in sediment composition, as well as in micro- and macrofossil assemblages (Digerfeldt 1988, 1997, Almquist-Jacobson 1995, Barnekow 2000, Koff *et al.* 2005, Punning *et al.* 2005, Valpola, Salonen 2006).

Lake-level changes have been studied rather intensively using subfossil cladoceran remains. Alhonen (1970a, 1970b) suggested that the ratio of remains of planktonic/littoral cladocerans in sediments reflects the volume or the extent of the pelagic and littoral area (planktonic/littoral ratio, P/L). Hypothetically, when the water level is rising, the size and volume of the pelagic area increase and subsequently, the proportions of remains of planktonic cladocerans in sediments grow. When the water level is low, the pelagic water volume is smaller and the size of the littoral area is proportionally larger, as well as the proportion of littoral cladocerans. After Alhonen's pioneer work, many studies concerning long-term lake-level changes during the Holocene were performed in

southern and northern Finland (Alhonen 1972, Donner *et al.* 1978, Hyvärinen, Alhonen 1994, Sarmaja-Korjonen, Alhonen 1999, Sarmaja-Korjonen, Hyvärinen 1999, Sarmaja-Korjonen 2001), as well as elsewhere in Europe (Mikulski 1976, Bradbury, Whiteside 1980, Gaşiorowski, Hercman 2005). Recently, Korhola *et al.* (2000) developed a Cladocera – lake-depth transfer model to estimate quantitatively lake-level fluctuations in Finnish Lapland. The model was applied later with success (Korhola *et al.* 2005).

The P/L method has been criticized (Hofmann 1996, 1998) since many factors besides water-level changes may affect the proportions of planktonic and littoral cladocerans (Frey 1986a). The extent of the littoral area is controlled by light penetration and the morphometry of the basin. The former can be altered e.g. during a period of phytoplankton maxima, following a nutrient increase or higher predation of fish on invertebrate grazers and resulting in decreased light penetration caused by higher algal concentration. The littoral area may even become larger during rising of the water level if the new shore area is flat. According to Sarmaja-Korjonen (2001), the method is most reliable in small, limnologically stable and oligotrophic lakes where there have been no large changes in the food web that could have affected the composition of cladoceran communities. Gaşiorowski and Hercman (2005) suggested that the method worked best in shallow lakes.

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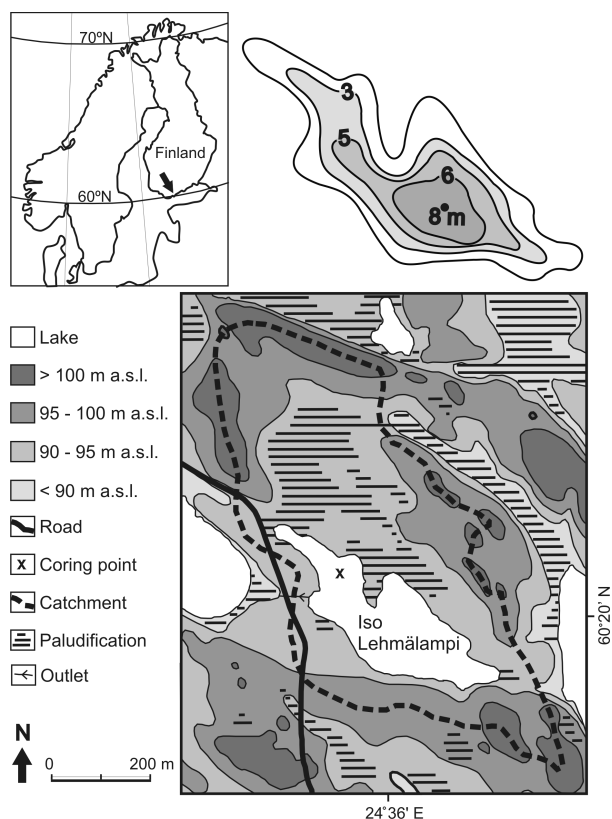


Fig. 1. Location, schematic bathymetry and catchment of Lake Iso Lehmälampi.

Also subfossil remains of larvae of non-biting midges, *i.e.* chironomids, provide information about past lake levels because chironomids live in the littoral and profundal zones of all lake types and according to Walker and MacDonald (1995), almost all of them have some preference for the water depth. Hofmann (1998) discussed that the size of littoral and planktonic communities change when the water level fluctuates. Korhola *et al.* (2000) showed, using multivariate methods, that the lake depth was the second most important factor explaining chironomid distribution in northern Finland, and developed a model for water-depth reconstruction.

Sarmaja-Korjonen and Alhonen (1999) and Sarmaja-Korjonen (2001) studied Lake Iso Lehmälampi with the cladoceran P/L method and found an evidence of lake-level changes during the Holocene. They also suggested that the small lake had been oligotrophic with stable limnological conditions. These studies, as well as almost all of the studies concerning lake-level changes in Finland, have focused on

long-term changes during the entire Holocene. Therefore, since Lake Iso Lehmälampi appears suitable for water-level studies, we aimed to distinguish short-term fluctuations during the late Holocene (0–2000 AD). To investigate these changes, we analysed a radiocarbon-dated short (24 cm) sediment core with 1 cm intervals using subfossil Cladocera and chironomids, together with loss-on-ignition (LOI) and statistical analysis (DCA).

STUDY SITE

Iso Lehmälampi (60°20' N, 24°36' E) is a small lake (5.1 ha) situated in southern Finland (Fig. 1). It lies in an upland area at an altitude of 91.7 m. The lake consists of two parts; the northwestern part is shallower (max. 5.4 m) and separated from the deeper (max. 8.1 m) southeastern part by a small peninsula (Fig. 1). The lake drains from the western shore and there are no inlets. Bedrock outcrops and mire patches characterize the ca. 30 ha catchment. The forest around the lake comprises mainly Scots pine (*Pinus sylvestris*), Norway spruce (*Picea abies*), and birch (*Betula* spp.). The shoreline is dominated by *Sphagnum* mosses and *Carex* spp. and the littoral zone by submerged *Nuphar lutea* and *Nymphaea* spp.

According to the diatom records, the lake has been acidic for most of the Holocene (Sarmaja-Korjonen, Alhonen 1999, Sarmaja-Korjonen 2001) but experienced a further acidification in the 1980s when pH dropped below 5.0 (Verta *et al.* 1990). The lake succeeded a chemical recovery process during the 1990s and during 2005 pH ranged between 5.1 and 5.8 (Tab. 1). During the severe acidification of the early 1980s, the lake became almost fishless. Afterwards, in the late 1980s and early 1990s, it experienced many fish introductions, including whitefish (*Coregonus lavaretus*), roach (*Rutilus rutilus*), and perch (*Perca fluviatilis*) (Kari Nyberg, pers. comm.) but only perch has succeeded and inhabits the lake today. The other basic limnological measurements of this oligotrophic lake (conductivity, oxygen, total phosphorous and total nitrogen) are shown in Tab. 1.

MATERIALS AND METHODS

Sediment and dating

A short sediment core was taken through the ice in February 2005 with a Limnos gravity corer. The water depth at the coring point was 4.12 m. The 24 cm sediment sequence consisted of fine detritus gyttja. The sediment was subsampled at 1 cm intervals in the field.

Only one terrestrial macrofossil (a piece of a tree) was found for dating and in addition to that, two bulk sediment

Table 1

Measured limnological variables of Lake Iso Lehmälampi

	pH	Conductivity $\mu\text{S cm}^{-1}$	Oxygen mg l^{-1}	Color Pt mg l^{-1}	TP $\mu\text{g l}^{-1}$	TN $\mu\text{g l}^{-1}$
Spring	5.3	14	8.4	20	< 10	343.4
Summer	5.1	17	8.9	30	25.4	381.6
Winter	5.8	20	18.1	40	10.3	456.8

Measurements for spring values were performed on 31.5.2005, for summer values on 15.8.2005, and for winter values on 16.12.2005

Table 2

Radiocarbon dates for Lake Iso Lehmälampi

Depth (cm)	Lab. no.	Dated material	Age BP	Age cal. BP	Year AD
13-14	Poz-18679	Piece of tree	930 ± 30	855 ± 46	1095
18-19	Poz-18680	Bulk	1530 ± 30	1438 ± 53	512
24-25	Poz-18681	Bulk	1910 ± 30	1861 ± 28	89

samples were dated at the Poznań Radiocarbon Laboratory, Poland, using AMS radiocarbon dating technique (Tab. 2). The dates were calibrated using the CalPal (The Cologne Radiocarbon Calibration & Paleoclimate Research Package) online calibration program (www.calpal.de). A second order polynomial function was fitted with the calibrated dates and a time-depth model was drawn based on the function (Fig. 2). The model was used in all the estimated ages presented in this study.

Cladocera

Volumetric sediment samples of 2 cm³, taken at 1 cm intervals, were prepared for subfossil Cladocera analysis using the method described in Szeroczyńska and Sarmaja-Korjonen (2007). The samples were heated and stirred in 10% KOH for 20 minutes in decanter glasses and sieved through a 44-µm mesh. The samples were then mounted in glycerine jelly stained with safranin. A minimum of 400 cladoceran remains (mostly headshields, shells, and postabdomens) were counted from each sample. The most common body part of each taxon was chosen to represent the number of individuals. The relative proportions for each taxon were calculated from the total sums of individuals of all taxa. The cladoceran nomenclature follows Røen (1995). *Chydorus sphaericus* was identified as *sensu lato (s.l.)* according to Frey (1986b). *Bosmina (Eubosmina)* is hereafter called *Eubosmina*.

Chironomids

Chironomid analysis was performed at 1 cm intervals. Subsamples of 0.3–0.6 g wet sediment were treated with 10% KOH and sieved through a 100-µm mesh. The sieved samples were transferred to a Petri dish and the chironomid head capsules were hand picked with fine forceps under a stereomicroscope (magnification 25x). The head capsules were mounted on microscope slides in Euparal. A minimum of 60 head capsules was counted from each sample which exceeded the minimum abundance criterion of 40–50 head capsules (Hofmann 1986, Heiri, Lotter 2001, Larocque 2001, Walker 2001). The head capsules were identified under a light microscope at 400 x magnification. The identification was based mainly on Wiederholm (1983). The key of Heiri *et al.* (2004) was used for the identification of the Tanytarsini, and the guide by Rieradevall and Brooks (2001) for the Tanytarsinae larvae.

Loss-on-ignition and data analyses

Loss-on-ignition (LOI) analysis was performed using wet sediment samples at 1 cm intervals to determine the or-

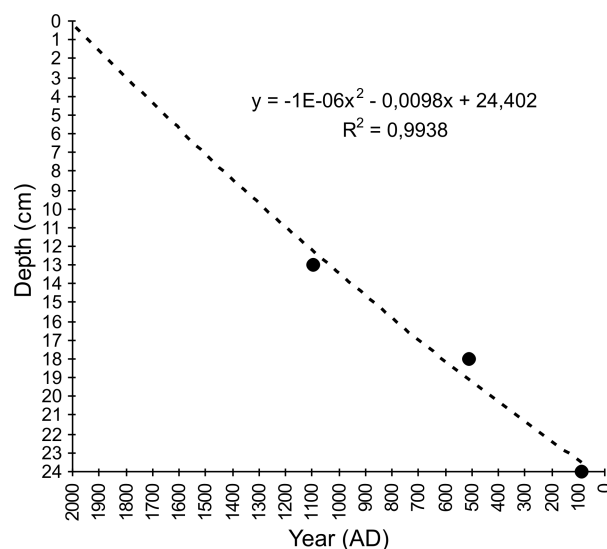


Fig. 2. Time-depth model for Lake Iso Lehmälampi

ganic content of the sediment. Approximately 10–12 g of wet sediment was dried at 105 °C for 12 hours and the dried sediment was ignited in an oven at 550 °C for 2 hours.

Detrended correspondence analysis (DCA) was used to identify variation in chironomid and Cladocera assemblages in the sediment sequence. DCA is a unimodal ordination method that summarizes variation in an ecological data set and shows relationships between samples in ordination diagrams, so that the longer the distance between sample scores, the more dissimilar the samples are. DCA, with detrending by segments, square-root-transformation of species, and down weighting of rare species, was performed with CANOCO program, version 4.52 (ter Braak 2003).

RESULTS

Cladocera

Relative proportions of the most common cladocerans through the sediment sequence are shown in Fig. 3. The cladoceran stratigraphy was divided into 5 local faunal zones (ILCLA1-5) using the programme ZONE version 1.2 (Juggins 1991). In the zone ILCLA1 (24–21.5 cm, *ca.* 100–300 AD), *Eubosmina* dominates (*ca.* 40%) and *Alonella nana*, *Alona affinis*, and *Alonella excisa* are the most common chydorids. *Eubosmina* decreases and *Alonella nana* increases markedly in the zone ILCLA2 (21.5–17.5 cm, *ca.* 300–600 AD). In the zone ILCLA3 (17.5–13.5 cm, *ca.* 600–1000 AD), *Eubosmina* is at its minimum (20%) and *Alonella nana* at its maximum (50%). *Alonella nana* starts to

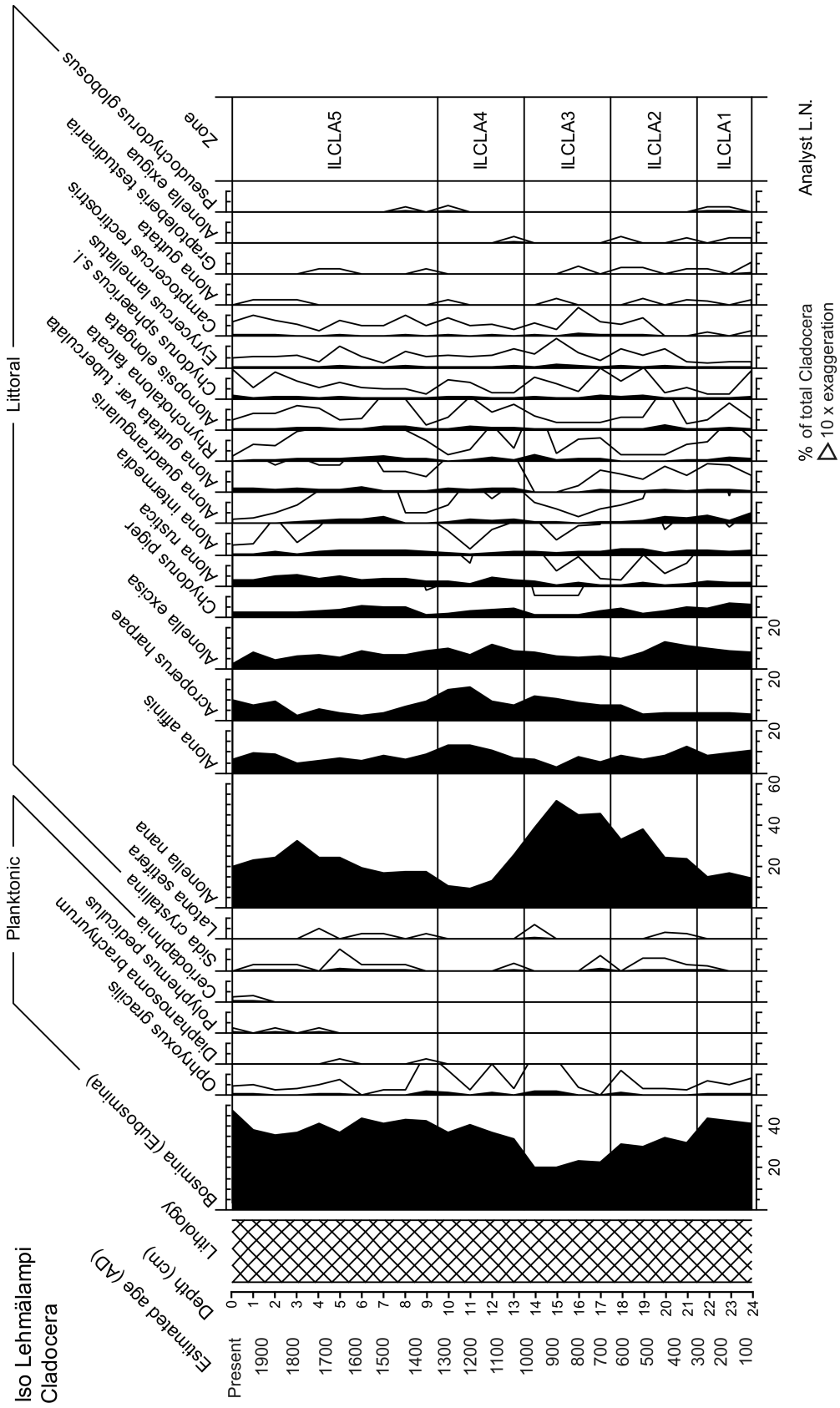


Fig. 3. Proportional abundance of cladocerans during the past 2000 years in Lake Iso Lehmälampi. The sediment is fine detritus gyttja.

decrease markedly in the top of the zone. *Eubosmina*, *Alona affinis* and *Acroperus harpae* increase in the zone ILCLA4 (13.5–9.5 cm, ca. 1000–1300 AD) and *Alonella nana* is at its minimum (ca. 10%). In the topmost zone ILCLA5 (9.5–0 cm, ca. 1300 AD–present), *Eubosmina* and *Alonella nana* are the most common taxa. *Alona affinis*, *Acroperus harpae*, *Alonella excisa*, *Chydorus piger*, and *Alona rustica* are constantly present at lower abundances. *Eubosmina* increases to almost 50% in the topmost sample.

Figure 4 presents the planktonic/littoral ratio of cladocerans in the lake. Planktonic taxa were abundant (ca. 40%) until 300 AD when they started to decrease. The proportion of littoral species increased from ca. 300 AD from ca. 60% to ca. 80%. The planktonic minimum and the corresponding littoral maximum occurred ca. 900–1000 AD, after which planktonic Cladocera increased and stayed at ca. 40%.

Chironomids

A total of 2128 chironomid head capsules were counted from the 25 samples and 34 different taxa were identified. Relative abundances of the most common chironomids are presented in Fig. 5. The stratigraphy was divided into 5 local faunal zones (ILCH1–5), which were identified by major changes in the chironomid assemblages using the programme ZONE version 1.2 (Juggins 1991).

The most common chironomids in the zone ILCH1 (24–20.5 cm, ca. 100–400 AD) are *Heterotanytarsus apicalis*, *Procladius*, *Dicrotendipes pulsus*, *Tanytarsus* undif., *Micropsectra* undif., *Cladotanytarsus mancus* group, and *Paratanytarsus penicillatus* type. Additionally, *Psectrocladius septentrionalis* group becomes frequent at 21 cm (13%). In the Zone ILCH2 (20.5–16.5 cm, ca. 400–800 AD), the most common chironomids are *Psectrocladius septentrionalis* group (9–23%), *P. sordidellus* group (14–18%), and *Tanytarsus* undif. (13–17%), while *Heterotanytarsus apicalis*, *Procladius*, *Micropsectra* undif., *Dicrotendipes pulsus*, *Cladotanytarsus mancus* group, and *Paratanytarsus penicillatus* type decrease. *Microtendipes pedellus* group becomes slightly more common and *Zalutschia zalutschicola* (11%) is abundant at the beginning of the zone. In the zone ILCH3 (16.5–8.5 cm, ca. 800–1400 AD), *Psectrocladius septentrionalis* group is still the most common taxon, varying between 9 and 30%. *Tanytarsus* undif. varies between 4 and 23%. *Ablabesmyia monilis* increase from 2–5% to 17% at 16 cm. *Psectrocladius sordidellus* group decreases in this zone. *Psectrocladius septentrionalis* group and *Tanytarsus* undif. are still the most common taxa in the zone ILCH4 (8.5–2.5 cm, ca. 1400–1800 AD). In the earlier part of the zone, *Procladius* increases markedly from 1 to 11%, and *Heterotanytarsus apicalis* increases in the mid zone up to 16–19%. *Procladius* and *Ablabesmyia monilis* decrease. *Tanytarsus* undif. (21–23%) and *Psectrocladius septentrionalis* group (13–18%) dominate the zone ILCH5 (2.5–0 cm, ca. 1800 AD–present). *Ablabesmyia monilis* increases sharply towards the topmost sample. *Chironomus anthracinus* type increases from 0 to 8% and *Paratanytarsus penicillatus* type and *Paratanytarsus austriacus* type disappear in the zone.

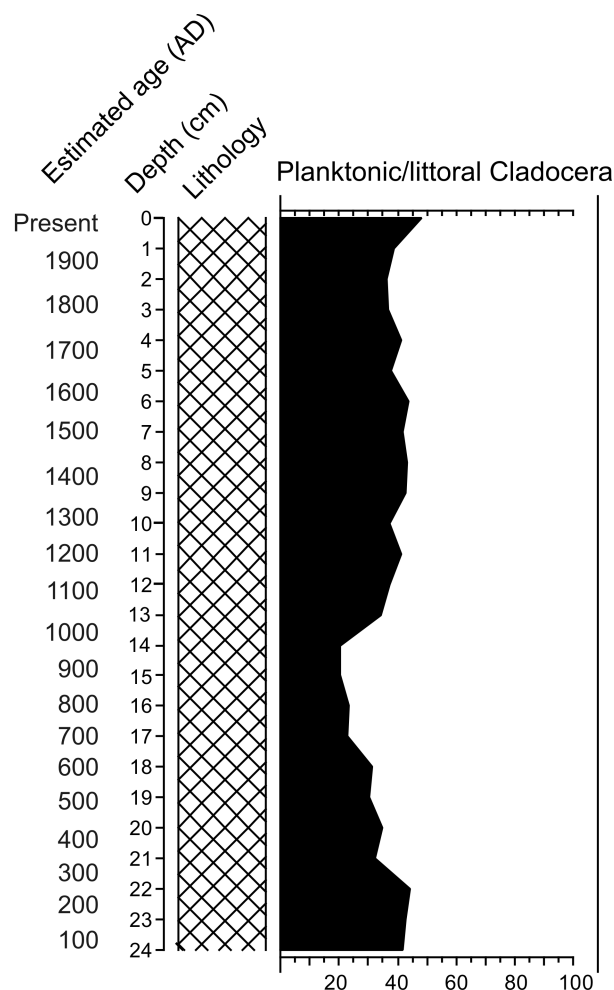


Fig. 4. Proportions of planktonic/littoral Cladocera in Lake Iso Lehmälampi. The sediment is fine detritus gyttja.

Loss-on-ignition and data analysis

Loss-on-ignition (LOI), *i.e.* the organic content of the sediment of Lake Iso Lehmälampi, varies between 63 and 74% (Figure 6). From 24 to 9 cm (ca. 100–1400 AD), LOI stays at a high value (70–74%) and starts to decrease steadily from 8 cm until 1 cm (20th century), where it reaches 63%. At 0 cm (present), LOI is 64.5%.

The scores in the DCA ordination diagram show clustering of the samples in both the cladocerans (Fig. 7A) and chironomids (Fig. 7B). In both diagrams, the oldest samples (24–21 cm, ca. 100–300 AD) and the youngest samples (2–0 cm, ca. 1800–2000 AD) have clearly separate scores from the other samples. In chironomids, the three topmost samples are in a separate cluster and have very low DCA axis 1 values. Intermediate samples (20–14 cm, ca. 400–1000 AD) are grouped more noticeably in cladocerans.

DISCUSSION

The time period between ca. 100 and 300 AD in Lake Iso Lehmälampi is characterized by cladocerans *Eubosmina*, *Alonella nana*, *Alona affinis*, and *Alonella excisa* (Fig. 3) which thrive in oligotrophic waters (Sandøy and Nilssen

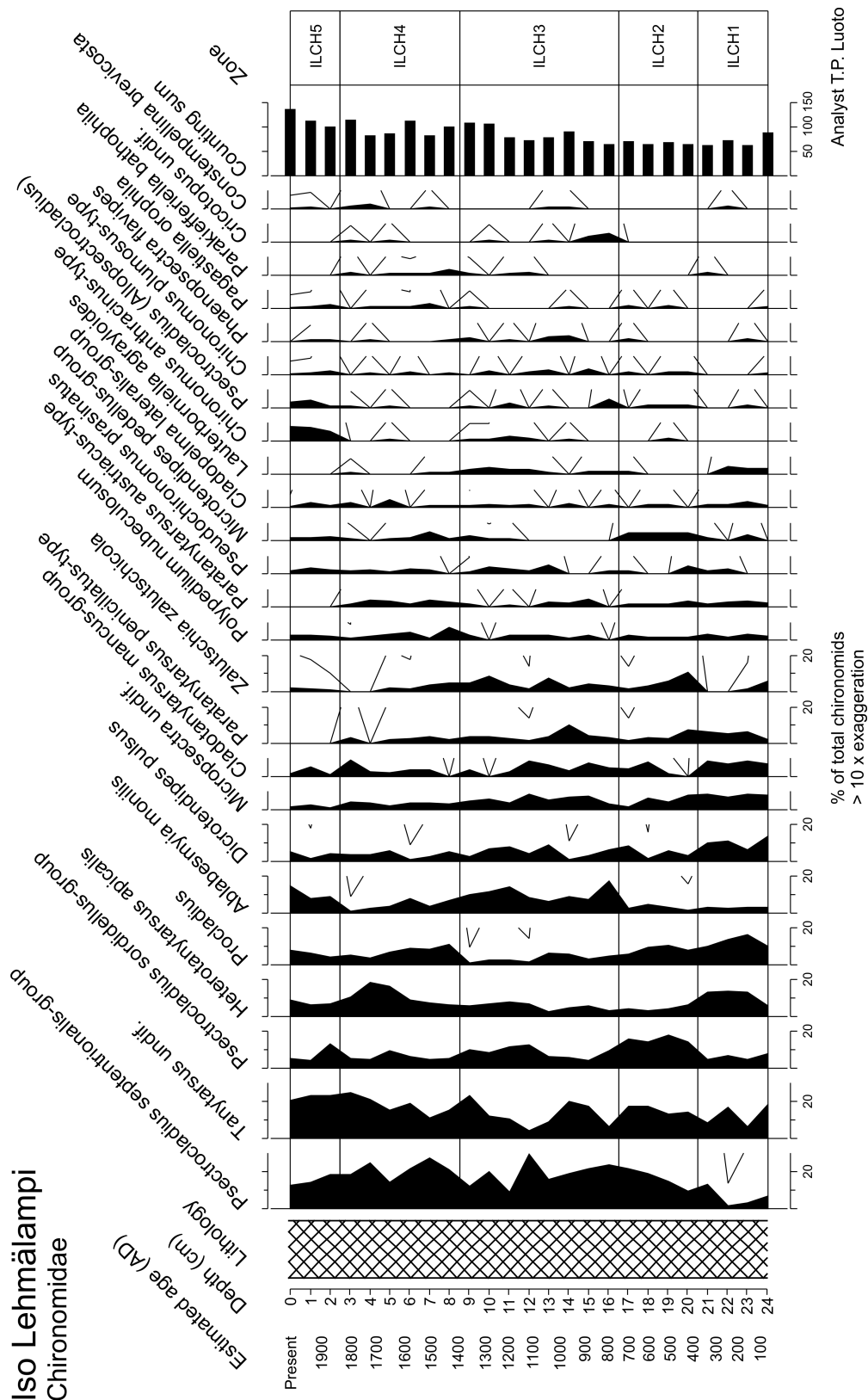


Fig. 5. Proportional abundance of the most common chironomids over the past 2000 years in Lake Iso Lehmälampi. The sediment is fine detritus gyttja.

1986, Uimonen-Simola and Tolonen 1987). The most common chironomids (Fig. 5) include acid-tolerant *Procladius*, *Dicrotendipes pulsus*, and *Heterotanytarsus apicalis* (Olander 1992, Ilyashuk and Ilyashuk 2004, Brooks 2006). These faunal assemblages imply that the lake was already then acidic and oligotrophic, which is indicated also by the fact that the very common but acid-sensitive planktonic cladoceran *Daphnia* was entirely missing.

These results are in accordance to Sarmaja-Korjonen (2001) who found in the diatom evidence that the pH of Lake Iso Lehmälampi had stayed very low during the Holocene, and suggested that the lake had been oligotrophic through its entire history. Lake Iso Lehmälampi is a typical naturally acidified lake since it is situated in a rocky and peaty upland and its small catchment (Fig. 1) is very poor in base elements and nutrients (cf. Korhola and Tikkanen 1991). In addition, the high proportion of planktonic Cladocera (Fig. 4) suggests that the lake basin had a relatively large pelagic area.

From ca. 400 AD onwards, some littoral chironomid taxa associated with aquatic macrophytes, such as *Psectrocladius septentrionalis* group and *Psectrocladius sordidellus* group (Brodersen *et al.* 2001, Tolonen *et al.* 2001), started to dominate the chironomid assemblages. Also *Zalutschia zalutschicola*, a chironomid typical in humic and oligotrophic lakes (Sæther 1976) and associated with peaty shorelines, increased around 400 AD (Fig. 5). Simultaneously around 400 AD, the proportion of the planktonic cladoceran taxon *Eubosmina* started to decrease while, the littoral species *Alonella nana* started to increase markedly (Fig. 3). According to Duigan and Kovach (1991) *Alonella nana* is associated with peat and moss habitats, and according to Korhola (1990), it is strictly associated with vegetation. These changes are visible in the changing sample scores in DCA for cladocerans and chironomids (Fig. 7). The sample scores representing the time from 400 AD onwards (samples <20 cm) locate in the middle of the ordination diagram, whereas the older samples (24–21 cm) have higher values for DCA axis 1.

During 700–1000 AD, *Alonella nana* increased to its maximum and the proportions of littoral cladocerans were at their highest, whereas the planktonic species decreased to a minimum and constituted only 20% of the community (Figs 3, 4). Simultaneously, in chironomids (Fig. 5), *Ablabesmyia monilis* increased noticeably. However, this species is considered to be eurytopic and cosmopolitan (Fittkau and Roback 1983) and unfortunately it is unclear to which environmental variables it responded.

According to Sarmaja-Korjonen and Alhonen (1999) and Sarmaja-Korjonen (2001), Lake Iso Lehmälampi experienced several short-term fluctuations in the water level during the late Holocene, 4000 BP onwards. Therefore, one major driving force for the faunal changes from 400 AD onwards may have been the water-level change and accordingly, the changes in the extent of the littoral area and macrophytes relative to the coring point. Since the increasing invertebrates, e.g. *Alonella nana* and *Zalutschia zalutschicola*, inhabit moss and peat habitats, it is possible that the lowering water level enlarged the area of aquatic bryophytes (mosses), characteristic to this lake also in the past (Sarmaja-Korjonen and Alhonen 1999). The slightly rising organic content of the sediment (Fig. 6) from 400 AD onwards may

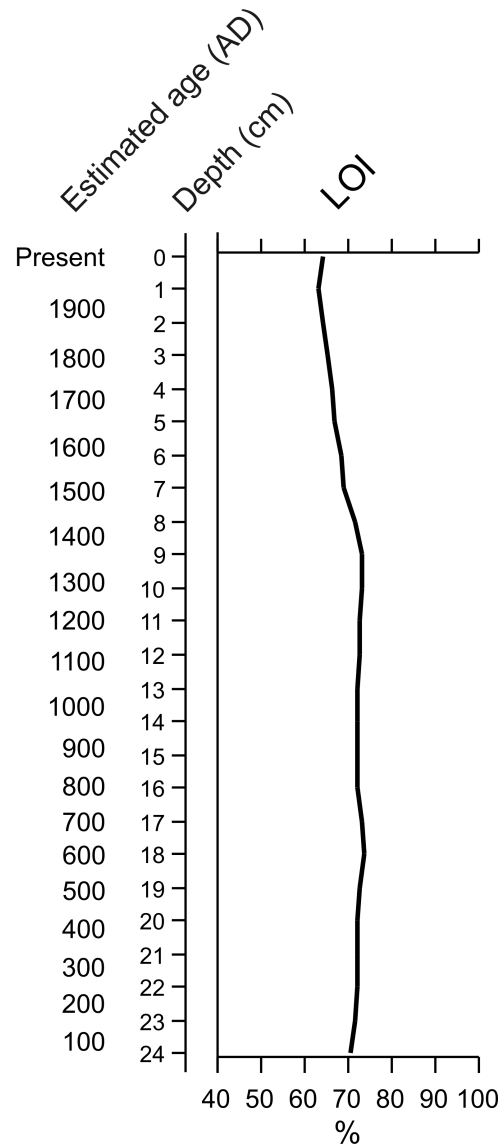


Fig. 6. Loss-on-ignition of the sediment of Lake Iso Lehmälampi. The sediment is fine detritus gyttja

also be a reflection of the increased proportion of the littoral zone. As the northeastern section of the lake is shallower than the southwestern one, lowering of the lake level could have considerably decreased the volume of the pelagic area (Fig. 1).

In the cladoceran assemblages, the planktonic cladocerans (mainly *Eubosmina*) increased back to ca. 40% and correspondingly, *Alonella nana* decreased sharply some decades after 1000 AD (Figs 3, 4), whereas in the chironomid community *Tanytarsus* undif., which is mainly a littoral genus (Sæther 1979), decreased from 20 to 4% (Fig. 5). These changes probably indicate a diminished proportion of littoral habitats and an enlarged pelagic area.

The proportions of planktonic cladocerans remained relatively constant towards the top of the core, suggesting that there were no significant water-level changes after ca. 1200 AD. The chironomid *Procladius* became frequent again from ca. 1400 AD onwards. *Procladius* often indicates accel-

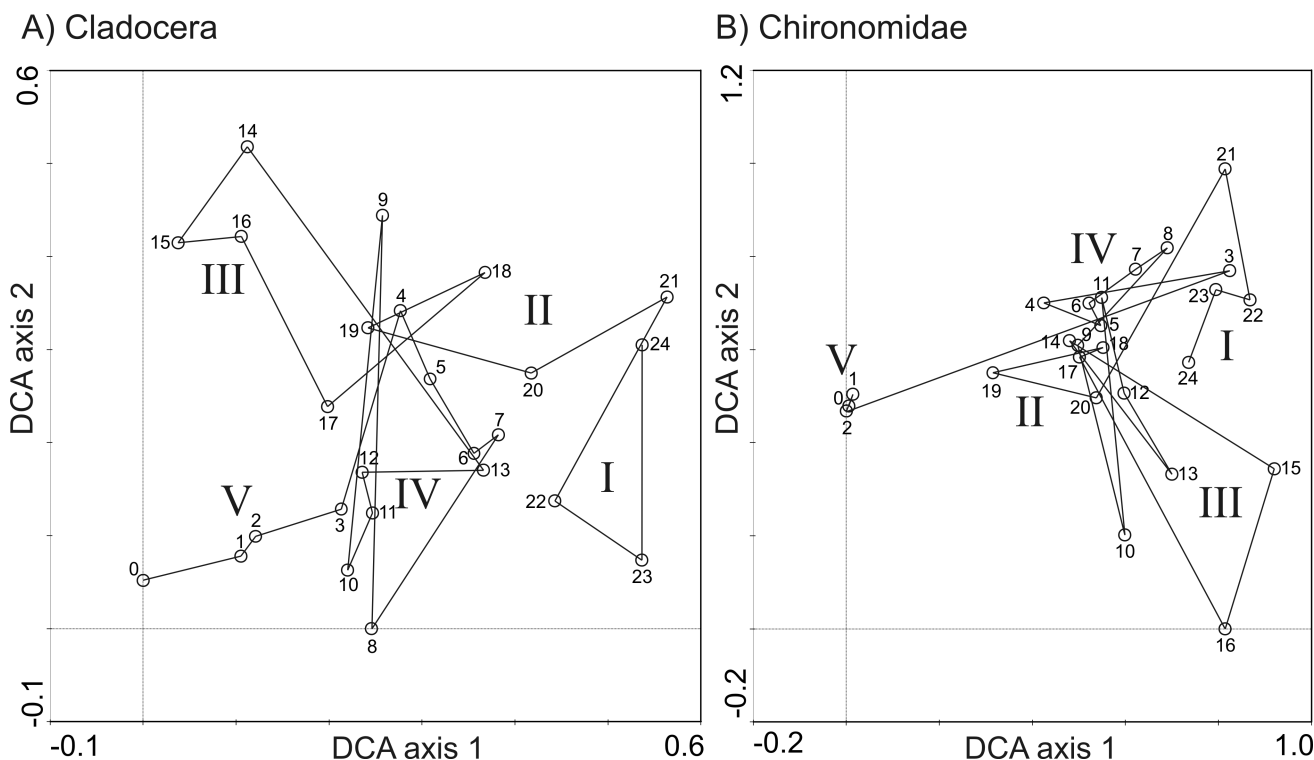


Fig. 7. DCA ordination diagram along axes 1 and 2 for a) Cladocera and b) chironomid assemblages. The numbers (0–24) indicate sample depths (0–24 cm), and the Roman letters indicate local faunal zones (ILCLA1–5 and ILCHII–5 in Figs 3 and 5).

ated deposition or disturbances in sedimentation processes, as Little and Smol (2000) showed. According to their results, *Procladius* increased after construction of a canal and the following flooding. Together with the increase of *Procladius*, the LOI values decreased several percents in Lake Iso Lehmälampi, indicating a lower organic content of the sediment (Fig. 6). A similar decrease in LOI towards the top was visible also in the cores studied (but not shown) by Sarmaja-Korjonen (2001), indicating that a similar change occurred in both sections of the lake. The drop of LOI may indicate that erosion from the catchment increased.

The pollen evidence from Iso Lehmälampi (Sarmaja-Korjonen 2003) indicates only very weak signs of anthropogenic activities but it is possible that *e.g.* small-scaled grazing in the forest may have been practised in the catchment area, intensifying towards modern times. This could have enhanced the nutrient input into the lake but there is no indication of a risen trophic state in the cladoceran and chironomid assemblages (Figs 3, 5) or in the diatom evidence (Sarmaja-Korjonen 2001). Therefore, we cannot exclude the possibility that the decrease in LOI was due to decreasing organic production, possibly resulting from the cold climate periods of the Little Ice Age (LIA).

The chironomid community from *ca.* 1900 AD until present is distinctive (Fig. 5), as shown in the DCA ordination (Fig. 7B). *Paratanytarsus austriacus* type and *Paratanytarsus penicillatus* type disappeared completely and *Ablabesmyia monilis*, together with *Chironomus anthracinus* type, increased markedly. Also *Procladius* increased. Ilyashuk *et al.* (2003) found from a severely metal-contaminated lake in the Kola Peninsula, Russia, that *Chironomus* and *Procladius* increased during the contamination process. In

Lake Iso Lehmälampi, *Chironomus anthracinus* type increased from 0 to 11% and *Procladius* from 4 to 11% during the 20th century. These shifts in the chironomid communities may be due to limnological changes caused by anthropogenic atmospheric pollution. It is known that Lake Iso Lehmälampi experienced a severe acidification process during the 1980s, caused by anthropogenic load of trace metals from industrial processes (Verta *et al.* 1990). It is likely that the influence of atmospheric loading started earlier, together with industrialisation. Huttunen *et al.* (1990) found that in southern Finland, the anthropogenic acidification has been going on since *ca.* 1900 AD, and this agrees with our chironomid evidence. A distinct change occurred also in the cladoceran community towards present times, shown best in the DCA ordination (Fig. 7A) but without such dramatic changes in the species assemblages as in chironomids.

CONCLUSIONS

The cladoceran and chironomid assemblages in Lake Iso Lehmälampi showed changes from 400 AD onwards that were probably caused by a lowering water level and the associated changes in habitats. We detected only one water-level minimum during the past 2000 years, occurring approximately in the period 800–1000 AD, after which the lake level rose. *E.g.* Digerfeldt (1988, 1997) and Korhola *et al.* (2005) showed that water levels have varied for several meters during the Holocene in southern Sweden and Finnish Lapland, respectively. However, it is impossible to estimate quantitatively the variations from the present data. The core was taken from the depth of 4.12 m and since all the evidence of drying of the coring point is missing, the lowering must have

been of a magnitude less than 4 m, compared to the present level.

According to Vassiljev (1998), the lake level is more sensitive to a decrease, since an increase can be compensated by increased outflow. Therefore, it is possible that there were fluctuations during the high water-level stage following the minimum, but these are not reflected in the current record. The low-water period occurred just before the Medieval Warm Period (MWP) and the water level stayed high during the MWP and the LIA. Whether these fluctuations reflect regional hydrological trends, remains unknown, as only synchronous lake-level fluctuations detected from more than one lake can be connected to climate-induced changes. There is hardly any high-resolution evidence about the effective moisture and lake levels in Finland during the MWP and LIA (or preceding them). Tiljander *et al.* (2003) examined annually laminated sediments from central Finland and found that during two periods, *ca.* 1580–1630 and 1650–1710 AD, sedimentation rates and accumulation of minerogenic material increased, indicating wetter and colder climate. More high-resolution multi-proxy palaeolimnological studies are required until a more detailed picture of moisture conditions during the MWP and the LIA in southern Finland can be achieved. Nevertheless, our study indicates that there were short-term lake-level changes in southern Finland during the past 2000 years.

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