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Forestry in catchments: Effects on water quality, plankton, zoobenthos and fish in small lakes

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Limnological responses of three small forest lakes in eastern Finland to forest clear cutting and soil scarification (in 15–33% of their catchments) were studied in 1991–1994, and compared with one reference lake. Increases in the concentrations of total phosphorus and iron indicated an increased inorganic load whereas the increase in water colour and chemical oxygen demand suggested an increased load of organic matter. No such changes were recorded in the reference lake. No clear response in phytoplankton biomass to catchment forestry was recorded. However, the changes in species composition, e.g. a bloom of cyanobacteria in one of the lakes in autumn 1993, indicated a slight eutrophication. Periphyton growth increased after the forestry operations resulting in increased concentrations of chlorophyll *a*. Zooplankton densities, both cladocerans and copepods, increased slightly in two of the lakes. Zoobenthos abundance increased in all the study lakes but increased biomass was recorded in only one. Population structure and growth of perch (*Perca fluviatilis*) remained unchanged in all the experimental lakes and in the reference lake, suggesting that there were no dramatic changes in the habitat of fish. Observed changes in zooplankton and zoobenthos community composition were also reflected in the diet of perch. The maximum Hg concentration in perch, 1.6 mg kg^{-1} (ww), was measured in a 19-year-old fish of 16.9 cm in total length. Otherwise, the mean Hg contents of 15 cm long perch were 0.4–0.8 mg kg^{-1} (ww), except in the reference lake where the mean concentrations were 0.1–0.2 mg kg^{-1}. After the clear cutting and soil scarification a slightly decreasing trend in Hg concentrations in perch was recorded. Generally, the limnological responses to catchment forestry were modest, partly due to the protective zones of ca. 50 m in width left at the shores of the lakes according to the recent recommendations of forest management in Finland.

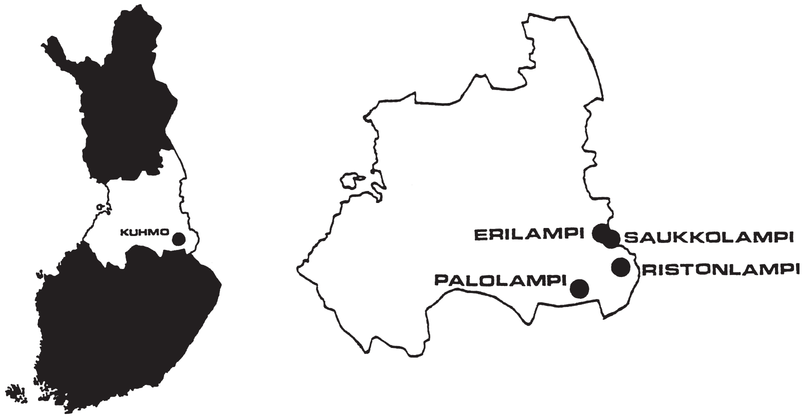

Fig. 1. The location of the studied lakes.

Introduction

Manipulations of silviculturales in catchments of lakes and rivers can affect the loads of elemental nutrients and organic compounds into waters thus changing the physicochemical and biological properties of aquatic ecosystems and thereby the living conditions of plankton, zoobenthos and fish (Ramberg 1976, Gregory *et al*. 1987). In some areas, forestry management, including clear cutting, ditching, scarification and other manipulations, is the most widespread type of land use. About two-thirds of the Finnish land area is forested and almost 80% of that is under silvicultural management. However, with only a few exceptions (Holopainen *et al*. 1991, Rask *et al*. 1993), little attention has been paid to forestry-induced limnological changes in Finnish lakes and running waters.

Generally, studies on effects of forestry have been focused on brooks and rivers (Hansmann & Phinney 1973, Murphy & Hall 1981, Bormann & Likens 1985, Simonsson 1987, Ahtiainen 1988, Holopainen *et al*. 1991, Holopainen & Huttunen 1992), whereas there are only some studies on the effects on lake ecosystems (Bormann & Likens 1985, Simonsson 1987, Rask *et al*. 1993). The knowledge of responses of lakes to forestry practices is largely based on whole-lake fertilization experiments (Schindler & Fee 1974, Jansson 1978, Langeland & Reinertsen 1982). Experimental studies on predation efficiency of common fish species under different light, thermal or oxygen conditions (Bergman 1988, Persson 1986, Tonn *et al*. 1992) can provide useful and applicable information.

In this study limnological characteristics of three small forest lakes were studied before, during and after forestry operations in their catchments and compared with an undisturbed reference lake.

Material and methods

The study was started in 1991 in Kuhmo, eastern Finland. Four small lakes (area 3–10 ha, maximum depth 4–9 m) in Kuhmo state forests were chosen for the investigation (Fig. 1). The lakes were oligotrophic or mesotrophic and acidic (pH 5.4–6.7) with moderate concentrations of humic substances (colour 70–140 mg Pt l^{-1}). The common fish species in the lakes were the European perch (*Perca fluviatilis*) and northern pike (*Esox lucius*). The catchments of the lakes, from 24 to 104 ha in area, were almost pristine at the onset of the study and they were covered with coniferous forests (scots pine and Norwegian spruce) and peatland.

In the summer 1991, a background study was conducted on the main limnological features of the lakes. In winter 1992, forestry treatments started in the catchments of three of the lakes Palolampi, Erilampi and Saukkolampi. The fourth lake, Ristonlampi, and its catchment were left untreated, and was used as a reference. In the treated catchments of Palolampi, Erilampi and Saukkolampi, 15, 24 and 33% of the area, respectively, was clear cut during 1992. Further, in early summer 1993, soil scarification was carried out in 15, 22 and 31% of the catchment area of the three lakes. According to the recent Finnish recommendations, a forested protective zone of 20–50 m in width was left at the shores of the lakes. The soil scarification was completed before the biological samples of summer 1993 were taken.

Water samples from the epilimnion, metalimnion and hypolimnion were taken with a Ruttner-type sampler (2 dm^3) in permanent sampling points in the middle of the lakes and from a littoral point four times each year. A total of 23 water quality parameters were analysed according to the Finnish standard methods (Mäkelä *et al.* 1992), and changes in the following are presented in this paper: chemical oxygen demand (COD), colour, total organic carbon (TOC), oxygen, total nitrogen, total phosphorus, inorganic phosphorus, potassium, iron, pH and alkalinity. Differences in the water quality parameters of the experimental lakes before and after the soil scarification were tested with Mann-Whitney *U*-test.

Composite samples (0–2 m and 2–4 m) for chlorophyll *a*, phytoplankton biomass and species composition evaluations were taken with a Ruttner sampler (2 dm^3) three times per year during July–September. Periphyton was sampled from lakes Erilampi, Saukkolampi and Ristonlampi 1–2 times per year during July–August. Polyacrylic plates (100 × 150 mm) were incubated at the depth of 0.4 m on an anchored stand for three weeks at a time. Composite samples of zooplankton (0 to 2 m, 2 m to bottom) were taken three times in July–September with a 6.5 dm^3 tube sampler in the middle of each lake. For details of processing of samples, see Arvola *et al.* (1986) and Rask *et al.* (1986). Zoobenthos was sampled with a Kajak-type tube sampler (54 cm^2) in September from five permanent sampling points per lake; five lifts from a point were pooled for one sample. Four of the sampling points were located at the depth of 2–3 m whereas the fifth was at the deepest point of the lake. The samples were sieved with a 0.5 mm mesh sieve and preserved in 70% ethanol.

Fish was sampled once a year during August with a series of eight gill nets (1.8 × 30 m) with mesh sizes varying from 12 to 60 mm. For details of sampling, see Raitaniemi *et al.* (1988). Age and growth determinations of fish were based on opercula and otoliths (perch), and cleithrum (pike) (Bagenal & Tesch 1978). A volumetric point method (Windell 1971) was used in diet analyses. Samples for mercury determination were taken from the dorsal axial muscle and kept frozen until the analysis.

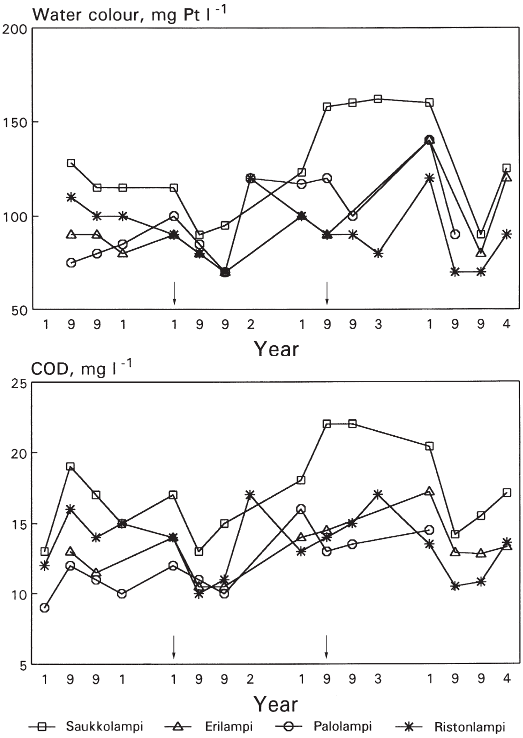

Fig. 2. The water colour (top) and the chemical oxygen demand (bottom) in the surface water of the study lakes in 1991–1994. Clear cutting took place in winter 1992 and soil scarification in early summer 1993 (arrows).

Concentration of total mercury was determined from HNO_3:H_2SO_4 (1:4) digestion using CVAAS (Armstrong and Uthe 1971).

Results

Water quality

Effects of forestry practices on water quality were recorded in the studied lakes with treated catchments. COD and the water colour increased (Fig. 2) at the end of the investigation period indicating an increased load of organic matter from the catchment after soil scarification. The increase in water colour was 25–50% ($p < 0.05$) in Saukkolampi and Palolampi. The chemical oxygen demand increased with 20–30% ($p < 0.05$) in Saukkolampi. No changes in the reference lake were recorded. Mean concentration (± SD) of TOC increased from 8.0 ± 1.5 mg l^{-1} in 1991 to 12.9 ± 2.8 mg l^{-1} in 1993. Despite of the increase in or-

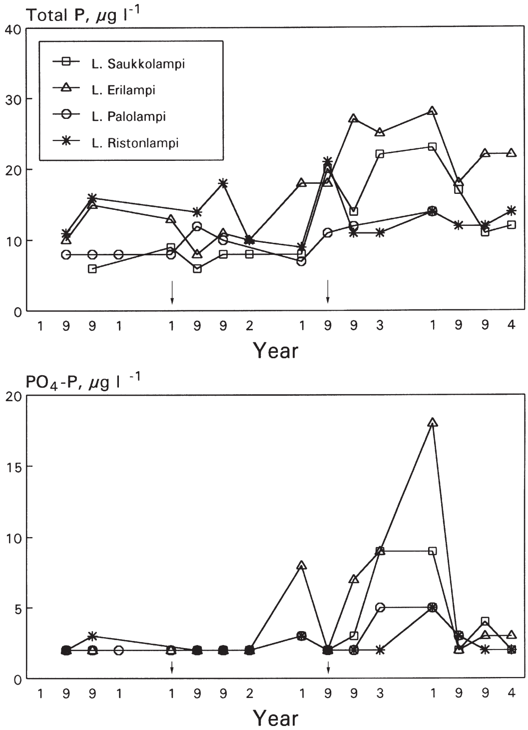

Fig. 3. The concentrations of total phosphorus (top) and phosphate phosphorus (bottom) in the surface water of the study lakes in 1991–1994. Clear cutting took place in winter 1992 and soil scarification in early summer 1993 (arrows).

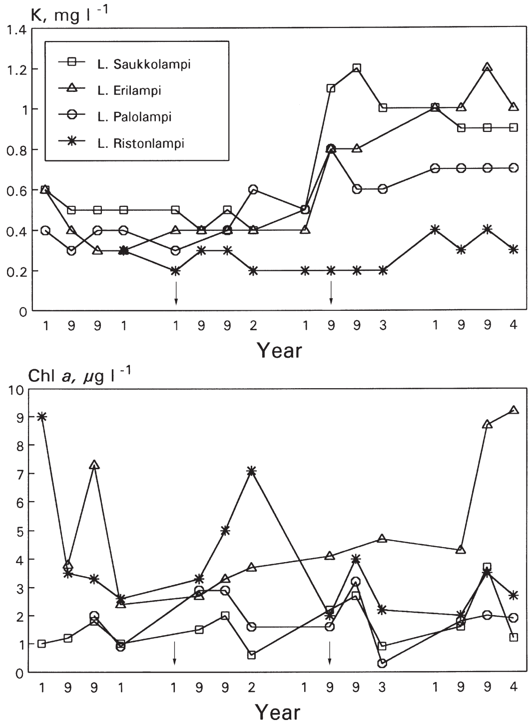

Fig. 4. The potassium concentrations (top) and the chlorophyll *a* concentrations (bottom) in the surface water of the study lakes in 1991–1994. Clear cutting took place in winter 1992 and soil scarification in early summer 1993 (arrows).

ganic load, no drastic changes in the metalimnetic or hypolimnetic oxygen conditions were recorded. For example, in March 1994 an oxygen concentration of 6.4 mg l^{-1} was measured in Saukkolampi at 7.5 m depth and 5.1 mg l^{-1} in Erilampi at 5 m depth indicating fairly good oxygen conditions. In Erilampi, the oxygen concentration at 7.5 m was 1.8 mg l^{-1} in March 1994 but the same value was alredy observed in 1991 before the forestry treatments.

Total nitrogen and phosphorus concentrations in the study lakes before the forestry treatments varied from 200 to 400 µg l^{-1} and 5 to 20 µg l^{-1}, respectively. After the treatments, the total concentrations were at the levels of 300–500 µg l^{-1} and 15–30 µg l^{-1}, respectively (Fig. 3). The difference in total phosphorus concentrations before and after the impact was significant in the treated lakes ($p < 0.5$ for Erilampi and Palolampi, and $p < 0.01$ for Saukkolampi). The PO_4-P concentrations before the forestry treatments were generally below the detection limit, but increased temporarily to 10–15 µg l^{-1} after the soil scarification in 1993 (Fig. 3). Among the base cations, potassium concentrations increased clearly ($p < 0.01$, Fig. 4) in the lakes with treated catchments. Alkalinity and pH in all four lakes remained at the same levels as measured before the forestry activities (pH 5.5–6.7, alkalinity 0.02–0.1 mmol l^{-1}).

Hydrobiology

Mean annual phytoplankton biomass remained relatively constant in all the experimental lakes, at 0.3–1.8 mg l^{-1} (ww). In the reference lake, Ristonlampi, which was more productive than the experimental lakes, the mean biomass of phytoplankton was 13.5 mg l^{-1} in 1993. In all four lakes the highest biomass was measured in 1992 or 1993. Chlorophyll *a* concentrations were low, and ranged from 1–3 µg l^{-1} in Saukkolampi to 2–9 µg l^{-1} in Erilampi

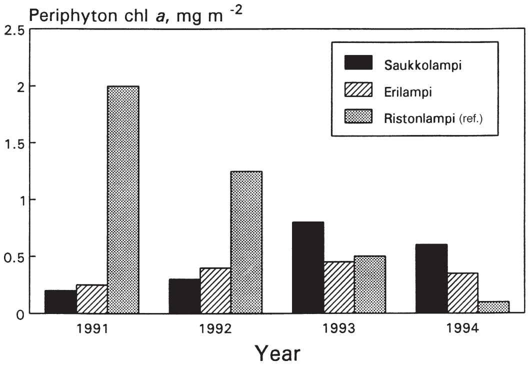

Fig. 5. Concentrations of chlorophyll *a* of periphyton in three lakes during 1991–1994.

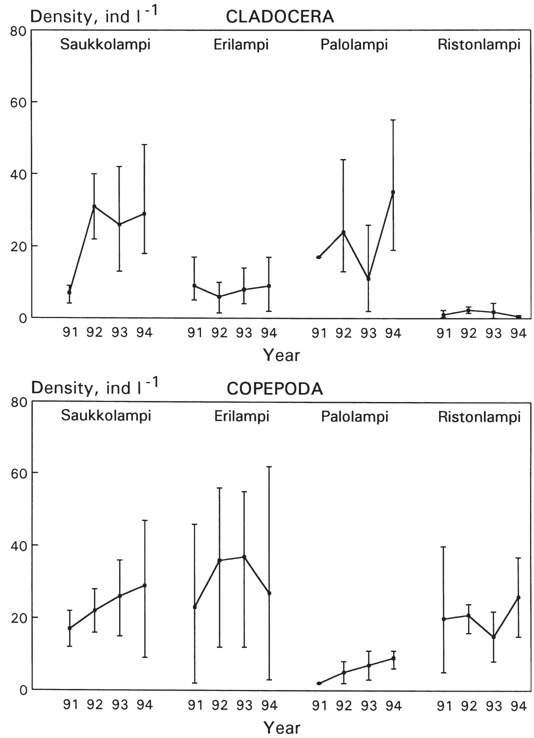

Fig. 6. The mean densities of crustacean zooplankton in the study lakes in 1991–1994, cladocerans (top) and copepods (bottom) given separately. Vertical bars = range.

and Ristonlampi (Fig. 4). The dominant algal groups (> 50% of the annual mean biomass) were Diatomophyceae in Palolampi and Saukkolampi in 1993 and in Erilampi and Ristonlampi in 1994, Cryptophyceae in Palolampi in 1992 and 1994 and Conjugatophyceae in Saukkolampi in 1991 and 1994 and in Ristonlampi in 1993.

Between 1991 and 1993, the amount of periphyton measured as chlorophyll *a* increased in the experimental lakes. In Erilampi the amount was doubled and in Saukkolampi the increase was fourfold, whereas in the reference lake a clear decrease was recorded (Fig. 5).

In the species composition and density of rotifers no systematic changes caused by forestry practices could be detected. In lakes Saukkolampi and Palolampi, a slight increase in the densities of the crustacean zooplankton was recorded (Fig. 6). Dominant rotifer species in Erilampi were *Conochilus unicornis* and *Keratella cochlearis*, in Saukkolampi *Polyarthra* sp. and *Keratella cochlearis,* in Palolampi *Kellicottia longispina*, and in Ristonlampi *Conochilus* sp. In all the experimental lakes, the most abundant zooplankton species was the cladoceran *Bosmina longispina*. Other common species were *Holopedium gibberum* (Erilampi and Palolampi), *Daphnia cristata* (Erilampi) and the copepod *Eudiaptomus graciloides* (Saukkolampi). In the reference lake, Ristonlampi, the density of cladocerans remained very low throughout the study period (Fig. 6) and the zooplankton community was dominated by copepods.

The total density of zoobenthos at 2–3 m depth in the study lakes varied from 900 to 13 800 ind. m^{-2}, and the total biomass between 1.3 and 12.4 g m^{-2} (ww) (Fig. 7). An increasing trend in the mean density of zoobenthos was recorded in all the experimental lakes, but also in the reference lake, Ristonlampi. This was cased by the increased density of chironomid larvae that always made up at least 50% and sometimes > 80% of the zoobenthos community (Fig. 8). The total biomass increased clearly only in Erilampi (Fig. 8). This was mainly due to the increased biomass of the small bivalve, *Pisidium* sp. In addition to it and chironomid larvae that could make a contribution higher than 3 g m^{-2} to the total zoobenthos biomass, only Neuroptera larvae exceeded a biomass of 1 g m^{-2}.

Fish

During the study period, population structure and growth of perch remained rather unchanged in all the experimental lakes suggesting that there were no clear changes in fish habitat and food supply caused by the forestry practices. The mean catches

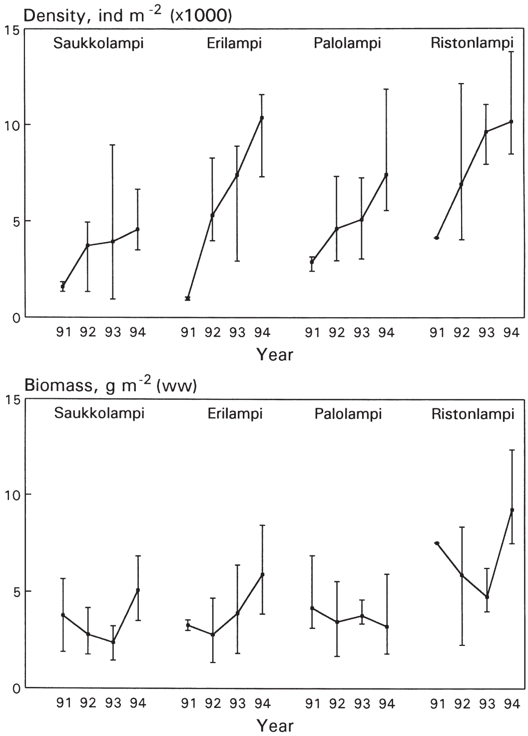

Fig. 7. The mean densities (top) and biomasses (bottom) of zoobenthos in the study lakes in 1991–1994. Each value is based on four (experimental lakes) or five (reference lake) samples taken from 2–3 m depth. Vertical bars = range.

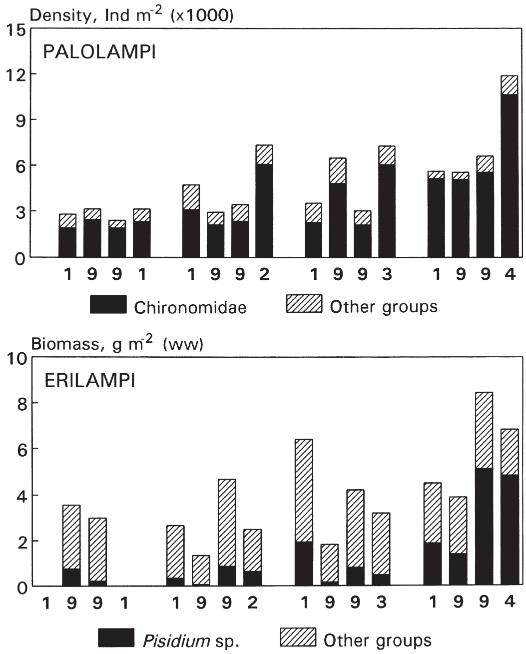

Fig. 8. The total density of zoobenthos in Palolampi (top) and the total biomass of zoobenthos in Erilampi in 1991–1994.

per gill net series (CPUE) varied from 3.6 kg in Saukkolampi to 12.7 kg in Palolampi. The proportions of perch in the catches were 71 and 97%, respectively. The mean CPUEs in Erilampi and in the reference lake, Ristonlampi, were 6.2 and 6.9 kg, with 93 and 75% of perch, respectively. The rest of the catch consisted of pike, and in Palolampi, also whitefish (*Coregonus* sp.) introduced to the lake during 1984–1988. The mean number and weight of perch in the catches in the experimental lakes were 190–230 and 13–45 g, respectively, whereas in the reference lake 66 and 59–113 g, respectively.

The growth of perch in the experimental lakes was slow (Fig. 9). The fish reached the mean length of 15 cm at the age of 5–6 years and the mean length of a ten year old perch was only 16–18 cm. In the reference lake the perch grew faster, exceeding the mean length of 20 cm during the sixth growing season. The comparison of back-calculated perch growth from the catches in 1991 and 1994 showed that no clear changes took place during the study and that the order of the growth rates among the lakes remained similar (Fig. 9).

The changes in the zooplankton and zoobenthos communities in some of the lakes were reflected in the diet of perch. In Saukkolampi, where the density of crustacean zooplankton increased after clear cutting but no increase in the zoobenthos biomass was recorded, zooplankton became more dominant in the diet of perch. In Erilampi, where the zoobenthos biomass increased but no clear change in zooplankton was recorded, the perch fed more on zoobenthos (Fig. 10). In the reference lake the diet of perch was unusual; large perch fed on zooplankton more than small perch (Fig. 10). Many perch larger than 30 cm in total length had their stomach full of *Bythotrephes cederstroemi*, a large predatory cladoceran.

The highest mercury concentrations in fish were recorded in Saukkolampi. The maximum Hg concentration in perch, 1.6 mg kg^{-1} (ww), was measured in a 19-year-old male fish of 16.9 cm in total length. In pike, the highest Hg concentration was 3.6 mg kg^{-1} (ww), measured in a 10-year-old female fish of 1.65 kg. Generally, the mean Hg concentrations in 15–20-cm perch were 0.4–0.8 mg kg^{-1} (ww) except in the reference lake, Ristonlampi, where the mean concentrations were around 0.1 mg kg^{-1} (Fig. 11). In that lake, the highest mercury concentration in pike was also fairly low, 0.61 mg kg^{-1}, measured from a 7-year-old 1.8 kg individual. After clear cutting and soil scarification a slight decrease in the perch mercury concentrations was recorded in Erilampi and Saukkolampi (Fig. 11).

Discussion

Water quality

Clear cutting seemed to have little effect on water quality as no changes were detected in 1992. The appearance of more clear changes after soil scarification in 1993 suggests that this treatment was the major cause of the limnological changes. Furthermore, the clearest responses were recorded in Saukkolampi where the largest proportion (33%) of the catchment was subject to forestry treatments. Between Palolampi and Erilampi (15% and 22% of the catchment treated, respectively) no difference could be seen.

Changes in surface water quality are commonly caused by catchment forestry. Most records so far are from running waters (Gregory *et al.* 1987, Simonsson 1987, Ahtiainen 1988) but changes were also observed in lakes, especially in small headwater lakes (Ramberg 1976, Simonsson 1987). In the lakes of this study the increase in organic or inorganic load was less striking than in the study of, a small lake, Nimetön, in southern Finland (Arvola *et al.* 1990, Rask *et al.* 1993). In lake Nimetön increases in nutrient concentrations were accompanied with increased pH and alkalinity, and decreased meta- and hypolimnetic oxygen concentrations. In the case of lake Nimetön, a larger proportion, i.e. about half of the catchment, was deforested and the logging waste burned. In the present study, protective zones may have mitigated effects of the logging by reducing the load of substances to the lakes. In a long-term study of brook catchments it was shown that a 10–50 m protective zone alongside the brook efficiently reduced the organic as well as the inorganic load to the brook (Ahtiainen 1988).

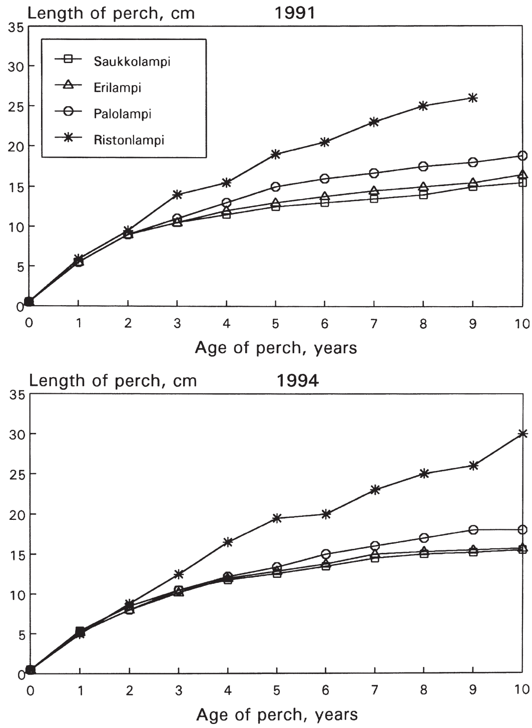

Fig. 9. Back-calculated growth of perch in the study lakes in 1991 and in 1994.

Hydrobiology

The conditions for phytoplankton in lakes can be affected by the increase in humic substances and subsequent changes in light conditions as well as by the increase of nutrient levels (Simonsson 1987). The responses of phytoplankton to the catchment forestry in this study resembled those in Nimetön (Rask *et al.* 1993) although they were not as clear. In Nimetön the doubling of mean chlorophyll *a* concentration and the three to six-fold increase in primary production was a clear indication of eutrophication. Similarly, an increase in the amount of Diatomophyceae was recorded as well as blooms of cyanobacteria. Observations of increased growth of periphytic diatoms on passive fishing gear in the lakes subject to catchment forestry (S.-L. Markkanen, pers. comm.) support the view that in lakes diatoms are commonly favoured by catchment forestry. As opposed to the lakes, in the brooks of the Nurmes Research, eastern Finland, Cryptophyceae showed the most prominent increase after clear cutting and soil scarification in the catchments

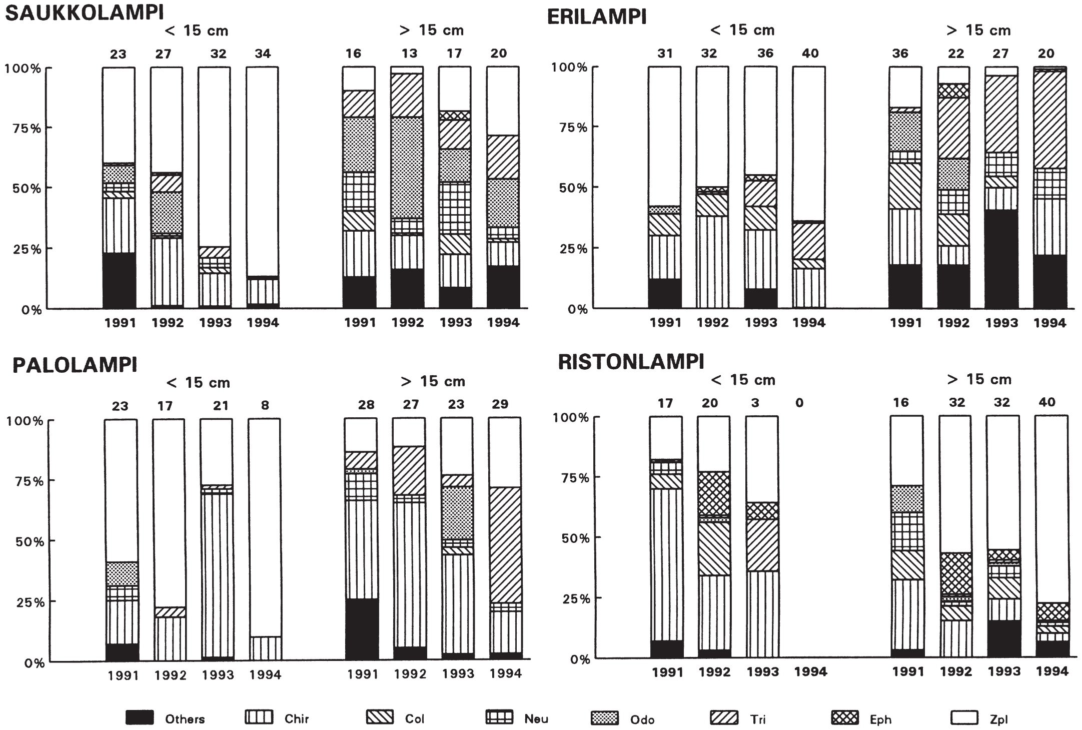

Fig. 10. The proportion of crustacean zooplankton (the uppermost part of the columns) and zoobenthos (the rest of the columns) in the diet of perch < 15 cm and > 15 cm total length in the study lakes in 1991–1994. Chir = Chironomidae, Col = Coleoptera, Neu = Neuroptera, Odo = Odonata, Tri = Trichoptera, Eph = Ephemeroptera, Zpl = zooplankton. Number of examined fish is given above each column.

(Holopainen & Huttunen 1992).

As in this study, only a slight increase in the phytoplankton biomass was recorded in two small Swedish lakes after ditching of the catchment (Bergquist *et al*. 1984). The increase in periphyton growth in our study was similar to that recorded by Marja-aho & Koskinen (1989) in lakes downstream of a peat mining area. The very different pattern of periphyton growth in the reference lake Ristonlampi compared with the experimental lakes, and the differences in other biological parameters as well, indicate that Ristonlampi was not a very good reference lake for hydrobiological comparisons.

Increasing amounts of inedible particles can reduce the filtering efficiency of cladocerans, whereas higher numbers of edible algae are beneficial to them (Simonsson 1987). In the study of lake Nimetön, the species dominance in the zooplankton community varied all along the five year study period (Rask *et al*. 1993). However, the variations were thought to be due to the occurrence of strong year-classes of plankton-eating perch rather than increased abundance of edible algae. In the lakes we studied, the effect of catchment forestry on the abundance of crustacean zooplankton was slightly positive, whereas negative effects were reported in a small lake in Sweden (Bergquist *et al*. 1984).

Forestry-induced changes in water quality may be harmful or beneficial to zoobenthos. A clear decrease in the thickness of oxygenated epilimnion as recorded in lake Nimetön (Rask *et al*. 1993) simply reduced a large part of the zoobenthos habitat, thus limiting its occurrence. Certain species like small *Pisidium* and some chironomid larvae may be positively affected by the increased sedimentation of particulate organic matter (Marja-aho & Koskinen 1989). This could explain the incease in the zoobenthos biomass in Erilampi and the increasing zoobenthos density in all the experimental lakes.

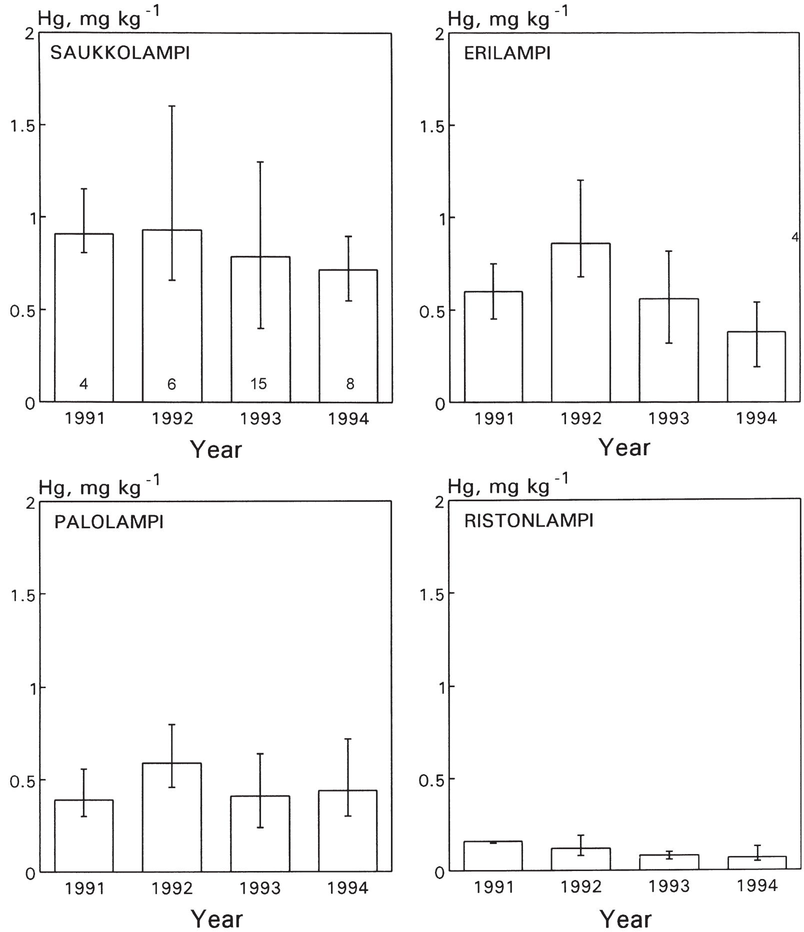

Fig. 11. The mercury concentrations of 15–20 cm long perch in the study lakes in 1991–1994. The number of analyzed samples is given in each column. Vertical bars = range.

Fish

The average catch of 200 perch per gill net series suggests a high population density in the experimental lakes. This is also supported by the very slow growth of the fish indicating a possible intraspecific food competition, and, occasionally, lack of food. This is typical of small humic forest lakes in Scandinavia (Alm 1946, Nyberg 1979) and Finland (Sumari 1971, Lappalainen *et al.* 1988, Rask 1989). In the reference lake, Ristonlampi, the conditions for perch were different from those in the experimental lakes. This resulted in large differences in all the measured parameters. The perch were larger but less numerous. Their growth was good, comparable to the Baltic coastal waters or large lakes (Koli *et al.* 1989, Rask & Raitaniemi 1988). Their diet was exceptional, as there are not many records on large perch (> 30 cm) feeding on zooplankton (cf. Klemetsen 1973). The faster growth of perch in Ristonlampi compared to other study lakes might be connected to the shallowness (2–3 m over the whole basin) of the lake which may enhance the productivity of benthic food chains and can be reflected in the functioning of the whole lake ecosystem. The higher productivity could also be the reason for the abundance of the predatory cladoceran (*Bythotrephes cederstroemi*).

The increasing trends in zooplankton and zoobenthos densities in some of the lakes might indicate of improved food availability for the perch. However, changes in the growth of fish were still very small. Besides, perch as a visual predator prefers large and motile benthic animals (Craig 1987). Therefore, increased in numbers of small bivalves, as in Erilampi or small chironomid larvae, as in all the experimental lakes, do not necessarily improve the food resources of perch. No negative effects of water quality changes on the perch populations were recorded, either. Changes in critical parameters like acidity, oxygen conditions and iron concentrations were so small that no responses of fish could be expected. As perch can thrive in dark-coloured waters (Sumari 1971, Rask 1989), the increasing trend in water colour could not have had any detrimental effects on its success as a predator.

Generally, perch and pike (and roach, *Rutilus rutilus*, in waters above pH > 6) are the common species best adapted to the special conditions of humic lakes of northern Europe (Sumari 1971). They are able to complete their entire life cycle in littoral waters and do not need hard bottoms for spawning, or oxygenated cool hypolimnetic waters during the warm season. This is why species like ruffe (*Gymnocephalus cernuus*), burbot (*Lota lota*), vendace (*Coregonus albula*) and whitefish can suffer more from the increased organic and inorganic load caused by the catchment forestry. Although no special surveys on the forestry-induced impacts on fish communities in lakes are available, it has been shown in other studies that increases in parameters like water colour or COD are negatively correlated with the catches or presence of coregonid species or the burbot (Ranta & Lindström 1990, Tonn *et al*. 1990).

Mercury concentrations of > 1 mg kg^{-1} (ww) in perch are very high considering that the lakes and their catchments were pristine until recently (Metsälä & Rask 1989). It has been shown that mercury tends to accumulate more effectively in food chains of humic lakes than in clear water lakes (Mannio *et al*. 1986, Metsälä & Rask 1989, Meili 1991) resulting in high mean mercury contents in fish of humic headwater lakes. This phenomenon may be associated with several properties of humic substances as summarized by Verta (1990): (1) humic substances can act as carriers of Hg and possibly also methyl Hg from the catchment or from sediments into lake water, (2) humic substances can cause abiotic methylation of mercury in the catchment and in the lake, and (3) microbial methylation of mercury may take place during the degradation of humic substances in water. Forestry operations in the catchment affect the load of both mercury and humic substances to the lakes, and thereby possibly increases the bioaccumulation of mercury in aquatic ecosystems (Lodenius 1983). However, in this study a slight decrease in the Hg concentration in perch was recorded. The most probable explanation is that the changes in water quality after the clear cutting and soil scarification affected the dynamics and enrichment of mercury in the food chains. However, this needs to be proven with a more detailed study.

Conclusions

The changes in the water chemistry showed that the forestry treatments, especially the soil scarification, increased both the organic and the inorganic load from the catchment to the lake. The increase in the periphyton chlorophyll *a* and the bloom of cyanobacteria in one of the lakes were indications of a slight eutrophication. The increased abundance of zooplankton and zoobenthos in some of the lakes suggest that the overall productivity of the lake ecosystems increased temporarily. The changes in the abundance of zooplankton and zoobenthos were reflected in the diet of perch but otherwise, no changes in the fish populations were observed.

The slight decrease in mercury concentrations in perch emphasize the complexity of the Hg dynamics in the catchment-lake system. An expected increase in the mercury load to the lake did not result in higher concentrations at the top of the food web.

It has to be kept in mind that the pre-treatment record of only one year as well as the entire study period of four years presented here are very short. It is probable that another four-year monitoring is needed until all changes in the lake ecosystems to the catchment manipulations may become obvious.

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