BOREAL ENVIRONMENT RESEARCH 3: 45–61
Helsinki 7 July 1998

ISSN 1239-6095

Palaeolimnological evidence of forestry practices disturbing small lakes in Finland

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Turkia, J., Sandman, O. & Huttunen, P. 1998. Palaeolimnological evidence of forestry practices disturbing small lakes in Finland. *Boreal Env. Res.* 3: 45–61. ISSN 1239-6095

The effects of forestry practices on lake water quality were traced in the sediments of six small lakes in Finland by studying the physical and chemical properties and the diatom composition of the sediments. Weighted averaging and a calibration data set of 89 lakes was used to reconstruct lake water pH, conductivity and concentration of total phosphorus on the basis of the sedimentary diatom assemblages. Palaeolimnological changes that can be connected with forest ditchings and fertilizations were detected, and a sudden eutrophication is shown in one case. The effects of clear cuttings seem to be dependent on the subsequent soil treatments (e.g. harrowing or screefing). Some changes in the diatom floras suggest an increase of humic matter in lake water. The links between forestry operations and *Aulacoseira distans* var. *tenella* (Nygaard) R. Ross as well as *Asterionella ralfsii* var. *americana* Körn. are discussed.

Introduction

Forestry and the forest industries are essential for the economy of Finland. In 1993, the share of forestry, wood products industry and pulp and paper industry amounted to 34.7% of the total exports and 7.3% of the gross domestic production. About 44.7 million m^3 of wood were cut in 1993, of which the commercial roundwood fellings were about 38.4 million m^3. More than 5 million ha of peatland has been ditched during the last 40 years to increase timber production, an area representing about half of Finland's peatlands. Forest stands were fertilized most actively in the early 1970s with nitrogen, phosphorus and potassium.

Some types of forest management are quite drastic and include ditching, fertilization, clear cutting and soil preparation by ploughing, harrowing or burning. These forestry practices affect water quality in nearby rivers and lakes. Although long term records of chemical water analyses or phytoplankton are usually lacking, distinct records of past changes in water quality are to be found in lake sediments.

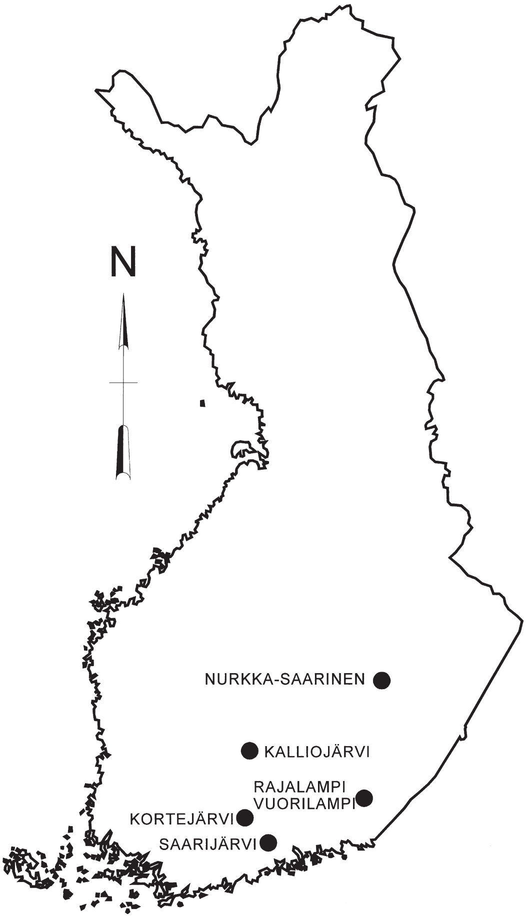

Fig. 1. Location of the study lakes in Finland. Lakes Rajalampi and Vuorilampi are situated close together.

In Finland, the effects of peatland management and forest clear cutting on water quality have been studied, e.g. by Kenttämies (1980), Ahtiainen (1988, 1992) and Holopainen *et al.* (1989). Simola (1983) used palaeolimnological methods to reveal the eutrophication of an oligotrophic lake that received most of its nutrient loading from treated peatlands. In addition, Simola *et al.* (1988) reported the eutrophication of another lake caused by peatland management and fuel peat mining. On the other hand, Rönkkö *et al.* (1988) found only a mild reaction of benthic diatoms in small forest streams to forest clear cutting and peatbog ditching. Rönkkö and Simola (1986) explained different reactions of sedimentary diatom flora to these forest improvement works by geological differences affecting the water quality. In many lakes, the eutrophication process is seen as a relative increase and distinct succession of planktonic diatoms up the core. In other cases, however, only the species abundances have changed, but not the species composition (Simola *et al.* 1995).

Over 90 lakes and drainage basins were inspected to find the best research objects for this project including larger lakes as well. Only a few lakes proved useful. Many lakes had to be excluded because forestry was not the only type of land use in the area, as the lakes were affected by agriculture as well. Some lakes could not be included in the study because of disturbances in sedimentation conditions. Excessive fracturing of diatom frustules was discovered in one of the sampled lakes and the diatom analysis was impossible. Otherwise, the diatoms were fairly well preserved although broken valves were discovered at some levels.

The study is part of the Finnish Joint Research Project on the Adverse Effects of Forest Management on the Aquatic Environment, and Their Abatement (METVE). The purpose of this paper is to identify the effects of the different forestry practices on small forest lakes using palaeolimnological methods.

Material and methods

The study lakes and silviculture in their catchment areas

Five of the study lakes are situated in southern Finland, one is in central Finland (Fig. 1). We chose lakes from predominantly forested areas. The catchments have been relatively undisturbed; only in the drainage basin of Lake Saarijärvi there is very little agriculture. The lakes are small but for Finnish lakes they are relatively deep. Most of them are oligotrophic and their water is coloured by humic matter (Table 1). In this respect, they are typical to Finland. However, two of the lakes (Lake Saarijärvi and Lake Rajalampi) are nowadays eutrophic and one (Lake Kortejärvi) is a clearwater seepage lake. All water quality data presented in this study are part of the national Environment Data System (EDS) of the Finnish Environment Institute. The water samples were collected and analysed mostly by the Regional Environment Centres in Finland. Standard methods (e.g. National Board of Waters 1981) were used.

The lake area of Kortejärvi has been mainly covered by spruce forest. Small forest cuttings were performed in the area; about 4 ha was cut in the 1950s and 2 ha was clear cut in 1972. Pine seedlings were planted on this clear cut area in 1976. The latest cutting was about 5 ha in 1987 when some trees were saved for natural regeneration. Lake Kortejärvi is a clearwater seepage lake.

There were minor forest cuttings in the catchment of the small Lake Nurkka-Saarinen in 1935 and 1955, both about 1–2 ha. A major part, 18 ha, of the scots pine forest in the catchment area was clear cut in 1975 and the logging waste was burned. The lake shore of pine swamp has remained uncut for at least 90 years. The lake is humic (Table 1).

Lake Vuorilampi is also small but deep. About 25 ha of its catchment area was clear cut in the beginning of the 1960s. Screefing and pine planting of the clear cut area followed. A further clear cutting, harrowing and pine planting was done on 2 ha in 1978. In addition, small-scale ditchings were done in the 1970s or 1980s.

Both the lake area and the drainage basin of Lake Rajalampi are the smallest of the studied lakes (Table 1). Two small clear cuttings of pine forest were performed in the catchment in 1965 and 1970, both about 1 ha. Subsequent screefing and pine planting of these areas was carried out. About 5 ha was clear cut in 1978, but a narrow protective zone around the lake was left uncut. Harrowing and pine planting followed this cutting. Fish deaths have been reported in the lake and loss of oxygen has been encountered in the hypolimnion.

Lake Kalliojärvi is the second largest of our study lakes (Table 1). In the catchment area, minor forest ditchings were done already in the 1940s. Greater mechanical ditchings of 25 ha were performed in 1968. Several forest fertilizations were carried out. In 1988, 74 ha was fertilized with 18 kg P and 150 kg N ha^{-1} and 26 ha with 40 kg P ha^{-1}. Altogether 3 580 kg P and 32 670 kg N has been spread on the catchment. The water is coloured by humic matter.

Lake Saarijärvi is the largest of our study lakes. Also the catchment area is much larger than in any of the other lakes (Table 1). A total of 529 ha of peatlands has been ditched in the catchment, but half of these are secondary, because their waters are flowing into the study lake through several other lakes. However, 192 ha of peatland was ditched straight into the lake in 1959. About 100 ha of this area was fertilized with 42 kg P and 93 kg N ha^{-1} in 1973. Additional ditchings of the area were done in 1975 and 1976 and re-fertilization with 52 kg ha^{-1} of readily soluble P in 1985. The latest ditching was 67 ha in 1988. Hypolimnetic oxygen depletion has been observed both in summer and winter.

Methods

The sediment cores were taken in 1989–93 from the deepest part of each lake. Five lakes were sampled through the ice in late winter but Lake

Table 1. Location of the study lakes, their main characteristics and forestry practices in the catchment areas.

	Kortejärvi	Nurkka-Saarinen	Vuorilampi	Rajalampi	Kalliojärvi	Saarijärvi
Latitude, N	60°54´	62°21´	61°15´	61°11´	61°55´	60°42´
Longitude, E	24°14´	27°39´	26°52´	26°51´	24°30´	24°14´
Lake area, ha	14	2	4	1	25	37
Maximum depth, m	10	6	17	6	13	12
Water colour, mg Pt l^{-1}	10	100	40	150	100	140
pH	6.5	5.9	5.9	5.4	5.7	6.8
Total phosphorus, μg l^{-1}	5	10	7	40	15	35
Total nitrogen, μg l^{-1}	250	400	300	1200	500	900
Catchment area, ha	78	25	33	10	309	1 800
Forest cuttings, ha	11	21	27	7		
Forest ditchings, ha			2		25	529
Forest fertilizations, ha					100	100

Saarijärvi was sampled from a boat during open water in the spring. We used a gravity corer (Axelsson and Håkanson 1978), except in one case (Kortejärvi) where the sediment was very soft, and a Limnos corer (Kansanen *et al.* 1991) was used. The cores were sliced in the field into 1 cm subsamples for chemical analyses and for sediment dating. In addition, we took small subsamples for diatom analyses by pipette at 0.5 or 1 cm intervals. All samples were stored in a cool room until being analysed.

Dry matter and ignition loss were analysed from the sediment samples according to the Finnish standard SFS 3008 (1981). Total nitrogen and total phosphorus were determined by codigestion (Zink-Nielsen 1975). The organic matter was removed by strong sulphuric acid treatment. Nitrate and nitrite were reduced to ammonia with Devarda solution. Ammonium sulphate was distilled and ammonium was titrated (Starck and Haapala 1984). Sulphuric acid was used to convert organic phosphorus and inorganic phosphate complexes to orthophosphate which was analysed according to the standard SFS 3025 (1986).

The sediments were dated by soot particle analysis (Renberg and Wik 1984). This dating method is based on the data about the use of coal and oil in Finland (Ministry of Trade and Industry in Finland). To ascertain the dating results, the cores from Lake Kalliojärvi and Lake Saarijärvi were also dated by the ^{210}Pb method but the data were unsatisfactory for constructing reliable chronologies.

Diatom frustules were cleaned by heating the samples up to 110°C in concentrated nitric and sulphuric acids for approximately four hours. The acids were then removed by repeated rinsing with distilled water using the centrifugation technique. Diluted diatom suspensions were dried on coverslips and mounted in Hyrax® or Naphrax®. Oil immersion and a PL Apochromat objective 100/1.32 for phase contrast was used in the microscopical diatom analyses, the total magnification being 1 250 ×. In each sample, over 400 diatom valves were counted. Identification and taxonomy of the diatom species is based mainly on such standard floras as Hustedt (1930, 1927–1966) and Krammer and Lange-Bertalot (1986–1991). Nomenclature is largely in accordance with Williams *et al.* (1988).

We used detrended correspondence analysis, DCA (Hill 1979) and CANOCO program (ter Braak 1987) in treating the diatom material. The aim was to detect objectively the main stratigraphic changes in the assemblages. Because DCA is sensitive to rare species, those diatom taxa whose abundance is less than 1% of all counted frustules in each sample were excluded from the analyses.

To infer past limnological conditions, we used a calibration data set containing 89 small forest lakes mainly in southern and central Finland. These data were collected during the Finnish Research Project on Acidification HAPRO, and it consists of surface sediment diatoms and the corresponding lake water chemistry (Huttunen and Turkia 1990, 1994). The calibration lakes are either acidic or circumneutral, their pH range being 4.7–7.3. About 30% of the calibration lakes are clear water lakes with total organic carbon < 5.0 mg l^{-1}, 45% are humic (TOC 5.0–10.0 mg l^{-1}), and nearly 25% are polyhumic (TOC > 10.0 mg l^{-1}).

Weighted averaging (WA) regression was used in estimating diatom indicator values in the calibration data set, and WA calibration was used in reconstructing lakewater quality from the diatom assemblages in the sediment samples. In both, WACALIB 3.3 (Line *et al.* 1994) was employed. The concentration of total phosphorus in lake water, conductivity at 20 °C and pH were reconstructed for each lake on the basis of the stratigraphic diatom assemblages. Error estimates for reconstructed variables in each sample were provided by a bootstrap root mean squared error of prediction (bootstrap RMSE).

Results

Lake Kortejärvi

The ignition loss values of this lake (Fig. 2a) reflect an early rise of erosion which is linked with the long history of land use in this area. Erosion reached its maximum in the early 1900s. There is a slight maximum of organic matter in the sediment depth of 4–6 cm and an erosion maximum at about 2–3 cm representing the 1970s. The sediment phosphorus concentration is quite even except for the maxima at 20–22 cm and at the top of the sediment.

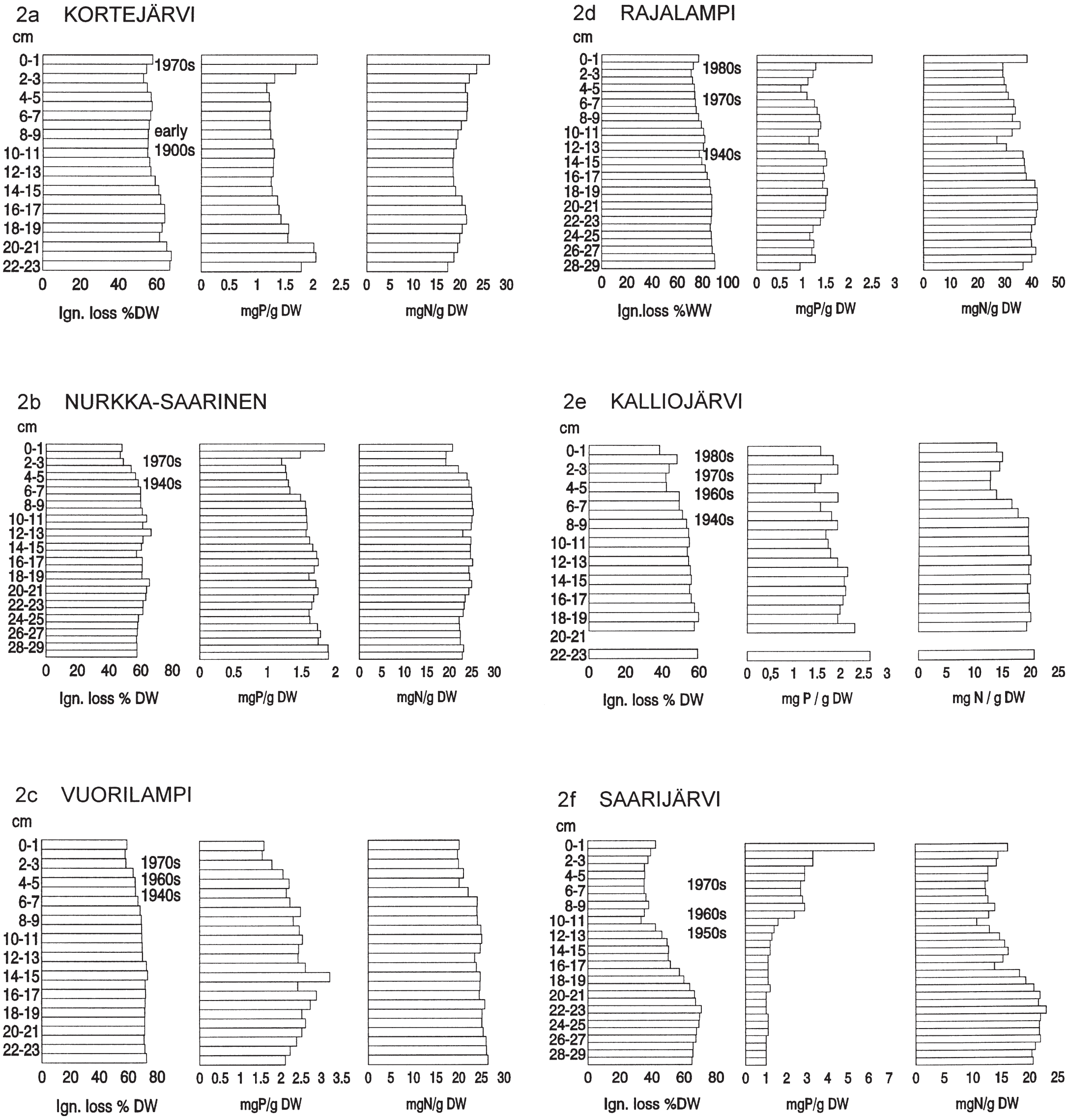

Fig. 2. Loss-on-ignition (percentage of dry weight) and concentrations of total phosphorus and nitrogen (mg g^{-1} of dry weight) in sediments of the study lakes. Sediment depths (in centimetres) are on the vertical axes. The sediments were dated by soot particle analysis.

Planktonic and meroplanktonic diatom species are dominant in the sediments of Lake Kortejärvi (Fig. 3). According to the diatom stratigraphy, *Aulacoseira subarctica* fo. *subborealis* (Nygaard) Haworth has previously been the dominating diatom. At the deepest analysed level of 28 cm, this diatom occurs with 47% of all counted diatom frustules decreasing towards the sediment surface. Above 10 cm it is very rare.

Another diatom that is abundant below the depth of 10 cm, even though rare in the two deepest samples, has long been called *Cyclotella kuetzingiana* var. *radiosa* Fricke but its proper identity is disputed. According to Håkansson (1990a), *Cyclotella kuetzingiana* Thwaites is conspecific with *C. meneghiniana* Kützing, and new names including *C. krammeri* Håkansson and *C. rossii* Håkansson have been proposed for closely similar forms within this group (Håkansson 1990b). Being most abundant in the topmost three centimeters, *C. kuetzing-*

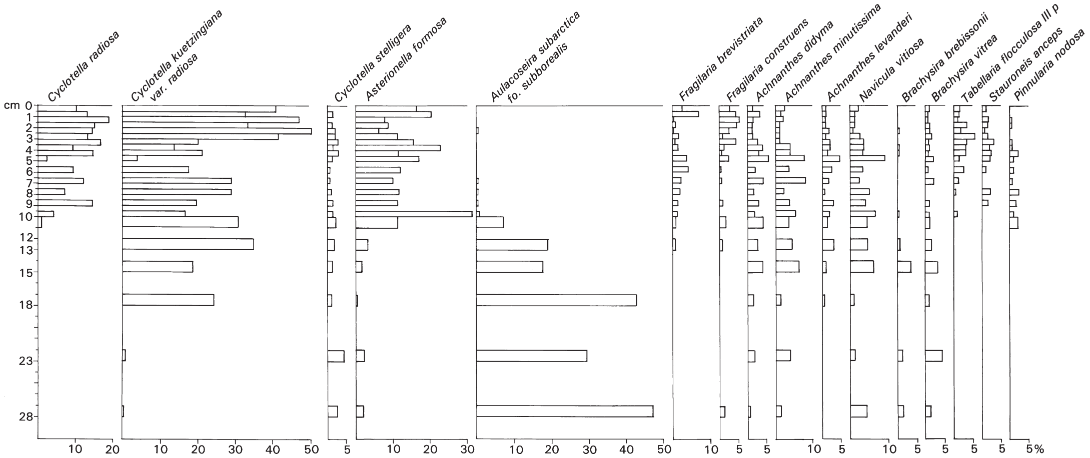

Fig. 3. Diatom stratigraphy in the sediment of Lake Kortejärvi. The relative abundances of the most important diatom taxa are presented on the horisontal axis and sediment depth is given on the vertical axis. The name *Cyclotella comta* should now again be used instead of *Cyclotella radiosa*.

iana var. *radiosa* gains a maximum abundance of 51% at 2.5 cm (Fig. 3). This taxon has been considered typical of clear waters indicating that Lake Kortejärvi has not received much humic substances from the surrounding forest areas.

Cyclotella comta (Ehrenb.) Kützing was found in every sediment sample above the depth of 11 cm, but did not occur in deeper sediment layers. This diatom has also been called *Cyclotella radiosa* (Grun.) Lemmermann (e.g. Krammer and Lange-Bertalot 1991a). *C. comta* is euplanktonic and especially common in eutrophic waters. *Cyclotella stelligera* (Cleve and Grun.) Van Heurck, also a species of fairly nutrient rich conditions, is present in almost all samples throughout the sediment profile but always in low numbers.

Asterionella formosa Hassall was found in every sediment sample. It is clearly more abundant above the depth of 11 cm, and in this respect, its distribution is similar to the occurrence of *Cyclotella comta*. Both species indicate the effects of an environmental change beginning in the early decades of this century. Results of the DCA-analysis (Fig. 4a) reveal that the greatest change of the diatom assemblages has occurred at this time.

The planktonic form of *Tabellaria flocculosa* (IIIp sensu Koppen) occurs here only above 10 cm. Also, some periphytic species like *Fragilaria brevistriata* Grun. and *F. construens* (Ehrenb.) Grun. were clearly more abundant at the sediment surface, though found only in low numbers. Several littoral diatoms like *Achnanthes didyma* Hust., *A. levanderi* Hust. and *Navicula vitiosa* Schimanski have their maxima at 5 cm but this is obviously because *Cyclotella kuetzingiana* var. *radiosa* is less abundant at this level (Fig. 3). In routine diatom analyses, the dominating taxa tend to hide the rare species.

Asterionella formosa and *Cyclotella comta* indicate that the nutrient content of the water has increased. According to our calibration data set, their estimated optima of total phosphorus are 17.4 $\mu g\ l^{-1}$ and 13.3 $\mu g\ l^{-1}$, respectively. The rise of the diatom-inferred (DI) total phoshorus and the DI lake water conductivity at 11 cm (Fig. 4a) as well as the preceeding erosion (Fig. 2a) suggest an early disturbance of the catchment and a change of water quality. The small forest cuttings have probably contributed to this change although individual cutting events cannot be distinguished in the sediment. The rise of the DI-total phosphorus at 5 cm may, however, reflect the cutting in the 1950s. The DI-pH increases slightly at the same time.

Lake Nurkka-Saarinen

The soot spherule analysis indicates a slow sedimentation rate in this lake. The minimum in soot spherules content of the 1940s seems to be extended, which may reflect an erosion maximum in the 1950s. The sediment is highly organic. The

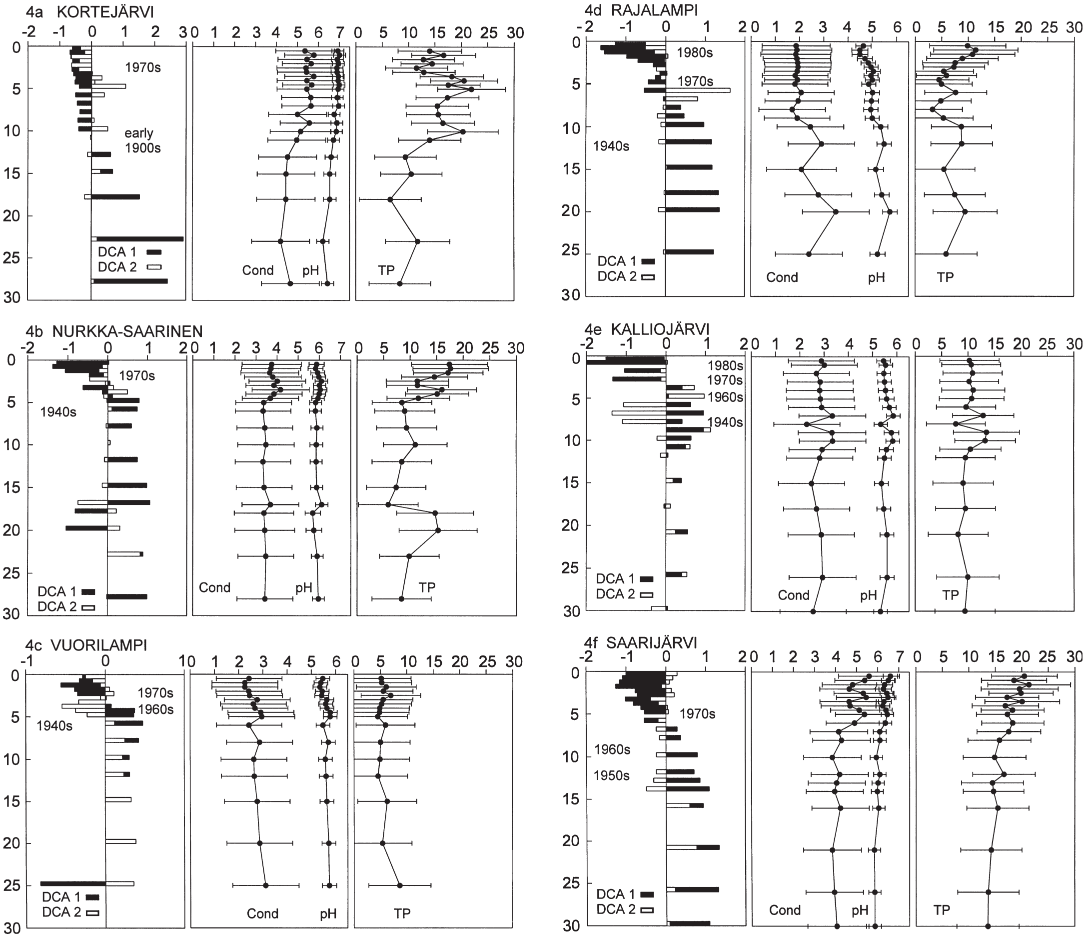

Fig. 4. Diatom-based parameters from sediments of the study lakes. For each lake, the left-hand panel shows Detrended Correspondence Analysis (DCA) of the sedimentary diatom samples; the sample scores on the two DCA-axes are presented on the horisontal axis. (Note the different scale for Lake Vuorilampi). Diatom-inferred conductivity (Cond), pH and total phosphorus (TP) in water are also given in the middle and right-hand panels, in which error bars represent the ± bootstrap RMSE. Sample depths in centimetres are on the vertical axes. Dating results were inferred from soot particle counting.

profile of ignition loss values (Fig. 2b) is quite even with a slight upcore decline from 5–6 cm onwards. There is a nitrogen minimum with a simultaneous organic maximum at 12–13 cm indicating allochthonous sediment. At 2–3 cm the relation of these elements indicates a high influence of drainage basin, too. There is a minimum in sediment phosphorus values at 2–7 cm because of the rise of minerogenic matter.

Aulacoseira distans var. *tenella* (Nygaard) R. Ross is very abundant in certain sediment layers of Lake Nurkka-Saarinen: At 20 cm, the share of this taxon is 72% and at 18 cm it is 68 (Fig. 5). The relative abundance of this diatom then suddenly decreases at 17 cm to only 1%, but increases again to 65% in the topmost sample. *Aulacoseira subarctica* fo. *subborealis* is also frequent with a maximum abundance of 49% at 17 cm. *Aulacoseira subarctica* fo. *subborealis* and *A. distans* var. *tenella* have almost opposing stratigraphies in this lake.

There are only minor changes in the stratigraphic abundances of periphytic diatoms. Many taxa, including the circumneutral *Tabellaria flocculosa* (Roth) Kütz. and *Brachysira vitrea* var. *lanceolata* A. Mayer as well as the acidophilous *Eunotia incisa*

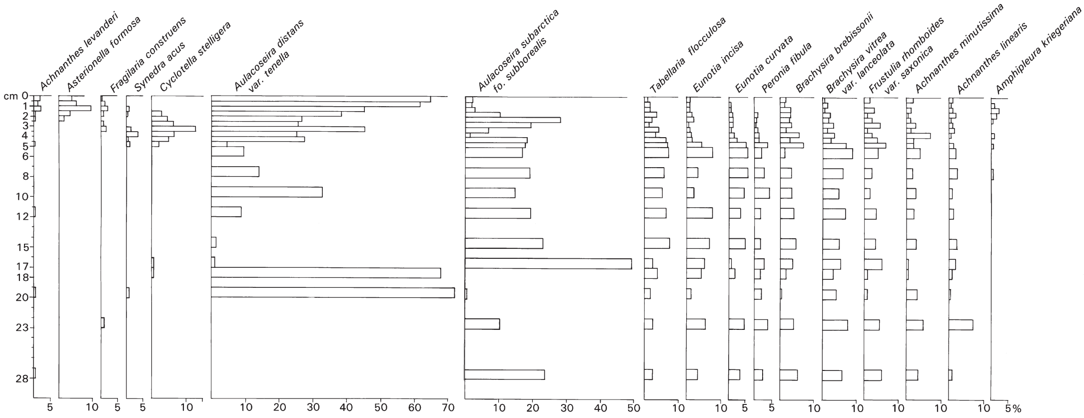

Fig. 5. Diatom stratigraphy of Lake Nurkka-Saarinen. The relative abundances of the most important taxa are presented. Sample depths are on the vertical axis.

W.Sm. ex Greg. seem to decrease near the sediment surface obviously because *Aulacoseira distans* var. *tenella* is so abundant. On the other hand, the small *Amphipleura kriegeriana* (Krasske) Hust. was only present above the depth of 8 cm. This species is from our experience very rare in Finnish lakes, and it is also reported to be rare elsewhere (Krammer and Lange-Bertalot 1986).

The alkaliphilous diatoms *Asterionella formosa, Fragilaria construens* and *Synedra acus* Kütz. are almost entirely confined to the uppermost sediment layers. *Achnanthes levanderi*, which has usually been classified as circumneutral, also occurred a bit more often near the sediment surface (Fig. 5). The circumneutral *Cyclotella stelligera* has its maximum abundance with 13% at 3.5 cm. According to the DCA-analysis (Fig. 4b) there is a major change of diatom assemblages at this level when *Aulacoseira distans* var. *tenella* becomes abundant again.

On the basis of the diatom assemblages, we estimated that there was a rise of lake water conductivity, pH and total phosphorus in Lake Nurkka-Saarinen already in the 1950s after the minor forest cuttings. Increase of minerogenic matter in the sediment is evident since the 1940s. The greatest change occurred in the 1970s indicating that the 18 ha forest clear cutting in the catchment has accelerated erosion. This clear cutting and the subsequent burning appears, unexpectedly, not to have increased the DI-conductivity or pH (Fig. 4b). Even though many alkaliphilous diatoms attain their highest abundances at the sediment top, the acidophilous *Aulacoseira distans* var. *tenella* is dominating the flora. The DI-total phosphorus has continued to rise (Fig. 4b).

Lake Vuorilampi

The watery (minimum dry matter percentage is 1.5) sediment of Lake Vuorilampi contains ca. 60–80% organic matter (Fig. 2c). The ignition loss values descend towards the sediment top. There is an early maximum at 13–15 cm and a fall from 6–7 cm (about 1940s) to the sediment surface. A clear minimum is from 3 cm upwards. The change seems to start after 1960s. The sediment phosphorus values are descending towards the sediment surface, which indicates possible events of hypolimnetic anoxia.

The results of the DCA-analysis (Fig. 4c) expose the exceptional diatom composition of the deepest analysed sample, at 25 cm, where *Aulacoseira distans* var. *tenella* is common with 30%. In other samples, this diatom is far less abundant or totally missing (Fig. 6). *Brachysira brebissonii* R.Ross and *Aulacoseira subarctica* fo. *subborealis* have been the dominating diatoms in Lake Vuorilampi, both with some 20%, but recently the share of the latter has declined. *Frustulia rhomboides* (Ehrenb.) De Toni and *F. rhomboides* var. *saxonica* (Rabenh.) De Toni are somewhat more abundant near the sediment surface; in the topmost sample their relative abundances amount to 21%. *Cyclotella kuetzingiana* var. *radiosa* is almost

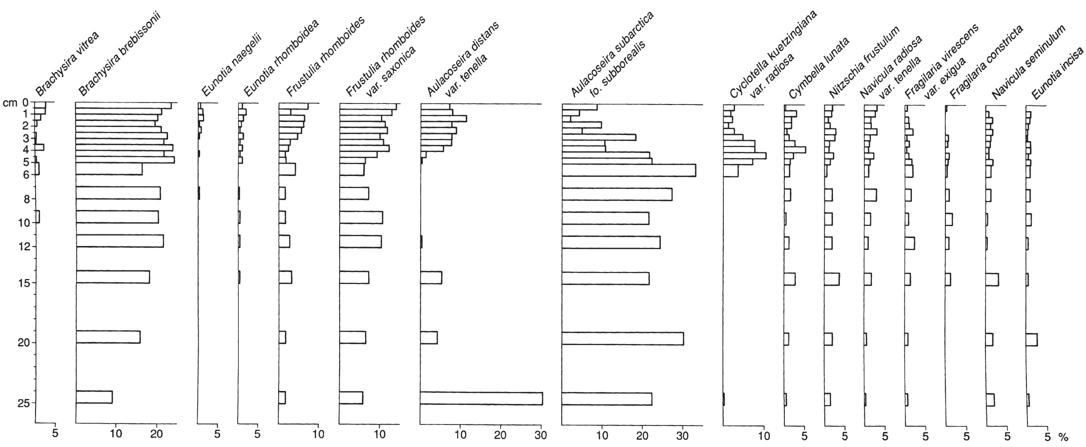

Fig. 6. Sedimentary diatoms in Lake Vuorilampi: relative abundances of the most important taxa are presented.

entirely restricted to the uppermost sediment layers having a maximum of 11% at 4.5 cm.

There are many periphytic species in the sediments of Lake Vuorilampi, which indicates a high diversity of the littoral environments. Only some of the littoral species, including *Brachysira vitrea*, *Eunotia naegelii* Migula and *E. rhomboidea* Hust., show slight stratigraphic changes and are more common at the sediment surface (Fig. 6). Most of the diatoms occur in low abundances, and display very little stratigraphic shifts. These include species of the periphytic genera *Cymbella, Eunotia, Fragilaria, Navicula* and *Nitzschia.*

Apart from the deepest diatom sample, which indicates high DI-total phosphorus, there are only minor changes in the sedimentary diatom assemblages of this lake (note the different scale of the DCA axes in Fig. 4c) and they do not indicate any distinct changes of lakewater quality. The DI-conductivity and DI-pH are, however, declining slightly near the sediment surface. The ignition loss of the sediment indicates that erosion was most rapid in the 1960s at the time of the major clear cutting and screefing. Despite these forestry practices the lake is still oligotrophic with fairly clear and slightly acidic water.

Lake Rajalampi

The watery sediment of Lake Rajalampi has an exceptionally high organic content: over 80% of dry weight (Fig. 2d). There is a minimum of ignition loss at 12–15 cm and a decline from 9 cm, from 1960s, to the sediment surface. The nitrogen values are very high, too. There are nitrogen and phosphorus minima in the sediment at 11–12 cm and from 6 cm upwards. The upper phosphorus minimum is quite prominent and may indicate anoxia.

Some acidobiontic diatoms like *Tabellaria quadriseptata* Knudson and *Navicula hoefleri* sensu Ross and Sims are extremely rare in the deepest sediment samples, but occur more often near the sediment surface, above 9 cm. *Tabellaria binalis* (Ehrenb.) Grun. is totally restricted to the sediment layers above 8 cm (Fig. 7). *Navicula tenuicephala* Hust. has a maximum abundance of 6% at 8 cm, where the DI-total phosphorus is at its lowest (Fig. 4d).

The acidophilous *Frustulia rhomboides* var. *saxonica* and *Brachysira brebissonii*, which originate from the littoral zone and often occur together in sediments, were found only above the depth of 9 cm. On the other hand, several acidophilous diatoms including *Eunotia monodon* Ehrenb., *Eunotia hexaglyphis* Ehrenb. and *Eunotia parallela* Ehrenb. are clearly less abundant in the topmost 5 centimeters. The acidobiontic *Navicula hoeflerii* Cholnoky is also more common at deeper sediment layers with a maximum abundance of 17% at 18 cm. *Pinnularia biceps* Greg., also acidophilous, is present in every sample, mostly with a fairly even distribution of a few per cent, but clearly more abundant at 10 cm with 32%. This sediment level is obviously the beginning of

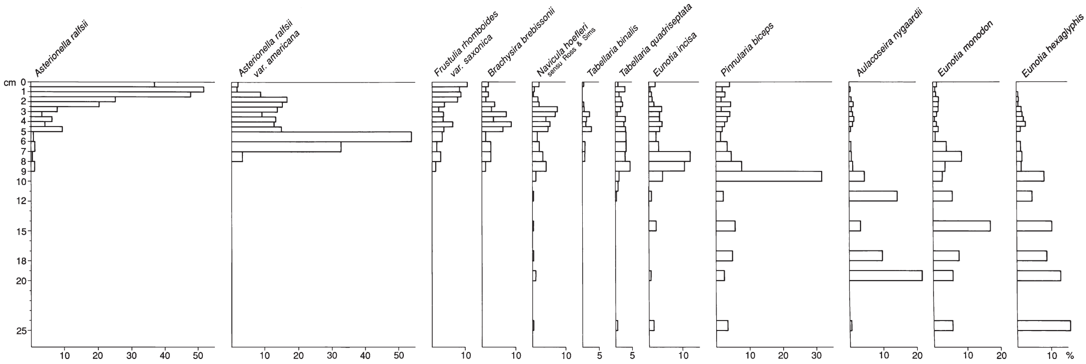

Fig. 7. Sedimentary diatoms in Lake Rajalampi: relative abundances of the most important taxa are presented.

a major change in the diatom assemblages, even if according to the DCA, the greatest change takes place at 7 cm from the sediment surface (Fig. 4d).

Asterionella ralfsii W.Sm. is first encountered at 9 cm, then occurring in every sediment sample (Fig. 7). It is most abundant at 1 cm with 52%. In the uppermost samples near the sediment surface, the valves of this diatom are very short, even less than 15 µm. The longer form, *A. ralfsii* var. *americana* Körn., appears at 8 cm, and is most abundant at 6 cm with 54%. It was, however, not always easy to distinguish these two taxa from each other, particularly at the depths between 2 and 5 cm. Even if the difference is sometimes clear, our samples apparently contain a continuum between the two taxa. The lake seems to have been acidic for a long time, but the increase of the nominate type of *Asterionella ralfsii* at the sediment top indicates a further acidification (Fig. 4d) probably as a result of acidic deposition.

The sedimentary records of Lake Rajalampi show that there are distinct differences in the composition of the stratigraphic diatom assemblages, which is an indication of a major change in the environmental conditions for the algae. According to the dating results, this change started in the 1970s. The sudden appearance of *Asterionella ralfsii* var. *americana* and then *A. ralfsii* denote that the concentration of humic matter in the lake water has increased. This is probably due to the forest cuttings and soil manipulation. The DI-total phosphorus is rising at the sediment top (Fig. 4d) revealing a trophic change that must be related to the forestry management because there is no other source of nutrient load in the area.

Lake Kalliojärvi

The ignition loss values are descending from about 9–10 cm towards the sediment surface. Especially at 5 cm there is a clear drop indicating increase of mineral matter (Fig. 2e). The total phosphorus content of the sediment is variable.

The acidophilous *Aulacoseira distans* var. *tenella* is abundant at many levels (Fig. 8) indicating that the lake has been humic for a long time. A clear change of the diatom assemblages occurs when *Asterionella formosa* and *Tabellaria fenestrata* (Lyngb) Kütz. appear at 11 cm and *Aulacoseira italica* (Ehrenb.) Simonsen at 10 cm. These diatom species are alkaliphilous; according to our calibration data set their pH optima are 6.5, 6.4 and 7.0, respectively. They indicate not only a decrease of lakewater acidity but also an early increase of the lake's trophic status. At the same time, the share of the acidophilous *Aulacoseira lirata* (Ehrenb.) R. Ross decreases but increases again near the sediment surface (Fig. 8).

Another change of the diatom assemblages occurs at 5 cm. It is characterized by the disappearance of *Asterionella formosa* and *Tabellaria fenestrata* and the steep but temporary increase of *Aulacoseira distans* var. *tenella* which is scarce at 6–8 cm. Results of the DCA-analysis indicate that the greatest relative change of the diatom assemblages takes place at 3 cm when *Asterionella ralfsii* var. *americana* and *Tabellaria flocculosa* become more common and *Aulacoseira subarctica* fo. *subborealis* disappears. These topmost sediment layers have been accumulating into the lake bottom for the last two decades. At 1 cm, *A.*

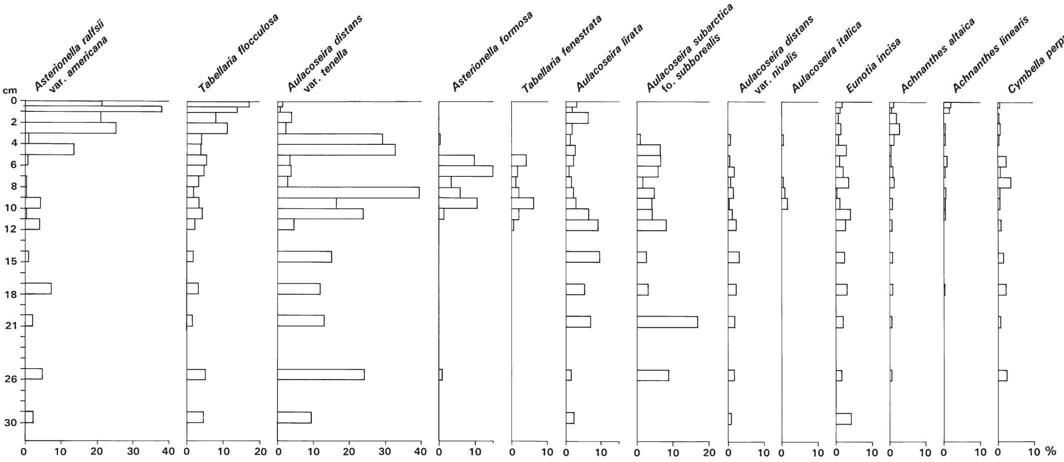

Fig. 8. Sedimentary diatoms in Lake Kalliojärvi: relative abundances of the important taxa are presented.

ralfsii var. *americana* clearly dominates the diatom flora with 38% proportion.

The diatom assemblages indicate high level of humic compounds in the water at the sediment depths of 9 and 5 cm where *Aulacoseira distans* var. *tenella* is abundant. These sediment layers seem to reflect the increase of humic matter due to the forest ditchings in the 1940s and 1960s. According to the results of ignition loss (Fig. 2e) the ditchings in 1968 also caused erosion. The dominance of *Asterionella ralfsii* var. *americana* at the sediment top is an indication of increasing trophic status probably as a consequence of the forest fertilizations. The lake has, however, remained slightly acidic, and the DI-conductivity indicates no change (Fig. 4e). Because the sediment samples from this lake were taken already in 1989 and 1990, the effects of the most recent forest fertilizations, in 1988, are only partly shown in our results. Therefore, it is not possible to judge accurately the extent of this trophic change. Detailed results on our sediment study have been published elsewhere (Sandman *et al.* 1992). For the recent changes of phytoplankton in Lake Kalliojärvi, *see* Lepistö and Saura (1998)

Lake Saarijärvi

There are great changes in element contents in sediments of Lake Saarijärvi. A clear decrease in organic matter from 22 cm upwards reflects an increase of erosion (Fig. 2f). Abrupt changes happen at 16 cm (early 1900s) and 10 cm (1950–60s). The proportion of nitrogen in relation to the organic matter is higher in the top 10 cms indicating growing autochtony. The sediment phosphorus has an early rise from 10 cm towards the sediment surface. The soot spherule stratigraphy shows two possible stages of high erosion (ca. 9–13 and 2–6 cm). As in other lakes with ditched catchments the isotope dating gives too old values in deeper sediments, but both methods indicate that the later erosion period begins in the 1970s. This phenomenon can also be seen in ignition loss results. The drainage basin is in two different parts (with and without preceeding sedimentation basins) and this must have an effect on the expression of catchment events in the sedimentary record.

The sedimentary diatom assemblages below the depth of 20 cm are very different from those of the upper layers (Fig. 9) showing that the environmental conditions in Lake Saarijärvi have changed. Many planktonic species that are common at the sediment top do not occur deeper down. The littoral diatoms that are frequent in the deeper samples are those which are typical of humic and slightly acidic waters: *Eunotia* and *Brachysira* species, *Frustulia rhomboides* and *Aulacoseira lirata* with their varieties.

A slight change of the diatom assemblages begins at about 13–15 cm sediment depth when the planktonic species including *Asterionella formosa, Tabellaria flocculosa IIIp* and *Aulacoseira distans* var. *tenella* begin to increase (Fig. 9). At the same

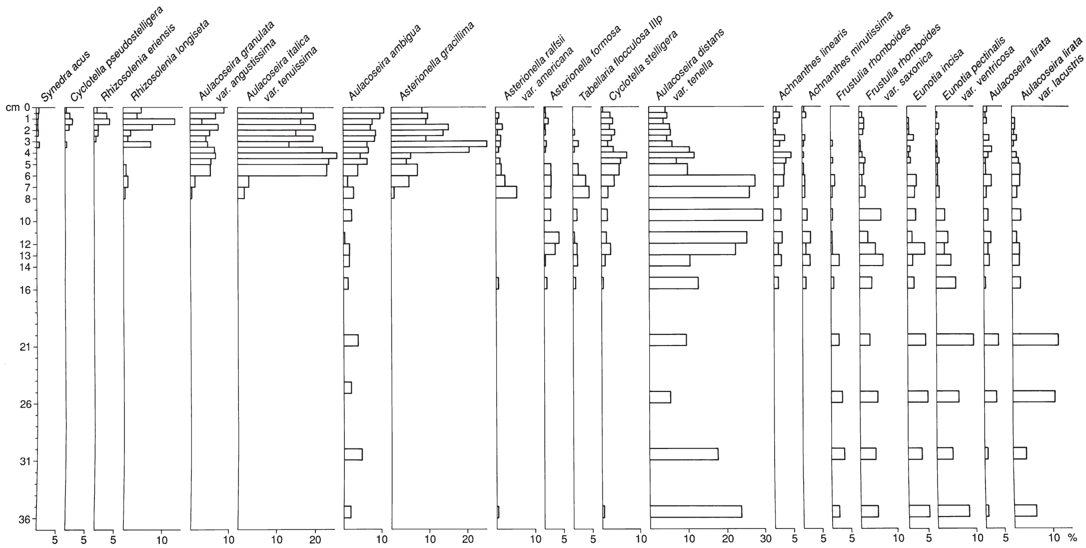

Fig. 9. Sedimentary diatoms in Lake Saarijärvi: relative abundances of the most important taxa are presented.

time, the littoral diatom communities also change. The circumneutral *Achnanthes* species, for example, turn up whereas many acidophilous diatoms, like *Aulacoseira lirata* var. *lacustris* (Grun.) R. Ross decrease. These changes reveal the rise of lakewater pH (Fig. 4f). Several species typical of eutrophic and mesotrophic lakes appear at 8 cm. These include *Aulacoseira granulata* var. *angustissima* (O. Müll.) Simonsen, *Aulacoseira italica* var. *tenuissima* (Grun.) Simonsen, *Asterionella gracillima* (Hantsch) Heiberg and *Rhizosolenia longiseta* Zach. (According to Round *et al.* 1990, the last mentioned taxon belongs to the genus *Urosolenia* as *Rhizosolenia* is a wholly marine genus). At 6 cm, these diatoms become more abundant, and also the relative share of *Aulacoseira ambigua* (Grun.) Simonsen begins to increase. Results of the DCA-analysis reveal the greatest relative diatom change at this level (Fig. 4f).

The sedimentary diatom record implies that Lake Saarijärvi has been a brown water lake for a long time, but some indicator species, e.g. *Aulacoseira distans* var. *tenella* and *Asterionella gracillima*, suggest that the concentration of humic matter has further increased during the second half of this century. This increase is certainly contributed by the forest ditchings. The descending ignition loss shows that erosion started much earlier because this area has been inhabited a long time. The diatom-inferred values of lake water conductivity, pH and total phosphorus increased rapidly in the 1960s. This development was evidently affected by the major forest ditching in 1959. A sudden eutrophication of the lake occurred in the mid 1970s, coinciding with the 100 ha forest fertilization and the additional ditchings. Since then, the same diatom species have dominated the flora suggesting almost no improvement of water quality. At the sediment surface, *Aulacoseira granulata* var. *angustissima, A. italica* var. *tenuissima* and *A. ambigua* comprise up to 38% of all counted frustules.

Discussion

Diatom taxa related to forestry practices

The small planktonic *Aulacoseira distans* var. *tenella* is abundant in many of the investigated cores. In the calibration data set of 89 lakes, this diatom occurs mainly in humic lakes and its estimated optimum of total organic carbon is high: 9.9 mg l^{-1} (Huttunen and Turkia 1994). Eloranta (1986), too, states that *A. distans* var. *tenella* seems to favour slight to moderate degree of dystrophy and dyseutrophy. In some of our study lakes the occurrence of this taxon seems to be related to the effects of peatland ditchings. In other cases, however, the relative abundance of this diatom was considerable in some deeper sediment levels as well, which is here interpreted as an indication of earlier land use events and an increase of allochtonous matter.

Another diatom whose occurrence shows some connections with silviculture is *Asterionella ralfsii* var. *americana*. This taxon was abundant in two cores, Lake Rajalampi and Lake Kalliojärvi (Fig. 7 and 8). But because it is rare in our calibration data set, no indicator values could be estimated; nor is the diatom included in the WA calibration in inferring the lake water characteristics. This is why the inferred values of lakewater pH, conductivity and total phosphorus do not indicate the obvious change adequately in these lakes (Fig. 4d and 4e).

In our calibration data set, *Asterionella ralfsii* occurs in lakes of low pH, high TOC and high aluminium. Its abundance weighted mean pH is only 4.9. *A. ralfsii* var. *americana* has obviously different ecological requirements. Both taxa are reported from more or less acidic waters. The short, nominate type is periphytic and seldom found in plankton. The longer var. *americana* is exceptional because it is planktonic, yet it occurs in acidic lakes at pH values well below 5.8. Charles *et al*. (1990) examined lake sediments in the Adirondack region of the United States and found the nominate type in low pH (< 5.0) lakes of coloured water while var. *americana* was present in lakes of higher pH and clearer water. They considered the nominate form acidobiontic and var. *americana* acidophilous.

In the sediment core of Lake Rajalampi, *Asterionella ralfsii* is abundant at 0–2.5 cm and the variety *americana* at 5–7 cm. We believe that these diatoms are members of the same population, and that the morphological differences may be due to changes of environmental conditions. According to Bellinger (1977) the cell length of *Asterionella formosa* is related to population size, and the same is probably true for *Asterionella ralfsii*. At times of maximum growth smaller cells are obviously better competitors of scarce nutrients. *Asterionella formosa* and *A. ralfsii* can shorten by means other than normal cell division. Kling (1993) presented a mechanism of rapid size reduction and stated that specific environmental conditions like increased phosphorus and low silica concentrations may be responsible for this phenomenon.

Gensemer (1991) showed in his laboratory culture experiments that high aluminium concentrations significantly reduced the growth rates of *A. ralfsii* var. *americana*, and that Al toxicity was pH-dependent. According to Davis *et al*. (1990), the acidification of Mud Pond in Maine led to a decrease of *A. ralfsii* var. *americana*. In their calibration data set of 60 lakes, the abundance weighted mean pH for this diatom is 5.5. Acidification together with the catchment deforestation and harrowing may have increased the aluminium concentrations in Lake Rajalampi.

Reconstructing lakewater quality on the basis of diatom assemblages

Different diatom indices have been developed for the inference of lakewater quality, such as acidity and also the trophic state (e.g. Whitmore 1989). The indices are based on diatom preference groups. This categorizing of taxa is always subjective, and some ecological information is lost because only those diatoms are included for which indicator status are available in the litterature.

The multivariate techniques of detrended correspondence analysis and weighted averaging (WA) regression and calibration are more advanced because they avoid the simple ecological categories. Agbeti (1992) has assessed the advantage of the new methods over a diatom-inferred trophic index. CCA and WA are theoretically superior to multiple linear regression, because they assume that individual diatom species respond in a unimodal, rather than linear manner over long environmental gradients. The use of these direct gradient analyses seems more satisfactory, because they provide a more objective inference of lakewater quality.

Ter Braak and Juggins (1993) tested the weighted averaging method by simulation and presented an improvement based on partial least squares regression. They state that weighted averaging is at its best with noisy, species rich, compositional data, with species that may be absent in many of the samples, and a long ecological gradient (> 3 SD units). Birks *et al*. (1990) have shown that the method of maximum likelihood did not perform as well in pH reconstruction as the simpler, approximating approach of weighted averaging. They recommend WA regression and calibration with classical regression deshrinking as the easiest and most reliable reconstruction procedure currently available.

Modern calibration data sets are needed when using weighted averaging in palaeoecological reconstructions. In the last few years, such data sets have been developed in many countries. The data sets contain information on the local ecological optima and tolerances of diatom taxa. Kingston and Birks (1990) announced that indicators from one region may show different and conflicting relationships elsewhere. Our calibration set of 89 lakes is satisfactory for the palaeoecological estimations of small Finnish lakes, but for bigger lakes a separate calibration set would be required.

Hall and Smol (1992) used weighted averaging in estimating optima of total phosphorus for 131 diatom taxa from 47 lakes in British Columbia, Canada and developed a model for inferring past lake water total phosphorus. Fritz *et al.* (1993) discussed the sensitivity of diatom-based calibration methods for assessing lake trophic change. They used weighted averaging for reconstructing of total phosphorus in four lakes, three of which showed a trend to higher phosphorus concentrations at the time of logging and settlement and a subsequent decline.

Phosphorus in lake sediments is very mobile (e.g. Carignan and Flett 1981). Consequently, sedimentary phosphorus profiles may not always exactly indicate the actual changes of phosphorus loading into a lake. This is especially so in cases when the capability of sediment to bind phosphorus is limited. Nevertheless, phosphorus reconstructions from diatom assemblages by weighted averaging have been used together with the results of the chemical sediment analysis. Anderson *et al.* (1993) compared the concentrations of phosphorus in sediments with the diatom-inferred phosphorus profiles and found them to be highly correlated.

The geochemical changes

Increase of minerogenic matter in the sediment indicates accelerated erosion. This appears commonly to have taken place in the latest times. Especially strong increase is evidenced in Lake Saarijärvi. Earlier forestry measures on drainage basins have often increased only the organic sedimentation. This difference points to the progression in ditching methods. In a summary based on North-American studies (Binkley and Brown 1994) the effects of road construction and harvesting are seen in increased amounts of suspended sediments. In the Nurmes-study (Ahtiainen 1992) the most substantial harmful effect of harvesting and corresponding cultivation was a considerable erosion of solid matter during several years following the measures. The same applies to the effects of peatland ditching.

The erosion caused by clear cutting and tilling seems to be modest in most of our study lakes. One reason is the coarse soil and the prevalence of rocks in the drainage basins of Lakes Rajalampi, Vuorilampi and Nurkka-Saarinen. The leached organic matter seems to cause anoxia and increased humus colouration of the water.

Sediment dating

Dating is the backbone of palaeolimnology. The ^{210}Pb analysis is perhaps the most frequently used method in short-core dating. For lakes with constant rates of sediment accumulation, the ^{210}Pb-derived dates have often been validated by independent dating techniques (e.g. Oldfield and Appleby 1984). Spheroidal carbonaceous particles, emitted from oil and coal combustion, have been used as an indirect dating method (e.g. Renberg and Wik 1984). According to our experience, the ^{210}Pb dating often indicates an age too old for the deeper sediment layers (Sandman *et al.* 1992, Sandman *et al.* 1994), but the soot spherule stratigraphy gives results which agree with the knowledge of the measures in drainage basin.

The soot spherule dating provides only an approximate time scale and may be affected by erosion material with low soot spherule content. This yields difficulties in the interpretation, but can give information about erosion phases in the past. The soot spherules are chemically resilient, and the effect of bioturbation can only level down the differences.

Conclusion

Lake Saarijärvi displays a very marked eutrophication history. The sedimentary results indicate that this lake was previously oligotrophic but turned eutrophic later, probably as a result of forestry practices in the catchment area. In the other lakes, the forestry operations appear to have caused less pronounced trophic alterations; especially in Lake Vuorilampi the recent changes are negligible. In some of the study lakes, the stratigraphic changes of diatom assemblages indicate an increase of humic matter in water. In addition, scattered records of blue-green algal blooms suggest an increase of nutrient concentrations.

A considerable load of nutrients into Lake Saarijärvi apparently comes from a peatland that has been ditched and fertilized several times. The input of nutrients from arable fields must be small, the field area being only about 10 ha here. Other anthropogenic loads should also be negligible. Recent analyses of water quality indicate that oxygen depletion causes phosphorus release from the sediment both in winter and late summer when also blooms of blue-green algae have been recorded. It is clear that an effective fertilization may dramatically change the trophic state of a lake (e.g. Simola 1983). The decreasing C/N ratio reflects a rise in the total biological productivity of the lake.

There have been attempts in Finland to diminish the minerogenic sediment load from treated catchments with the aid of sedimentation basins dug within the artificial drainage networks, but the results are not very promising. Furthermore the often quite coarse minerogenic fraction is poor of elements; especially phosphates tend to be incorporated into the organic constituents of runoff and are thus not readily retained in the sedimentation basins. There are many mechanisms for transfer of phosphates from drainage basin to lake sediments; the phosphorus may enter sediment directly with allochtonous organic matter (Boström *et al.* 1988), or it may enhance autochtonous production in the lakes. Eroded organic matter may cause anoxia that leads to phosphorus escape from sediments (e.g. Nürnberg 1987). Sedimentary phosphorus anomalies that point to this feature are evident in Lakes Rajalampi and Saarijärvi.

The possibilities to prevent eroded organic matter from entering the recipient lakes should be examined. In soil and sediments with large amounts of iron and aluminium hydrous oxides, sorption-desorption reactions are largely responsible for determining the level of orthophosphate in the solution at equilibrium (Holtan *et al.* 1988). The possibilities to bind the phosphorus escaped from soil, with e.g. iron compounds, should be considered especially in cases of fertilized catchments.

The narrow protective zones around the lakes Rajalampi and Nurkka-Saarinen have obviously provided very little shelter from the material inflow. Lakes Vuorilampi and Rajalampi are exposed to acid rain in South-Eastern Finland. This may have an effect on the leached elements and pH of the lake water. Comparing the results of Lakes Rajalampi and Vuorilampi, it is apparent that clear cutting and harrowing caused a marked change of water quality whereas clear cutting and screefing only had a minor effect.

In Finland, the best (fine-grained) soils have been largerly taken into cultivation. Thus, for studies of forestry effects on lakes, catchments with meagre soils will probably be over-represented, and our results may therefore be partly misleading. If one wants to view separate measures of forestry practices, there will be great difficulties to find satisfactory drainage basins and lakes as the different operations have often followed closely one another.

The impacts of forest management on lakes appear to be long-lasting (e.g. Ahtiainen 1993). There are evident difficulties in dating forestry changes with ^{210}Pb (Sandman *et al.* 1992, Sandman *et al.* 1994), and the soot spherule dating unfortunately does not provide a very exact chronology. The results of this study support the view that the effects of modern forestry practices will typically prevail several years in individual cases (*see* also M. Saura, T. Sallantaus, Ä. Bilaletdin & T. Frisk unpubl.) As forestry operations (e.g. forest ditchings and clear cuttings) are being continuously pursued on most catchments, also the effects on lakes tend to be long-lasting or permanent.

Acknowledgements: We thank Kaarle Kenttämies from the Finnish Environment Institute for his valuable comments and assistance in the fieldworks. The study was financed by the METVE joint research project. The Regional Environment Centres of Uusimaa, Häme, South-East Finland and South Savo gave readily sampling aid. Pirjo Piipari analyzed the sediment chemistry and counted the soot spherules accurately in the laboratory of South Savo Regional Environment Centre. We are also very grateful to Heikki Simola from the University of Joensuu for a careful revision of the manuscript.

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Received 20 November 1996, accepted 26 February 1998