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IMPACT OF NATURAL AND MAN-MADE PROCESSES ON THE DEVELOPMENT OF LAKE LINAJÄRV, NE ESTONIA

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Abstract. To obtain objective information about human impact on Lake Linajärv a comprehensive study of a sediment core was performed using geochemical (heavy metals, stabile isotopes of carbon and oxygen) and biological (pollen, diatoms, cladocerans) methods. For dating the ^{14}C and ^{210}Pb methods and soot-ball distribution were used. The obtained data enabled us to reconstruct the development of the lake during the Holocene and establish the relationships between the influencing external forces and the changes in the biogeochemical matter cycle as well as in the biotic communities in the ecosystem. These baseline data allow of the separation of human impact from natural factors.

Key words: paleoecology, historical monitoring, human impact, biogeochemistry, biostratigraphy.

INTRODUCTION

Objective information about the human impact on the biogeochemical matter cycle and the development of ecosystems can be obtained only on the basis of comprehensive investigations of the natural processes in the study area. Variable natural conditions and corresponding reactions in the development of landscapes lead to essential changes in the geochemical matter cycle. The formation or disappearance of geochemical barriers may cause total reorganization of the state and structure of ecosystems. The changes in energy flows lead to the reforming of biotic communities in ecosystems. As a result of these processes the ecosystem will reach a new state, which will determine its further development.

An understanding of these processes is of principal importance for reconstructing the dynamics of ecosystems in the past, the estimation of human impacts on the environment, and for compiling scenarios for the main trends of ecosystems under different land-use regimes. Therefore, the paleoecolocical approach, which is based on the study of bog and lake sediments, is widely used in the landscape study (Berglund, 1991; Mannion, 1989; etc).

In this research the paleoecological—geochemical approach was used to study the lacustrine sediments in Lake Linajärv in NE Estonia.

STUDY AREA

Lake Linajärv, a small closed lake, is situated in northeastern Estonia (59° 14′ N, 27° 32.5′ E, 48 m above sea level). The dominating relief form in this area is the Kurtna (Illuka) Kame Field, formed on the marginal formation of the last continental glaciation period, during the Pandivere stage about 12 200—12 300 years ago. The relief is rich in glaciokarstic hollows, where most of the lakes were formed during the Preboreal climatic period. The main natural factors influencing the dynamics of the environment in this area were changes in different hierarchic climatic conditions (besides global ones, regional changes related to the dynamics of the Baltic Sea) and the tectonic uplift (especially its glacioisostatic compound). The latter had an important influence on the hydrological regime, and therefore also on the paludification and water-level changes in the lakes.

Before World War II the human impact in the region was rather modest and consisted mainly in surface water regulation to drain the surrounding bogs and pastures. A sharp increase in human activities occurred in the early 1950s. Of major importance was the use of some waterbodies as reservoirs for industrial water supply. The use of groundwater, which started in the 1970s, resulted in a considerable drop of the water level in several lakes and a consequent shore and slope erosion. In 1951 the oil-shale-fired Ahtme Power Plant was built only a few kilometres from Lake Linajärv. During the 1960s and 1970s several larger powerf plants, emitting a huge amount of fly ash, were built in northeastern Estonia. Fly ash deposition caused an increase in the accumulation rates of several chemical elements in the sediments (Varvas & Punning, 1993).

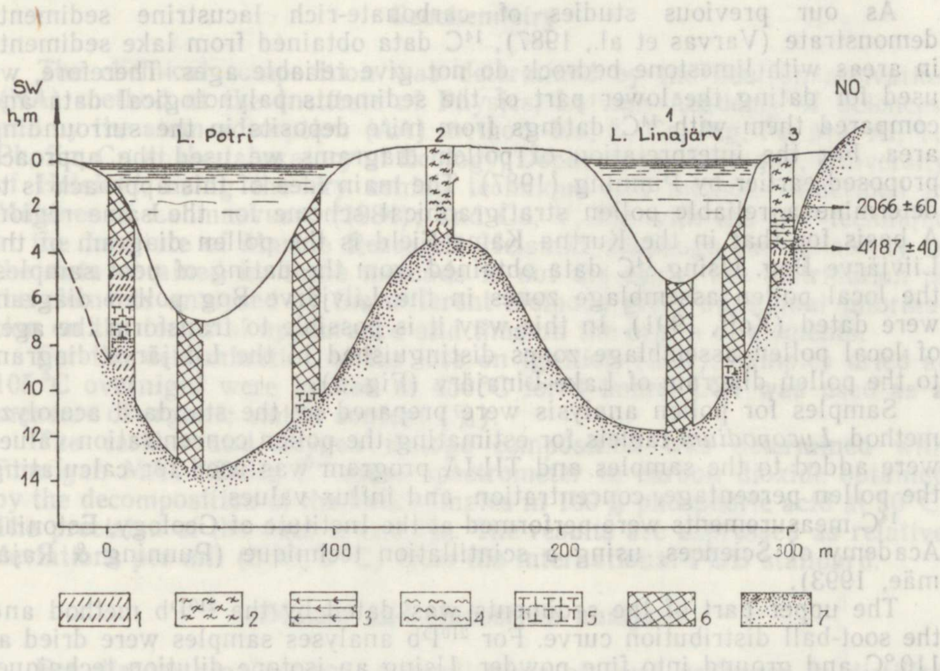


Fig. 1. The profile of the sites studied.

1, *Bryales* peat; *2*, *Sphagnum* peat; *3*, *Carex* peat; *4*, *Scheuchzeria* peat; *5*, lime; *6*, gyttja; *7*, sand and gravel.

Lake Linajärv is situated in the southeastern part of the Kurtna Kame Field. It is a small lake (area 0.6 ha, volume about 38000 m^3, maximum water depth 7.3 m, mean water depth 3.8 m) with swampy shores, except for a small area in the east. The lake water is greenish-yellow with a transparency of *c.* 1.9 m and strongly stratified (Mäemets, 1977).

The lacustrine sediments with a maximum thickness of 560 cm in the centre of the lake, lie on the fluvioglacial poorly sorted sand and gravel. The sediments in the sequence consist mainly of brown and dark-brown gyttja. In peripheral areas thin interlayers of peat and lime lie in some places on the fluvioglacial sediments.

The lake is surrounded by mires. The interlayers of lacustrine lime under the organic sediments (Fig. 1, data from M. Ilomets, pers. comm.) refer to a complicated history of the development of the lake, first of all, to water-level fluctuations.

METHODS

Sampling

The samples from the upper part of the sediments (from the surface of sediments down to 60 cm) were taken with a pistonless corer. Samples for analysis were taken continuously with an interval of 1—2 cm. The lower part of the sediments (from 60 cm up to the fluvioglacial mineral matter) was sampled with a Belarus (Russian) peat sampler (inner diameter 70 mm). Subsamples (1 cm in thickness) were obtained every 20 cm. The freeze-core method was used for obtaining *in situ* frozen cores necessary for lamination studies.

Pollen analysis and dating

As our previous studies of carbonate-rich lacustrine sediments demonstrate (Varvas et al., 1987), ^{14}C data obtained from lake sediments in areas with limestone bedrock do not give reliable ages. Therefore, we used for dating the lower part of the sediments palynological data and compared them with ^{14}C datings from mire deposits in the surrounding area. For the interpretation of pollen diagrams we used the approach proposed earlier by Punning (1987). The main idea of this approach is to determine a reliable pollen stratigraphical scheme for the same region. A basis for that in the Kurtna Kame Field is the pollen diagram of the Liivjärve Bog. Using ^{14}C data obtained from the dating of peat samples, the local pollen assemblage zones in the Liivjärve Bog pollen diagram were dated (Koff, 1991). In this way it is possible to transform the ages of local pollen assemblage zones distinguished in the Liivjärve diagram to the pollen diagram of Lake Linajärv (Fig. 2).

Samples for pollen analysis were prepared by the standard acetolyze method. *Lycopodium* tablets for estimating the pollen concentration values were added to the samples and TILIA program was used for calculating the pollen percentage, concentration, and influx values.

^{14}C measurements were performed at the Institute of Geology, Estonian Academy of Sciences, using a scintillation technique (Punning & Rajamäe, 1993).

The upper part of the sediments was dated by the ^{210}Pb method and the soot-ball distribution curve. For ^{210}Pb analyses samples were dried at 110 °C and ground into fine powder. Using an isotope dilution technique, ^{210}Pb was detected via its granddaughter isotope ^{210}Po (Varvas & Punning, 1993). For calculating the ages the CRS model was used (Appleby & Oldfield, 1978).

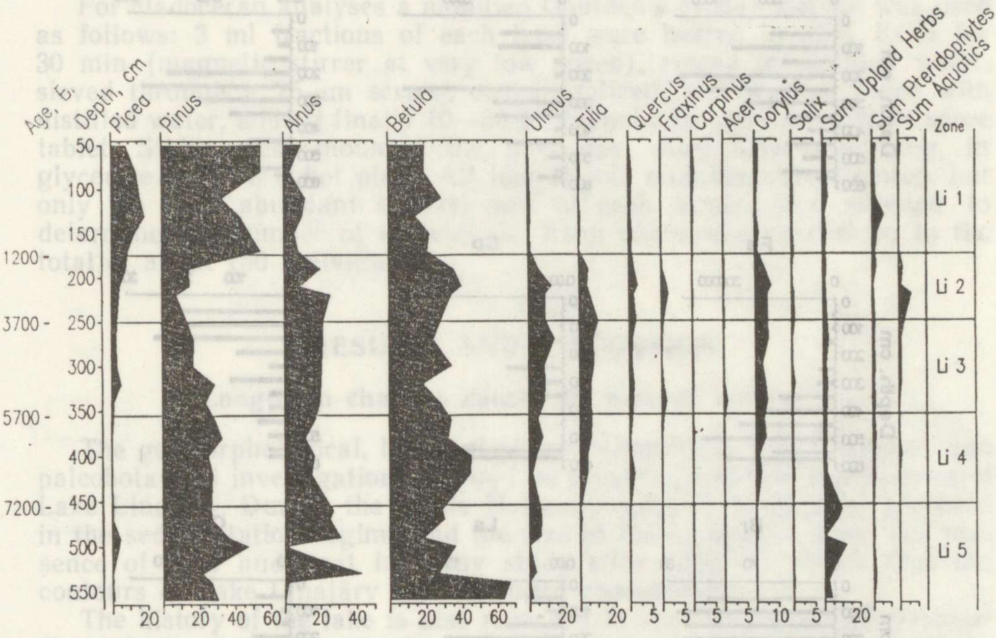


Fig. 2. Percentage pollen diagram for profile 2 (see Fig. 1).

In the soot-ball dating, the original approaches by Renberg & Wik (1983, 1984, and pers. comm.) were followed. The figures are based on duplicate (or triplicate) analyses.

Geochemistry

The chemical composition was determined by the neutron activation (NA) method at the Institute of Physics, Latvian Academy of Sciences, and by the atom adsorption (AA) method: Na, K, Ca, Mg, Fe, Mn, Al, Ti, Pb, Zn, Cu at the laboratory of Ecology, Department of Botany, University of Helsinki, using the dry ashing technique and methods described in Mäkinen & Lehmusvuori (1984); and Cd, V, Hg with the ICP-technique at the Institute of Marine Research, Helsinki. Although the reliability of the data obtained by these methods is not the same, the distribution of the elements analysed by the different methods gives additional information on the forms of appearance and thus on the origin of elements.

For the determination of the loss on ignition (LOI), samples dried at 105 °C overnight were ignited at 450 °C for 4 hours. LOI was used as a measure of organic matter content (%).

The carbon and oxygen isotope composition was determined with Finnigan MAT "Delta E" mass spectrometer in carbon dioxide obtained by the decomposition of the bulk samples in 100% phosphoric acid at 50 °C. The precision of the data is ±0.2‰. The results are expressed as relative deviations per mil ($\delta^{18}O$, $\delta^{13}C$) from the international PDB standard.

Diatom and cladoceran analyses

For diatom preparations, a small piece of fresh sediment in distilled water was treated with an ultrasonic (model Brasonic B) bath for several minutes and mounted in Hyrax. On an average about 360 frustules were counted from each level.

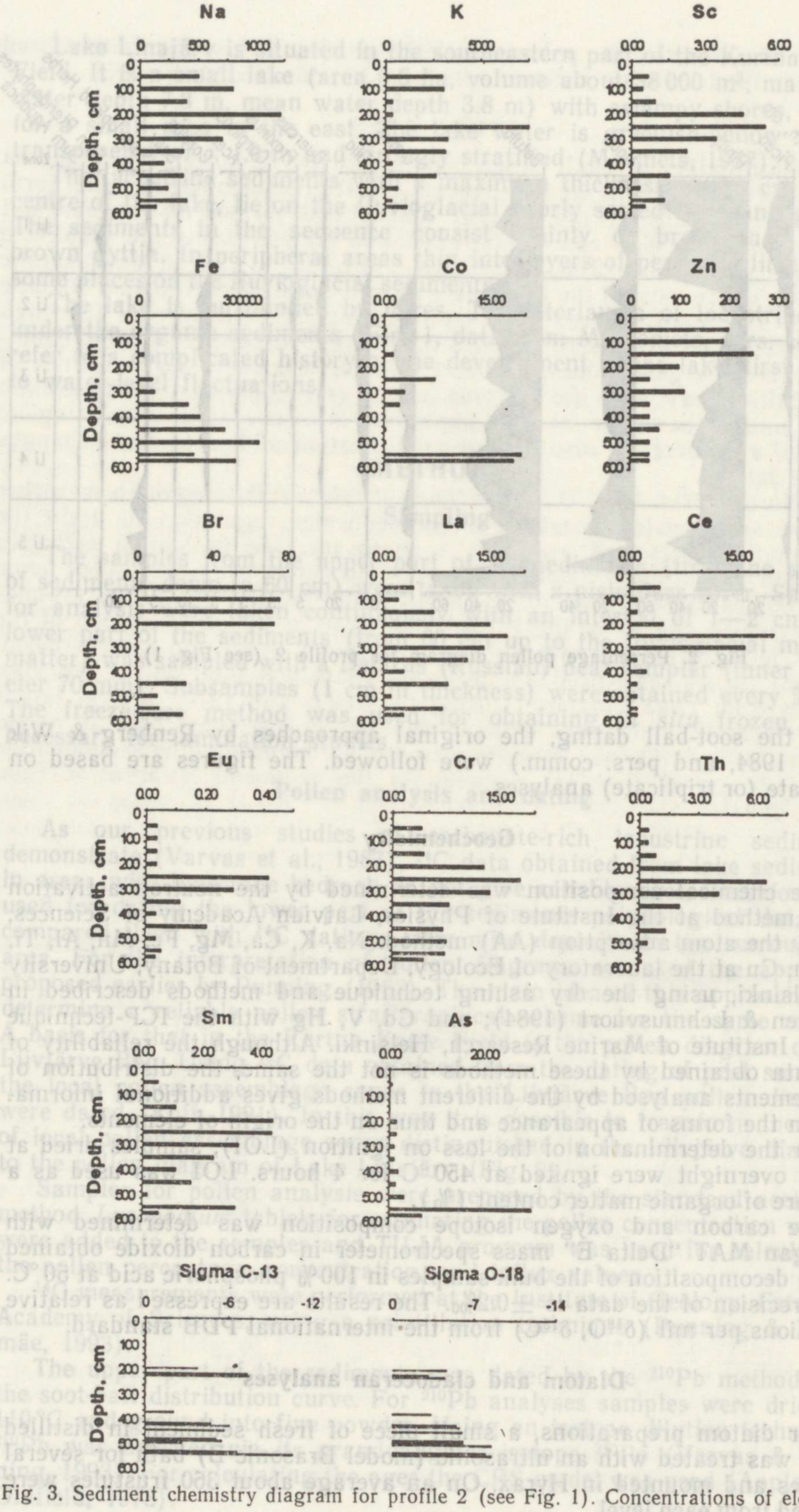


Fig. 3. Sediment chemistry diagram for profile 2 (see Fig. 1). Concentrations of elements are given in ppm, $\delta^{18}O$ and $\delta^{13}C$ in ‰.

For cladoceran analyses a modified Goulden's (1964) method was used as follows: 3 ml fractions of each level were heated in 10% KOH for 30 min (magnetic stirrer at very low speed), rinsed in distilled water, sieved through a 25-μm screen, centrifugalized, and washed twice with distilled water, adding finally 10—30% ethanol and one *Lycopodium* spore tablet. Slides were mounted the next day, after careful stirring, in glycerine jelly on a hot plate. All identifiable remains were counted, but only the most abundant skeletal part of each taxon was selected to determine the number of individuals. Each count was carried on to the total of about 150 individuals.

RESULTS AND DISCUSSION

Long-term changes caused by natural processes

The geomorphological, lithological, geochronological, geochemical, and paleobotanical investigations allowed us to reconstruct the development of Lake Linajärv. During the whole Holocene remarkable changes occurred in the sedimentation regime and the size of the catchment area. The presence of lime and peat in many study sites (Fig. 1) shows that the contours of Lake Linajärv have changed considerably.

The history of the lake is also recorded in the distribution of chemical elements in the sediments. In the basal layers the concentrations of As and Ca, typical elements for the Ordovician aquifer in this area, are relatively high. The predomination of groundwater in the water budget in the beginning of the Holocene and the intensive rise of the water level are also indicated by the negative values of $\delta^{18}O$ in $CaCO_3$ from the basal layers of gyttja (Fig. 3). Since about 8000 yr BP the rate of the water-level rise has stabilized and the share of surface water in the hydrological balance increased, as documented by the increase of $\delta^{18}O$ values. In the layers formed about 6000 yr ago the content of Na, K, and lithophilic elements is higher. This was most probably due to intensive erosion (Fig. 3).

The decrease in the concentration of Fe indicates a decrease in the pH value, which might be caused by an influx of humic acid substances from the catchment area. The increase of $\delta^{18}O$ and $\delta^{13}C$ values (Fig. 3) shows that evaporation from the surface of the lake intensified, the share of the surface water in the hydrological balance increased, and sedimentation of $CaCO_3$ took place under stable hydrological conditions.

Most probably Lake Linajärv and Lake Potri, which is about 200 m SW from Lake Linajärv and is now separated from it by a fen with a thickness of peat above 5 m, were formed from a common waterbody. This conclusion is based on the presence of gyttja at a depth of 310—330 cm in site 3 (Fig. 1). The ^{14}C data suggest that the lakes developed separately up to about 4000—4200 yr BP, when the water in both lakes reached a level of about 350 cm below the present one. About 4200 yr ago the area of the lake surface exceeded the present one. After that the rise of the water level stabilized and the centre of the waterbody, where the depth of water was diminutive, became swampy. Intensively increasing fen peat and the stabilization of the water-level rise led again to a separation of the lakes and to a continuous decrease in the surface areas of both lakes (Fig. 4).

The understanding of the dynamics of the lake is important for the interpretation of the development of the vegetation on the basis of pollen diagrams (Fig. 2). It is well known that pollen composition and influx are dependent on the size of the bog or lake (Jacobson & Bradshaw, 1981). The surfaces of those will determine also the share of pollen of regional and local origin in the pollen spectra. The share of local tree pollen in the total amount of pollen rain is in close relation to the distance from the

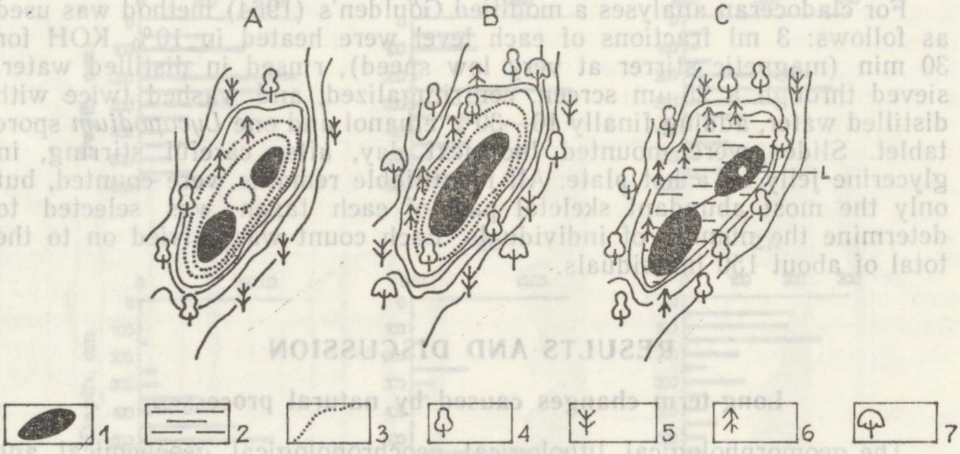


Fig. 4. Development of Lake Linajärv. *A*, 6000 yr BP; *B*, 4000 yr BP; *C* modern. *1,* lake; *2,* bog; *3,* isolines below modern surface; *4, Betula*; *5, Pinus*; *6, Picea*; *7,* broad-leaved trees; L, study site.

tree stand to the sampling point. If there is a change in the surface of the lake, or in the expansion of the mire around the lake, the distance between the tree stand and the sedimentation area will not be constant.

The time dependence of the influx of the tree pollen is in good correlation with the general trends in the development of Lake Linajärv (Fig. 4). The maximum influx took place at a time when the lake had its maximum surface and the open water was close to the mineral soil and trees (Punning & Koff, 1995).

Development of Lake Linajärv during the last centuries

Age-scale

For the estimation of the extent of human impact on the formation and composition of the sediments, the upper part of the sediments (above 60 cm) was studied in detail. The *in situ* frozen sediment core from the deepest part of Lake Linajärv was distinctly laminated with a regular alternation of black or dark brown, green and/or yellow layers in the uppermost 40-cm section. The layers were easily countable in the colour photos in the sediment section of 10—34 cm, but above and below it the lamination was less clear. We guess that the laminations are annual, i. e. varves. This claim is based on our experiences with laminated sediments in numerous small lakes in Finland in which fibrous plants have been soaked and where the laminations were proven to be annual (Saarnisto et al., 1977; Simola, 1977; Tolonen, 1978; Vuorinen, 1978). If each black layer represents one year then the uppermost 34 cm of the core corresponds to 140 years. The ^{210}Pb data agrees with the varve dating back to about 1970 but in older layers it resulted in an increasingly older dating (Fig. 5).

The soot-ball stratigraphy was compared with the two alternative time-scales, based on the laminations and ^{210}Pb data (Fig. 5). Since the varves were counted from the frozen core, the obtained chronology was correlated to the fresh core (from which the soot balls were counted) on the basis of sediment depth. This correlation was supported by the existence of a *c.* 3-cm-thick black band at about 22 cm in all cores. The number of soot spherules increases gradually from the depth of 12 to 5 cm, although

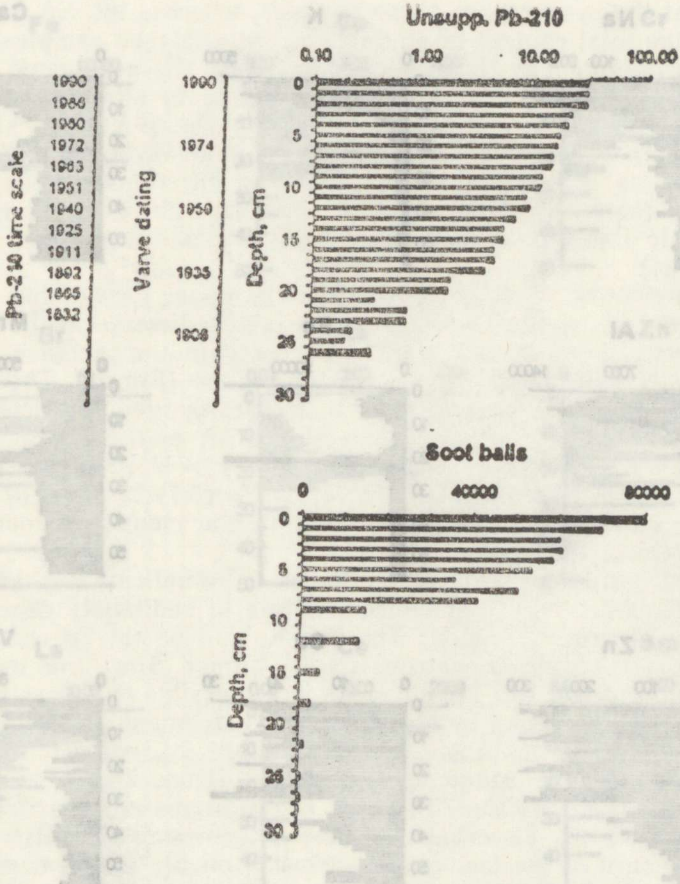
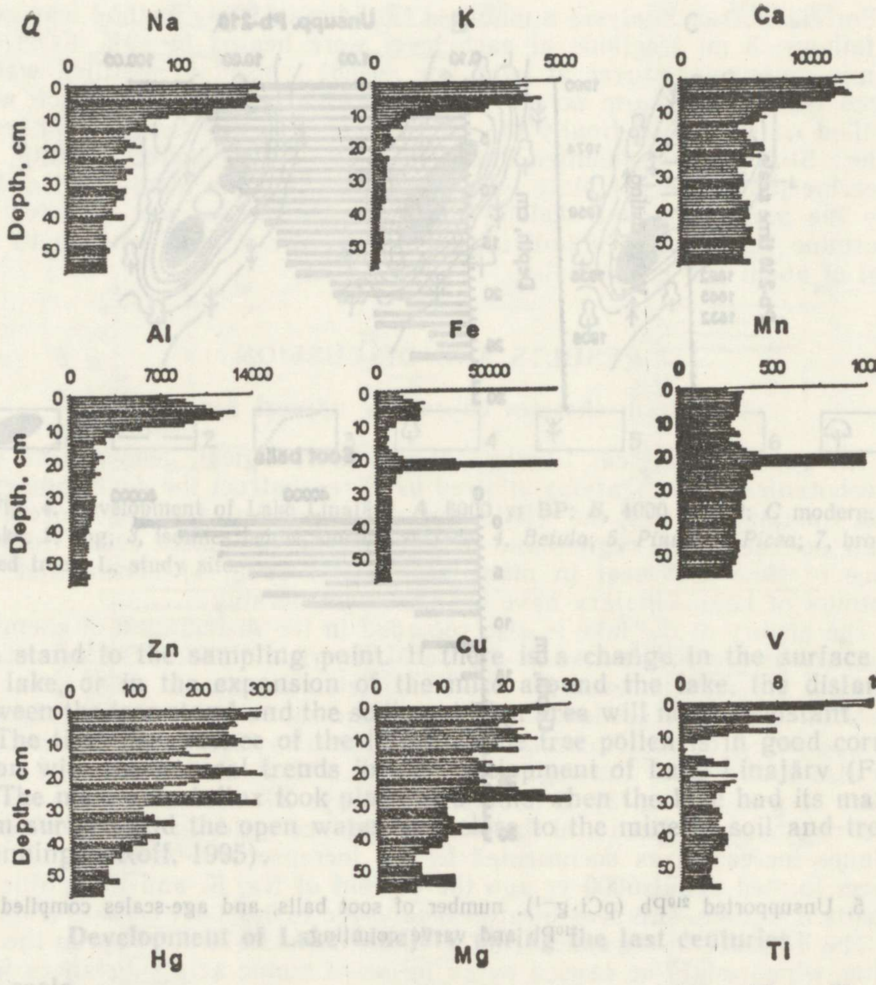


Fig. 5. Unsupported ^{210}Pb ($pCi \cdot g^{-1}$), number of soot balls, and age-scales compiled by ^{210}Pb and varve counting.

they are observed in the deepest layers studied as well. As is known, the fly ash emission started from Ahtme TPP in 1951; a remarkable decrease of emission took place at the end of the 1970s, when an electrical ash precipitator was installed. This is visible in the soot-ball distribution curve, although the emissions from other TPPs in the region have masked this effect to some extent.

The number of soot balls is much higher in Lake Linajärv than in Finnish lake sediments, especially in the younger layers, rising up to 81 000 per gram dry sediment. The maximum is about 300-fold the baseline. The highest recorded soot-ball figures established by long-term studies of Tolonen in Finland are *c.* 27 000, and in a study by Wik & Renberg (1991) in a big set of lakes ($n=144$) in Sweden 48 000. This demonstrates a very high level of emissions in NE Estonia.

In the base of the varve counting a rise in the soot particles as well as in the concentrations of heavy metals started at the end of the fifties, about ten years later than the actual emission from the Ahtme TPP. Therefore, ^{210}Pb data seem to be more correct, but as our previous experience in some other lakes in the Kurtna Kame Field (Varvas & Punning, 1993) as well in some Finnish lakes (Tolonen et al., 1992) shows, it often gives older than expected dates. Therefore, the question which time scale is more exact is still open and needs further study. We used both of them as alternative ones (Fig. 5).



a
Na
K
Ca
Al
Fe
Mn
Zn
Cu
V
Hg
Mg
Ti
Pb
LOI
Depth, cm
0
100
5000
10000
7000
14000
50000
500
1000
200
300
10
20
30
8
16
0.00
0.20
0.40
2000
400
60
120
50

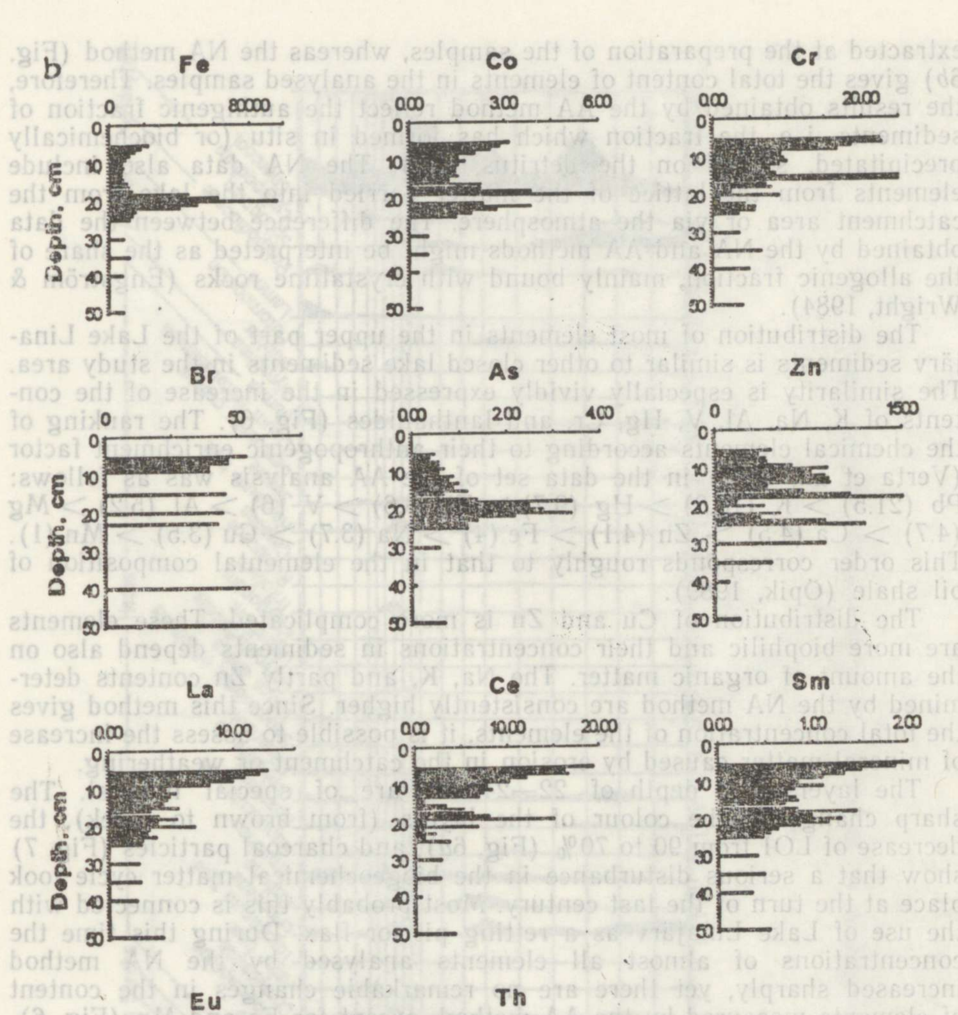


Fig. 6. Sediment chemistry diagrams for upper layers measured by AA (*a*) and NA (*b*) methods. Concentrations in ppm, LOI in %.

Biogeochemical processes

A previous study of the distribution pattern of chemical elements in the bog and lake sediments in the Kurtna Kame Field area shows that the main human impact has come through airborne load since the beginning of the 1950s (Varvas & Punning, 1993). Due to the different methodologies, the AA method (Fig. 6*a*) gives the content of elements in a fraction extracted at the preparation of the samples, whereas the NA method (Fig. 6*b*) gives the total content of elements in the analysed samples. Therefore, the results obtained by the AA method reflect the authigenic fraction of sediments, i. e. the fraction which has formed in situ (or biochemically precipitated, sorbed on the detritus, etc.). The NA data also include elements from the lattice of the matter carried into the lake from the catchment area or via the atmosphere. The difference between the data obtained by the NA and AA methods might be interpreted as the share of the allogenic fraction, mainly bound with crystalline rocks (Engström & Wright, 1984).

The distribution of most elements in the upper part of the Lake Linajärv sediments is similar to other closed lake sediments in the study area. The similarity is especially vividly expressed in the increase of the contents of K, Na, Al, V, Hg, Cr, and lanthanides (Fig. 6). The ranking of the chemical elements according to their anthropogenic enrichment factor (Verta et al., 1987) in the data set of the AA analysis was as follows: Pb (21.5) $>$ K (18.8) $>$ Hg (9.7) $>$ Ti (8.6) $>$ V (6) $>$ Al (5.2) $>$ Mg (4.7) $>$ Ca (4.5) $>$ Zn (4.1) $>$ Fe (4) $>$ Na (3.7) $>$ Cu (3.5) $>$ Mn (1). This order corresponds roughly to that in the elemental composition of oil shale (Õpik, 1989).

The distribution of Cu and Zn is more complicated. These elements are more biophilic and their concentrations in sediments depend also on the amount of organic matter. The Na, K, and partly Zn contents determined by the NA method are consistently higher. Since this method gives the total concentration of the elements, it is possible to assess the increase of mineral matter caused by erosion in the catchment or weathering.

The layers at a depth of 22—24 cm are of special interest. The sharp change in the colour of the layers (from brown to black), the decrease of LOI from 90 to 70% (Fig. 6*a*), and charcoal particles (Fig. 7) show that a serious disturbance in the biogeochemical matter cycle took place at the turn of the last century. Most probably this is connected with the use of Lake Linajärv as a retting pit for flax. During this time the concentrations of almost all elements analysed by the NA method increased sharply, yet there are no remarkable changes in the content of elements measured by the AA method, except for Fe and Mn (Fig. 6). This allows us to suppose that the increase in the density of sediments and the decrease in LOI are connected mainly with an input of mineral matter from the catchment area.

Biostratigraphy

The presence of pollen that are indicators of human activity, especially those of cultivated plants, is the most reliable evidence of human activity (Behre, 1981). However, pollen productivity, dispersion, and deposition make interpretation quite complicated (Birks & Birks, 1980).

There are many natural as well man-made factors that have an essential influence on the formation of the pollen spectra. One of them is forest fires. In Fig. 7 two maxima of charcoal particles at depths 34 and 14 cm can be clearly distinguished. Taking into account historical data on the distribution of cultivated land and lithological data, we can say that the peaks of charcoal particles in sediments reflect forest fires in the Kurtna Kame Field area.

Each of the fires is connected with certain changes in the composition of the pollen spectra. A common feature in all of them is the synchronous decrease of pollen of coniferous trees, especially *Pinus*, which is the dominating taxon on the Kurtna heath. Characteristic is also the appearance of pollen of broad-leaved trees during or immediately after the maxima of charcoal particles (Fig. 7). The lower maximum of charcoal

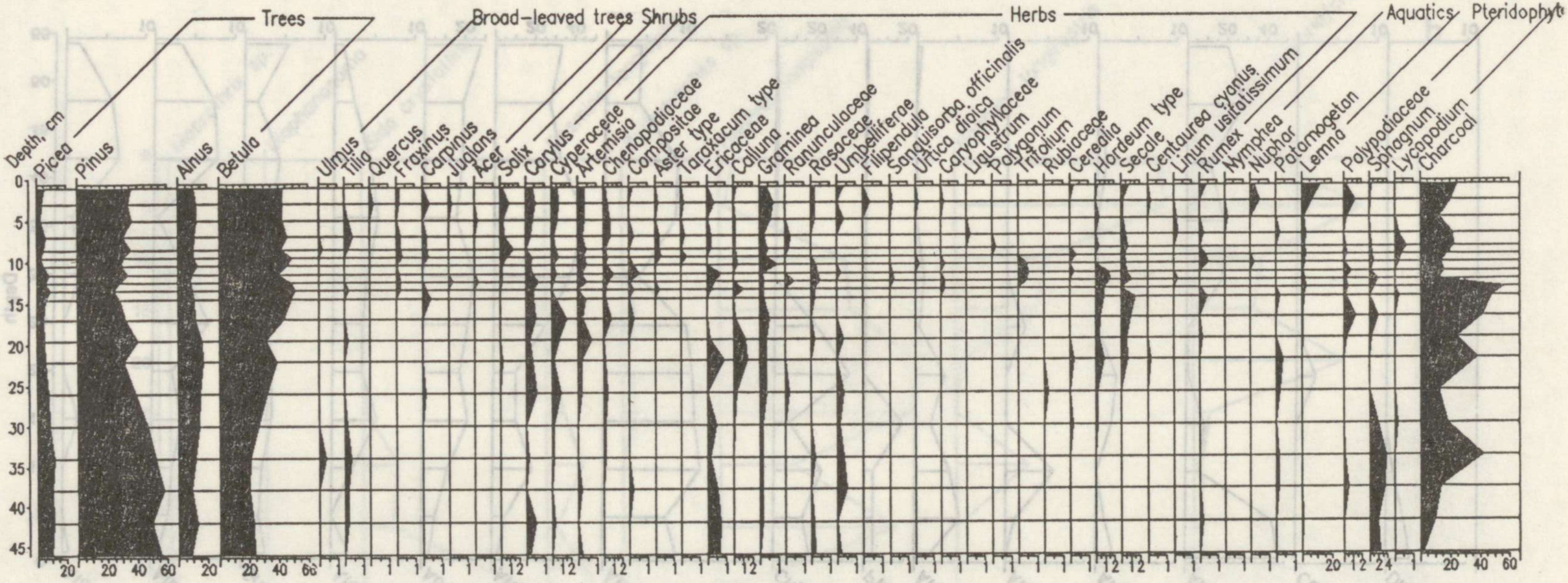
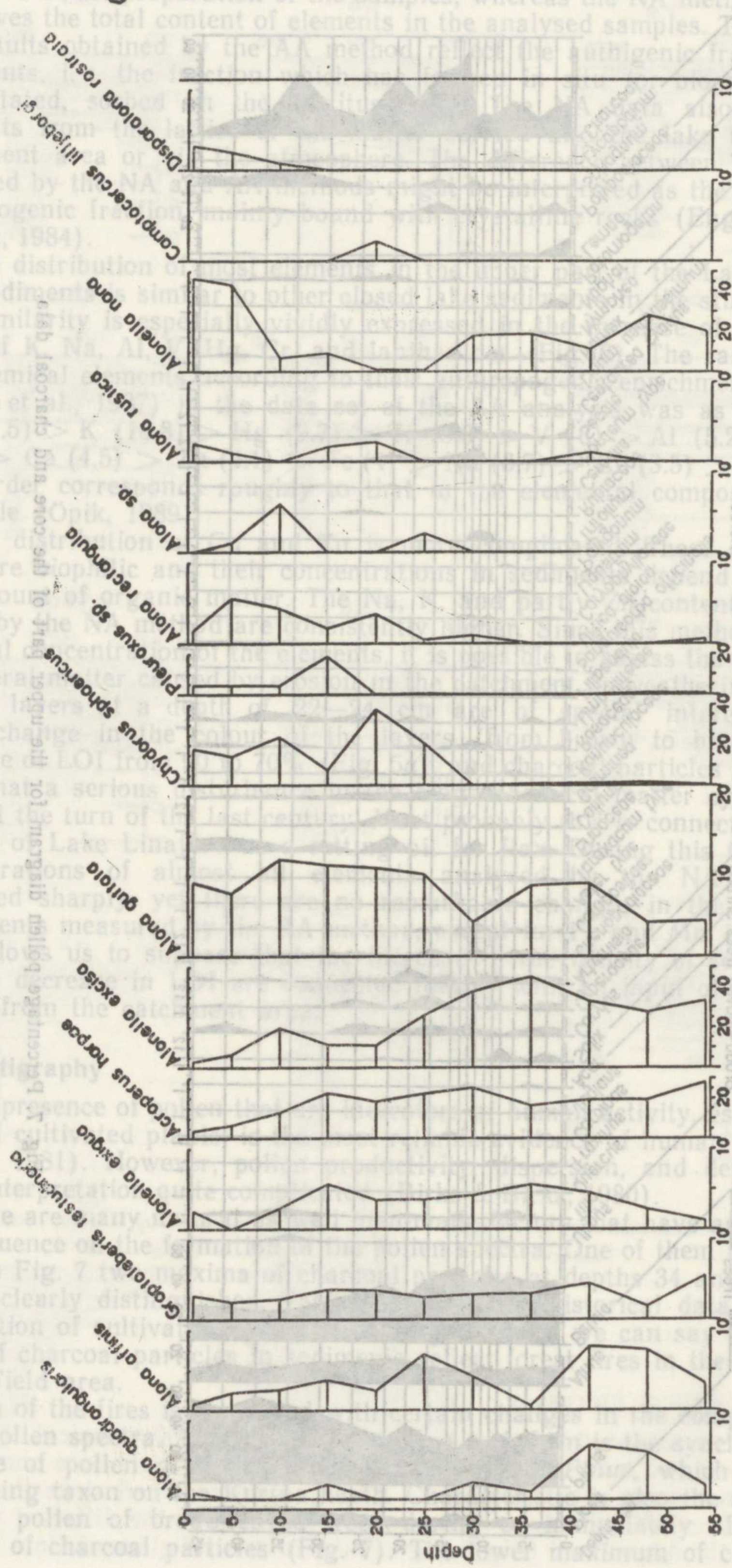


Fig. 7. Percentage pollen diagram for the upper part of the core and charcoal data.


a
Disparalona rostrata
Camptocercus lilljeborgi
Alonella nana
Alona rustica
Alona sp.
Alona rectangula
Pleuroxus sp.
Chydorus sphaericus
Alona guttata
Alonella excisa
Acroperus harpae
Alonella exigua
Graptoleberis testudinaria
Alona affinis
Alona quadrangularis
Depth
0
5
10
15
20
25
30
35
40
45
50
55

particles occurs at a depth of 34 cm. The wide maximum in the charcoal distribution curve shows that the fire was long-lasting and its centre changed during this period.

Most remarkable is the appearance of *Cerealia*- and *Hordeum*-type pollen after the maximum of charcoal particles at a depth of 34 cm. The upper maximum of charcoal particles is found in layers from the beginning of the 1940s (14 cm). This fire is well documented (Mäemets, 1987) and it caused a complete destruction of the forest on the southern part of the Kurtna heath.

A major change in the pollen diagram is the appearance of pollen of broad-leaved trees, among them of exotic species such as *Juglans* and *Carpinus*, which in Estonia are found only in some old parks. The sharp increase of indicators of eutrophication (*Lemna* pollen) testifies that Lake Linajärv has been intensively used by man in recent decades. The corresponding pollen spectra are characterized by an increase in the pollen of herbs like *Artemisia*, Chenopodiaceae, Rosaceae, and *Rumex*, which are indicators of human activity. Above these layers in the spectra one can also find pollen grains of *Linum usitatissimum*, which was cultivated in this area from the beginning of the last century.

Remains of 36 taxa of Cladocera were found in the sediments at the 11 depths studied (Fig. 8). The total number of individuals varied between c. 2800 and 7800, increasing clearly up core. This was concurrent with the rise in the non-chydorid : chydorid ratio, notably from 25 cm upwards.

Three successive stages can be distinguished in both the chydorid (Fig. 8a) and non-chydorid (Fig. 8b) frequencies of the 22 most abundant taxa. Unusually great successive changes in the dominant species characterize the non-chydorid stratigraphy. *Sida crystallina*, the most abundant species (70%) until about 40 cm, was first replaced by *Daphnia longispina* (90%), and finally by *Bosmina longirostris* (over 90%). The vigorous spread of the last species belongs to the "classical" cladoceran succession, indicating eutrophication of the lake (Hofmann, 1978; Boucherle & Züllig, 1983). The intervention of the *Daphnia* fauna in between indicates a temporary meso-dystrophic stage. Most probably this is coupled with an increase in the input of organic matter due to the soaking of fibrous plants in the basins.

A succession from a quite acidic to alkaline and temporarily to a nutrient-rich stage can be seen in the chydorids. At first, the *Alonella excisa* (up to 40%), a species that according to Krause-Dellin & Steinberg (1986) belongs to acidobiontic algae, is predominant. It is accompanied by *Alona rustica* and *Acroperus harpae*, both typical of small acidic lakes (cf. Uimonen-Simola & Tolonen, 1987). Then the succession led to a species-rich assemblage with *Chydorus sphaericus* (up to 40%), *Alona guttata*, *A. rectangula*, *A. costata*, *Camptocercus lilljeborgi*, and *Pleuroxus* sp. *Ch. sphaericus* and *A. rectangula* have been found most commonly among macrophytes rich in organic detritus on the bottom (Whiteside, 1970; Hofmann, 1978). Finally, *Alonella nana* increased (over 45%) at the expense of the previous group implying a return to more oligotrophic conditions.

The lack of diatom frustules hampered the diatom analyses below 15 cm. At that level also very low diatom preservation was observed. Nevertheless, the floral composition and its change within the uppermost 15 cm correspond to the cladoceran record (Table 1).

Synedra ulna (22—38%), a species typical of eutrophic and alkaline waters, dominated or was very abundant at all depths analysed. It was accompanied by *Achnanthes minutissima* v. *cryptocephala*, a circumneutral taxon. At 5 cm, *Cyclotella pseudostelligera* (30%), a species found to indicate nutrients, notably P in small lakes in Finland, predominated. But

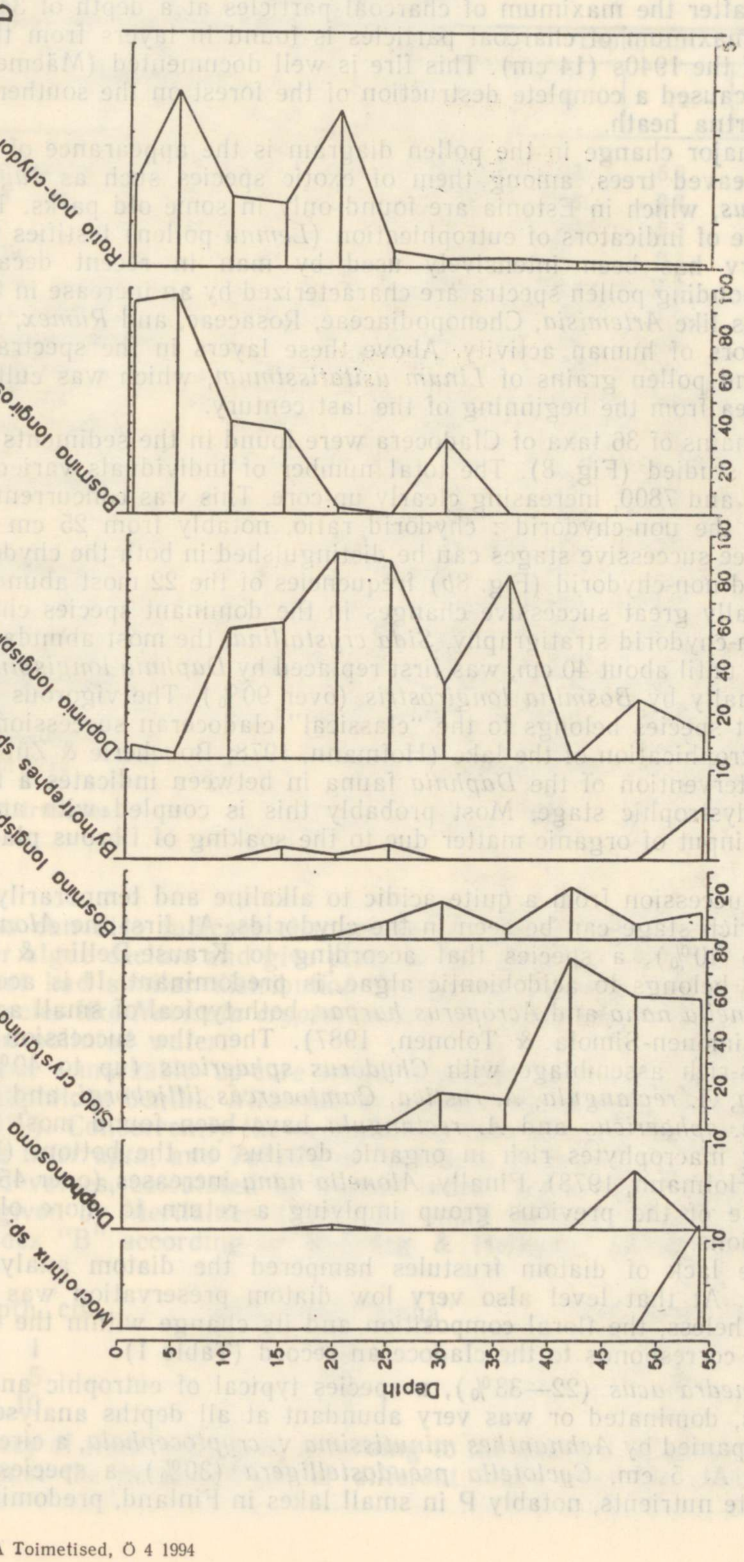


Fig. 8. Chydorid (*a*) and non-chydorid (*b*) percentage diagrams for the upper part of the sediments.

particles occurs at a depth of 34 cm. The wide maximum in the charcoal distribution curve shows that the fire was long-lasting and its centre changed during this period.

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A major change in the pollen diagram is the appearance of pollen of broad-leaved trees, among them of exotic species such as *Juglans* and *Carpinus*, which in Estonia are found only in some old parks. The sharp increase of indicators of eutrophication (*Lemna* pollen) testifies that Lake Linajärv has been intensively used by man in recent decades. The corresponding pollen spectra are characterized by an increase in the pollen of herbs like *Artemisia*, Chenopodiaceae, Rosaceae, and *Rumex*, which are indicators of human activity. Above these layers in the spectra one can also find pollen grains of *Linum usitatissimum*, which was cultivated in this area from the beginning of the last century.

Remains of 36 taxa of Cladocera were found in the sediments at the 11 depths studied (Fig. 8). The total number of individuals varied between *c*. 2000 and 7800, increasing clearly up-core. This was concurrent with the rise in the non-chydorid : chydorid ratio, notably from 25 cm upwards.

Three successive stages can be distinguished in both the chydorid (Fig. 8*a*) and non-chydorid (Fig. 8*b*) frequencies of the 22 most abundant taxa. Unusually great successive changes in the dominant species characterize the non-chydorid stratigraphy. *Sida crystallina*, the most abundant species (76%) until about 40 cm, was first replaced by *Daphnia longispina* (90%), and finally by *Bosmina longirostris* (over 90%). The vigorous spread of the last species belongs to the "classical" cladoceran succession, indicating eutrophication of the lake (Hofmann, 1978; Boucherle & Züllig, 1983). The intervention of the *Daphnia* fauna in between indicates a temporary more dystrophic stage. Most probably this is coupled with an increase in the input of organic matter due to the soaking of fibrous plants in the basins.

A succession from a quite acidic to alkaline and temporarily to a nutrient-rich stage can be seen in the chydorids. At first the *Alonella exisa* (up to 40%), a species that according to Krause-Dellin & Steinberg (1986) belongs to acidobiontic algae, is predominant. It is accompanied by *Alonella nana* and *Acroperus harpae*, both typical of small acidic lakes (cf. Uimonen-Simola & Tolonen, 1987). Then the succession led to a species-rich assemblage with *Chydorus sphaericus* (up to 40%), *Alona guttata*, *A. rectangula*, *A. rustica*, *Camtocercus lilljeborgi*, and *Pleuroxus* sp. *Ch. sphaericus* and *A. rectangula* have been found most commonly among macrophytes rich in organic detritus on the bottom (Whiteside, 1970; Hofmann, 1978). Finally, *Alonella nana* increases (over 45%) at the expense of the previous group implying a return to more oligotrophic conditions.

The lack of diatom frustules hampered the diatom analyses below 15 cm. At that level also very low diatom preservation was observed. Nevertheless, the floral composition and its change within the uppermost 15 cm corresponds to the cladoceran record (Table 1).

Synedra acus (22—33%), a species typical of eutrophic and alkaline waters, dominated or was very abundant at all depths analysed. It was accompanied by *Achnanthes minutissima* v. *cryptocephala*, a circumneutral taxon. At 5 cm, *Cyclotella pseudostelligera* (30%), a species found to indicate nutrients, notably P in small lakes in Finland, predominated. But

Table 1

Distribution of 22 most common diatom taxa (%) in samples from 1—15 cm. The remaining 23 taxa occurred in very low frequencies and they are summed as 'Other diatom taxa'

Diatom taxa	Depth, cm 1	5	10	15
Achnantes conspicua	16.5	7.3	5.9	5.6
A. kryophila	0.9	0.8	2.3	0
A. linearis	5.1	0.6	2.3	2.8
A. marginalis	0.9	0	0.3	2.8
A. minutissima v. *cryptoc.*	26.3	19.1	27.3	27.8
Anomoeoneis serians	4.5	2.8	1.5	2.8
Cyclotella pseudostelligera	0.3	30.3	0.6	16.7
Cymbella hybrida	1.2	0.3	0	2.8
Eunotia pectinalis	1.5	0.6	0.6	0
Gomphonema angustata	0.6	0.3	2.6	0
G. parvulum	0	0.3	1.2	0
Navicula cryptocephala	0	0.3	1.8	0
N. pupula	1.5	0.8	2.3	2.8
N. radiosa	0.9	1.4	0.6	0
Nitzschia perminuta	0.3	0.3	1.5	0
N. pálea	0.3	1.4	2.6	0
N. paleacea	0.9	0.6	0.6	2.8
Pinnularia interrupta	0.3	0.8	0	0
Stauroneis phoenicenteron	0.3	0.8	0.3	5.6
Synedra acus	32.6	20.5	34.6	22.2
Tabellaria flocculosa	1.5	0.6	1.2	2.8
Other diatom taxa	3.0(6)	5.3(9)	4.4(10)	2.8(1)
Total diatom frustules	334	356	341	36

the species can also indicate changes in the water turbulence, so that some other algae decline and give place to fast-growing *Cyclotella*. Other species that had similar distribution in the core include several alkaliphilous species like *Navicula cryptocephala* and *Nitzschia palea*, a species common in polluted water.

The most remarkable up-core trend, however, is the replacement of these alkaliphilous benthic *Nitzschia* by acidobiontic *Anomoeoneis serians* (up to 4.5%). Concurrently the acidophilous taxa like *Eunotia pectinalis*, *Pinnularia interrupta*, and *Tabellaria flocculosa* increased.

The pH values, calculated by diatom index "alpha" according to the equation given by Meriläinen (1967) for small lakes in Finland and by diatom index "B" according to Renberg & Hellberg (1982), were as follows:

Depth, cm	pH, index "alpha"	pH, index "B"
1	6.9	6.4
5	7.2	6.6
10	7.3	6.7

The accuracy of these equations, according to the authors, is about 0.3 pH units against the measured pH of different lakes from the calibration data sets.

CONCLUSIONS

Data on the long-term changes in the palynological and geochemical composition of the sediments in Lake Linajärv demonstrate clearly the importance of the reconstruction of the development of the landscape for the interpretation of paleoecological records in order to understand the influence of local natural or man-made processes on the development of the ecosystem. The comprehensive study of the impact of man-made disturbance on the ecosystem of Lake Linajärv has great importance for understanding the cause—consequence relationships between the changes in the biogeochemical matter cycle and the state of ecosystems in semi-closed small lakes (Table 2).

Table 2

Characteristic ecological and geochemical indices for the upper part of the sediment core

Chronology, AD ^{210}Pb	Varves	Depth, cm	Litho-logy	Content of chemical elements	Pollen	Non-chydorids	Chydorids	Charcoal max-s
1990	1990	0		Max. cont.				
				of K,Ca,			*Alonella*	
1983	1983	3		Mg,Na			*nana*	
						Bosmina	more oli-	
1972	1974	6		Max. cont.		*Longirost-*	gotrophic	
				of Al,Ti		*ris* -		
1957	1968	9				indicator		
				Increase of		of eutroph.		
1940	1959	12		most elem.				
					Lemna,			
1920	1948	15			*Linum,*			
					Juglans			
1892	1935	18					Species	
							rich =	
1832		21		Max. cont.			nutrient	
	1918			of Fe,Mn,	*Cerealea,*		rich	
		24		Co	*Centaurea*			
	1908					*Daphnia*		
		27				*longispina*		
	1890					-		
	1876	30				dystrophic		
						stage		
		33						
	1851				*Ulmus,*			
		36			*Tilia*			
		39					*Alonella*	
							excisa -	
		42				*Sida*	acidic	
						cristallina		
		45						
		48						
		51						

These regularities suggest that the events in the 1940s made the landscape more open. The treeless landscape was the reason for a falling pollen influx and the predominance of pollen grains transported over long distances.

The pollen composition and cladoceran record in the uppermost part of the core are in good correspondence with the distribution of chemical elements and soot balls as well as with the lithological structure of the sediments. A comparison of the historical data on the human impact with biological records demonstrates good temporal correlation between the influencing forces (oil-shale-fired power plants, use of lakes for retting flax) and the trophic state of the lake. The transition periods between the appearance of the influencing forces and changes in the lake ecosystem are rather short and during the last years the state of Lake Linajärv has been improving.

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