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Long-term effects of forestry managements on water quality and loading in brooks

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The concentration of suspended solids in a meso-eutrophic basin remained unchanged in the years following clear felling (1983–85). The amount of suspended solids increased upon ditching, ploughing and mounting to a mean level of 81.8 mg l^{-1} in 1986–88, decreased to a level of 7.8 mg l^{-1} for 1989–91 and 4.5 mg l^{-1} for 1992–94. Total phosphorus concentration increased four-fold (142 µg l^{-1}) in 1983–85 following clear felling, and remained at three times the reference concentration (95.4 µg l^{-1}) in 1986–88 following ditching and site preparation. Phosphate phosphorus concentration increased more than five-fold after clear felling (97.8 µg l^{-1}) in 1983–85 and was more than two-fold the reference (39.5 µg l^{-1}) following ditching and site preparation in 1986–88. The concentrations of total phosphorus and phosphate phosphorus returned to the level recorded in a natural state by 1989 onwards. Total nitrogen concentrations doubled (965 µg l^{-1}) upon clear felling, and remained the same after ditching and site preparation in 1986–88. Where a protective strip of forest was left between the felling site and the brook, suspended solid did not increase in response to either clear felling or ploughing of the felled area, nor were any changes observed in total phosphorus, phosphate phosphorus or nitrogen componds.The ditching of peatland down to the level of the mineral soil led to an increase in the suspended solid concentration (17.8 mg l^{-1}) by a factor of more than 12 in the first three years (1983–85) and by a factor of more than four (5.7 mg l^{-1}) in the following three years (1986–88) compared with the reference period. Total nitrogen, nitrate and nitrite concentrations of ground water were markedly low all the time the forests remained in their natural state, but began to rise gradually following clear felling. A high increase was recorded as a consequence of ditching and site preparation.

Introduction

As point loading of lakes and rivers has diminished as a cause of eutrophication, diffuse loading has gained in importance, with eutrophication, turbidity and silting up being observed in areas where forestry is the main form of land use (Kauppi *et al.* 1990, Heikkilä 1991, Ollikainen 1992, Sandman *et al.* 1994a, 1994b, Vuori and Joensuu 1996).

Forestry in Finland over recent decades has been characterized by large-scale ditching of mires, the clear felling of extensive areas, with associated site preparation before replanting, fertilization of the forests and the construction of a comprehensive network of forest roads. It is inevitable that the cumulative effects of these managemeants will be seen in the lakes and rivers even though forestry methods are improved.

The leaching or washout of nutrients and inorganic solid matter from catchments occupied by natural, undisturbed forests is usually of minimal importance (Kauppi 1979, Rosen 1982, Ahtiainen 1988, Rekolainen 1989, Alasaarela 1995, Finer *et al.* 1995), although the proportion of mires has some effect on the washout of organic matter (Kauppi 1975). The amounts of solid particles, organic matter and nutrients contained in runoff water are dependent on precipitation, the hydrological conditions and movements of water in the soil, the properties of the loose deposits, the topography of the area and the vegetation of the catchment and the stage in the vegetation succession (Lepistö and Kivinen 1994).

The effects of various felling and soil preparation techniques on the hydrology of catchment areas and water quality have been studied from the late 1960s onwards (Bormann *et al.* 1968, Horn beck *et al.* 1975), and research carried out in the USA in the early 1980s laid much emphasis on the benefits of various protective zones left alongside streams and rivers on the water quality and hydrobiology of these (*see* Cassell *et al.* 1982). Modelling has been used to assess the cumulative effects of forestry managements and as means of reducing their impact on lakes and rivers (Ziemer *et al.* 1991).

The effects of forestry managements on the hydrology and water quality of streams have usually been studied using small catchments and reference areas for comparison (Bormann *et al.* 1968, Lynch *et al.* 1980, Seuna 1983), and this has been looked on as a simple and reliable approach (Brink *et al.* 1979, Nik *et al.* 1983). The purpose of the present study was to use the results obtained from the Nurmes Project in 1978–1994 to examine the influence of various forest management measures on water quality and loading in nearby brooks and assess the duration of these effects.

The study area

The six small catchments included in the Nurmes Project are located in two areas in Eastern Finland some 30 km apart. Two of them, Murtopuro and Liuhapuro are in Valtimo (63°45´N, 28°30´E) and the other four in Sotkamo (63°52´N, 28°39´E) (Fig. 1). The Murtopuro and Liuhapuro basins lie at altitudes of 170–246 m a.s.l. and those in Sotkamo at 200–220 m a.s.l. The basins vary in size between 54 and 494 ha (Table 1), and the brooks are 0.5–1.5 m wide and 0.1–0.5 m deep at the sampling points. The brooks range from 300 to 1 560 m in length and have gradients of 0.3%–1.5%. They also flow partly through subterranean channels. The proportions of mires in the basins vary from 32% to 70% (Ahtiainen *et al.* 1988).

Variations in the natural state of water quality in these brooks were monitored for an initial four years (1978–1982), after which the National Board of Forestry subjected the areas to certain forestry managements in accordance with a predetermined scheme (Table 1). Two of them, Liuhapuro in Valtimo and Välipuro in Sotkamo, were left untouched to serve as control sites. Timber was felled in 1982–83 partly by hand and partly using machines, after which the mineral soil was ploughed and the mires ditched and mounted in summer 1986. A protective zone of width 30–50 m was left between one of the felling sites and the brook, and at another site the ditches were not linked with the brook but a protective strip of unditched land was left between them. The forestry managements extended over 13%–58% of the basin (Table 1).

The water quality of the brooks were monitored from 1978 onwards (Ahtiainen 1990, 1992, Ahtiainen *et al.* 1988, 1993), and the hydrobiolo-

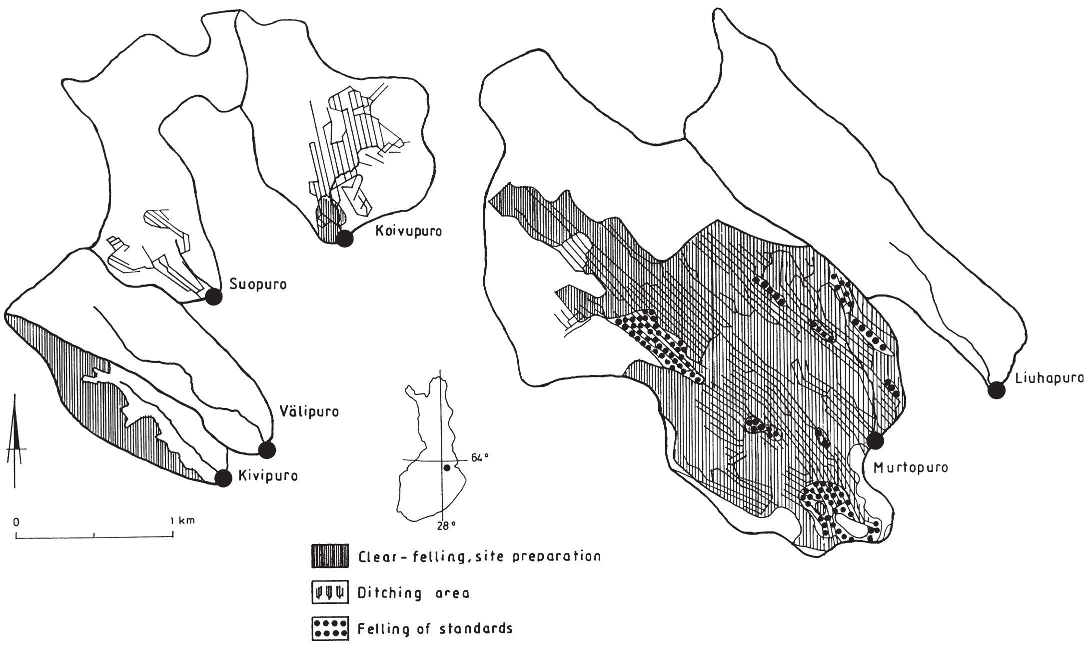

Fig. 1. The brook basins of the Nurmes Project and their location.

gical investigations began in 1982 (Holopainen *et al*. 1988, 1991, Holopainen & Huttunen 1992, 1998, Huttunen & Holopainen 1993, Huttunen *et al*. 1990).

Table 1. Forestry work carried out in 1982–1989.

Brook	Area (ha)	Mire (%)	Forestry work	Percentage of basin
Murtopuro	494	50	clear felling 286 ha (1983)	58
			ploughing 80 ha (1986)	16
			ditching 198 ha (1986)	40
			mounting 49 ha (1986)	10
			replanting with pine (1987)	58
Liuhapuro	165	48	none (control site)	
Suopuro	113	70	ditching with protective zone 15 ha(1983)	13
Välipuro	86	56	none (control site)	
Kivipuro	54	32	clear felling 36 ha (1983)	56
			ploughing 32 ha (1986)	56
			replanting with pine (1987)	56
Koivupuro	118	57	clear felling 6 ha (1983)	5
			ditching 32 ha (1983)	27
			mounting and ditching 4 ha(1986)	3
			replanting with pine (1987)	3
			fertilization 6 ha (1989)	5

Material and methods

Water samples were usually taken once or twice a month from the overflow of a measuring weir, except at times of low water, when they were taken from a few metres above the weir. The samples from Koivupuro in 1978–82 were taken 200 m upstream the weir. The sampling and analyses were carried out by the Northern Karelia District Office according to the National Board of Waters and the Environment (National Board of Waters 1981, 1984).

The concentrations of total nitrogen, nitrite-, nitrate- and ammonium nitrogen, total phosphorus, phosphate-phosphorus and suspended solids are examined here in the form of monthly means for five periods, the reference period of 1979–82 and four periods following the forestry work: 1983–85, 1986–88, 1989–91 and 1992–94. Annual loading were also calculated from the monthly loadings recorded during the same periods. The nutrient loads quoted here are discharge-weighted figures calculated by the method of Rekolainen *et al*. (1991).

The additional loads caused by the forestry work were calculated relative to the reference period and the readings obtained at the control sites, the expected loads for the other brooks without forestry measures being obtained from a linear model constructed by the authors for the relations between these and the control brooks during the calibration period 1979–82. Liuhapuro was used as the reference brook for Murtopuro, and Välipuro for all the others. The additional loads determined by subtracting the expected loads from the actually recorded figures will be referred to below as the specific loadings related to the forestry managements concerned.

Results

Concentrations and loading in a natural state

Low concentrations of suspended solids and nutrients were recorded in the calibration period 1979–82 in the water of the brooks with the nutrient concentrations largely reflecting those coming from the surrounding soils. Murtopuro differed somewhat from the other brooks having a high content of total and phosphate phosphorus. Liuhapuro and Kivipuro did not differ from each other, while Koivupuro, Välipuro and Suopuro had markedly lower values (Table 2). Total nitrogen concentrations > 450 $\mu g\ l^{-1}$ were recorded in Murtopuro, Liuhapuro, Kivipuro and Välipuro, with a slightly lower concentration in Suopuro and less than 300 $\mu g\ l^{-1}$ in Koivupuro. The amount of suspended solids in the brooks were low during the calibration years 1979–82, < 2 $mg\ l^{-1}$. The variations in all the concentrations measured remained conspicuously low throughout in the control brooks Liuhapuro and Välipuro (Table 2).

Effects of felling and site preparation (Murtopuro)

The concentration of suspended solids in Murtopuro remained unchanged in the years following clear felling (1983–85). The amount of suspended solids increased upon ditching, ploughing and mounting to a mean level of 81.8 $mg\ l^{-1}$ in 1986–88 (Table 2), decreased substantially 7.8 $mg\ l^{-1,}$ for the three-year period 1989–91 and 4.5 $mg\ l^{-1}$ for 1992–94. Total phosphorus increased four-fold in the three-year period following clear felling, and remained at three times the reference level following ditching and site preparation. The concentration of total phosphorus returned to the level recorded in a natural state by 1989 and remained at that level thereafter (Table 2). Phosphate phosphorus increased more than five-fold after clear felling and was likewise three times the reference level following ditching and site preparation, but similarly regained normal levels from 1989 onwards.

Total nitrogen concentrations doubled upon clear felling, and remained the same after ditching and site preparation. The recorded levels in 1989–94 were virtually at the reference level (Table 2). The nitrate and nitrite nitrogen content similarly doubled after clear felling, but increased further to four times the reference value following ditching and site preparation. The concentrations were still double the reference value in 1989–91, but decreased to 1.5-fold in 1992–94. Mean ammonium nitrogen concentrations practically quadrupled following felling and remained at this level for the three years after ditching and site preparation. They then fell to double the reference value in 1989–91 and the normal level was reached over the last three years.

The Murtopuro spring

Total nitrogen, nitrate and nitrite concentrations were markedly low all the time the forests remained in their natural state, but began to rise gradually following clear felling. A high increase was recorded as a consequence of ditching and site preparation (Fig. 2).

Specific loading attributable to felling, ditching, ploughing and mounting (Murtopuro)

The increase in suspended solids in Murtopuro, a brook with a high proportion of peatlands in its

Table 2. Monthly mean concentrations measured in the brooks in the calibration period (1979–82) and successive three-year periods following forestry work (1983–85, 1986–88, 1989–91 and 1992–94).

Period	Tot.P (µg l^{-1})	PO_4-P (µg l^{-1})	Tot.N (µg l^{-1})	NO_2 + NO_3-N (µg l^{-1})	NH_4-N (µg l^{-1})	Solids (mg l^{-1})
Clear felling, site preparation and ditching (Murtopuro)						
1979–82	33.3	17.1	456	26.0	19.2	1.2
1983–85	142	97.8	965	50.4	74.6	1.3
1986–88	95.4	39.5	954	101	77.8	81.8
1989–91	28.2	12.8	550	68.9	43.4	7.8
1992–94	26.0	11.2	475	36.9	16.9	4.5
Clear felling and site preparation with protective zone (Kivipuro)						
1979–82	27.1	8.0	464	11.5	11.1	1.4
1983–85	26.1	8.0	548	12.2	13.0	1.0
1986–88	22.9	8.0	464	14.7	11.4	0.6
1989–91	20.9	6.9	483	14.1	8.4	0.7
1992–94	21.8	6.9	500	9.1	6.7	0.8
Natural state (Liuhapuro)						
1979–82	23.7	8.8	450	19.2	13.8	0.5
1983–85	23.3	7.3	514	20.4	10.2	0.4
1986–88	21.9	7.2	475	19.0	8.5	0.5
1989–91	21.6	7.2	513	13.8	9.7	0.5
1992–94	24.0	8.5	535	18.1	7.8	0.5
Ditching, additional ditching and fertilization (Koivupuro)						
1979–82	12.2	4.1	295	12.7	9.1	1.9
1983–85	32.2	9.9	645	27.4	90.2	6.9
1986–88	24.3	8.1	601	62.5	133	2.3
1989–91	16.4	6.6	512	44.1	78.5	1.6
1992–94	16.1	6.5	468	31.1	44.1	1.4
Ditching with protective zone (Suopuro)						
1979–82	13.0	2.7	390	9.7	36.7	1.4
1983–85	19.9	3.5	570	15.4	46.2	17.8
1986–88	15.5	4.3	494	22.2	56.3	5.7
1989–91	12.2	2.9	458	12.0	29.0	1.2
1992–94	12.7	3.1	477	12.7	18.7	3.8
Natural state (Välipuro)						
1979–82	20.3	5.1	510	20.0	29.3	1.4
1983–85	17.7	4.4	545	13.4	8.4	0.9
1986–88	18.4	5.3	537	33.1	12.8	0.6
1989–91	18.9	5.0	550	13.0	10.9	0.7
1992–94	17.4	5.0	541	17.9	10.3	0.7

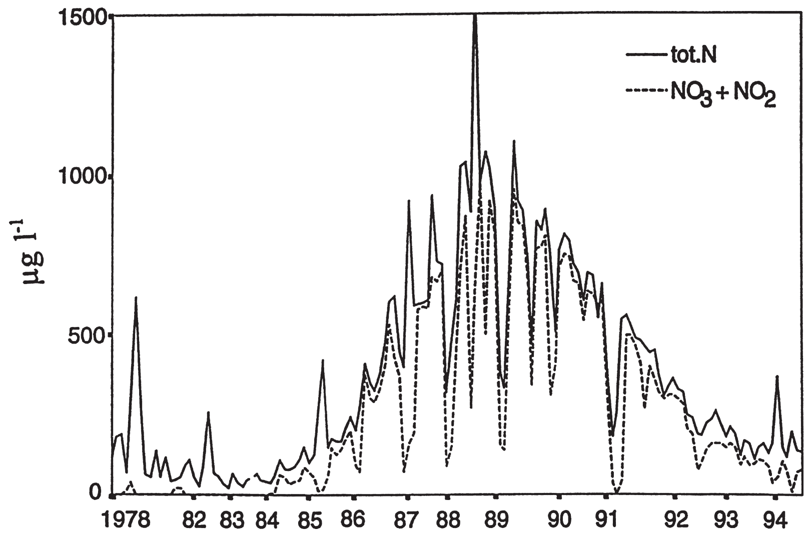

Fig. 2. Variations in total nitrogen and nitrate and nitrite nitrogen in the Murtopuro spring in 1979–94 (μg l^{-1}). Clear felling took place in the Murtopuro basin in 1983, ditching, ploughing and mounting in 1986 and replanting in 1987.

catchment, over the three years following the clear felling operations of 1983, i.e. the specific loading resulting from this activity, amounted to 4 kg per hectare of forest felled per year, while the mean specific loading of total phosphorus over the same period was 0.7 kg ha^{-1} a^{-1} and that of total nitrogen 2.6 kg ha^{-1} a^{-1} (Table 3).

Ditching, ploughing and mounting in 1986 gave rise to a specific loading of total phosphorus of 1.1 kg ha^{-1} a^{-1}, of which phosphate phosphorus accounted for 0.4 kg ha^{-1} a^{-1}. The corresponding figure over the period 1989–94 varied between 0.1 kg and 0.2 kg ha^{-1} a^{-1}, a loading which consisted predominantly of phosphate phosphorus. The specific loading values for total nitrogen over the same two periods were 7.1 kg ha^{-1} a^{-1} in 1986–88 and approx. 2 kg ha^{-1} a^{-1} in 1989–94. It can be calculated from the above that the cumulative total phosphorus loading over the monitoring period 1983–1994 was 6.3 kg per hectare of forest felled, of which phosphate phosphorus accounted for 3.7 kg, while the corresponding cumulative sum for total nitrogen was almost 40 kg per hectare (Table 3).

The site preparation carried out on the fine-grained soil of the Murtopuro catchment area brought about a considerable increase in the loading of suspended solids, the mean annual specific loading for the period 1986–88 being 1 243 kg ha^{-1} and that for the subsequent six years 148–161 kg ha^{-1} a^{-1}, given a cumulative load over the period 1983–1994 of 4 672 kg ha^{-1}. This meant that the basin above the measuring weir on Murtopuro had to be emptied of sediment several times in the course of the monitoring period, a total of 1 300 m^3 of material having been removed by 1989 and about 200 m^3 thereafter.

Effects of clear felling and ploughing with a protective zone (Kivipuro)

Suspended solids did not increase in response to either clear felling or ploughing of the felled area in the Kivipuro basin, where a protective strip of forest was left between the felling site and the brook, nor were any changes observed in total phosphorus, phosphate phosphorus or nitrogen compounds. Thus it may be said that felling and site preparation as such had only minor effects in the presence of the protective zone, the rises in loading that were recorded being attributable largely to the increased volumes of water entering the brook as a result of these managements. The mean specific loadings of total phosphorus in the three-year period following the two interventions were 0.02–0.03 kg per hectare per year of land affected, of which 0.01–0.04 kg ha^{-1} a^{-1} was phosphate phosphorus, and the corresponding figure for 1989–91 was 0.01 kg ha^{-1} a^{-1}, after which no further specific loading was observed. The specific loading of total nitrogen was 0.7 kg ha^{-1} a^{-1} in 1983–85, 0.5 kg ha^{-1} a^{-1} in the following two three-year periods and 0.1 kg ha^{-1} a^{-1} in the last period (Fig. 3 and Table 3).

Effects of ditching, mounting and fertilization (Koivupuro)

Concentrations of suspended solids in Koivupuro increased by 7 mg l^{-1} in the three years following the clear felling and ditch ing, returning in 1986–88 to the reference level. Total phosphorus tripled in the first period, was double the reference value on average in the next three years and settled at 25% above the reference value for the remaining six years. Phosphate phosphorus increased 3-fold at first, 2.5-fold for the next three years and settled at more than 1.5-fold for the following six years. Total nitrogen concentrations doubled in 1983–88 in response to the felling and ditching, but decreased slightly after that, being 1.5 times the reference value in 1992–94. Nitrate and nitrite concentrations correspondingly doubled initially, rose to a level five times that of the calibration period for the next three years, remained at four times the base level for a further three years and dropped to 2.5-fold in the last period studied (Table 2). Ammonium nitrogen rose by a factor of 10 in response to the interventions, rose further to 15 times the reference level in 1986–88, dropped to 9-fold thereafter and was 5-fold for the last three years.

Specific loading attributable to ditching, mounting and fertilization (Koivupuro)

The mean specific loading of suspended solids in Koivupuro in response to felling and ditching over

Table 3. Increases of annual loads due to the forestry practice work (specific loads, in kg ha^{-1} a^{-1} of land affected) as means for three-year periods, total sum for three-year periods and total sum for the whole twelve year monitoring period.

Period	Tot.P		PO_4-P		Tot.N		Solids	
	$\bar{x}$	Σ	$\bar{x}$	Σ	$\bar{x}$	Σ	$\bar{x}$	Σ
Clear felling, site preparation and ditching (Murtopuro)								
1983–85	0.7	2.2	0.5	1.6	2.6	7.7	4	13
1986–88	1.1	3.2	0.4	1.3	7.1	21.3	1 243	3 731
1989–91	0.1	0.4	0.1	0.4	1.6	4.9	148	444
1992–94	0.2	0.6	0.1	0.5	1.9	5.7	161	484
Total		6.3		3.7		39.6		4 672
Clear felling and site preparation with protective zone (Kivipuro)								
1983–85	0.03	0.09	0.01	0.02	0.7	2.1	3	7.4
1986–88	0.02	0.05	0.04	0.11	0.5	1.5	1	2.1
1989–91	0.01	0.03	0.00	0.01	0.5	1.2	0	1.2
1992–94	0.00	0.01	0.01	0.02	0.1	0.4	1	1.4
Total		0.17		0.16		5.1		12
Ditching, additional ditching and fertilization (Koivupuro)								
1983–85	0.2	0.6	0.06	0.19	3.9	11.7	59	178
1986–88	0.2	0.5	0.05	0.15	3.5	10.4	35	104
1989–91	0.1	0.2	0.04	0.11	2.4	7.2	8	24
1992–94	0.1	0.3	0.08	0.23	1.6	4.7	8	23
Total		1.7		0.68		34.0		329
Ditching with protective zone (Suopuro)								
1983–85	0.35	1.1	0.02	0.07	2.7	8.6	800	2 400
1986–88	0.19	0.6	0.05	0.16	2.5	7.4	49	148
1989–91	0.05	0.2	0.03	0.09	1.3	3.9	17	50
1992–94	0.08	0.3	0.06	0.19	2.6	7.7	118	355
Total		2.2		0.51		27.1		2 953

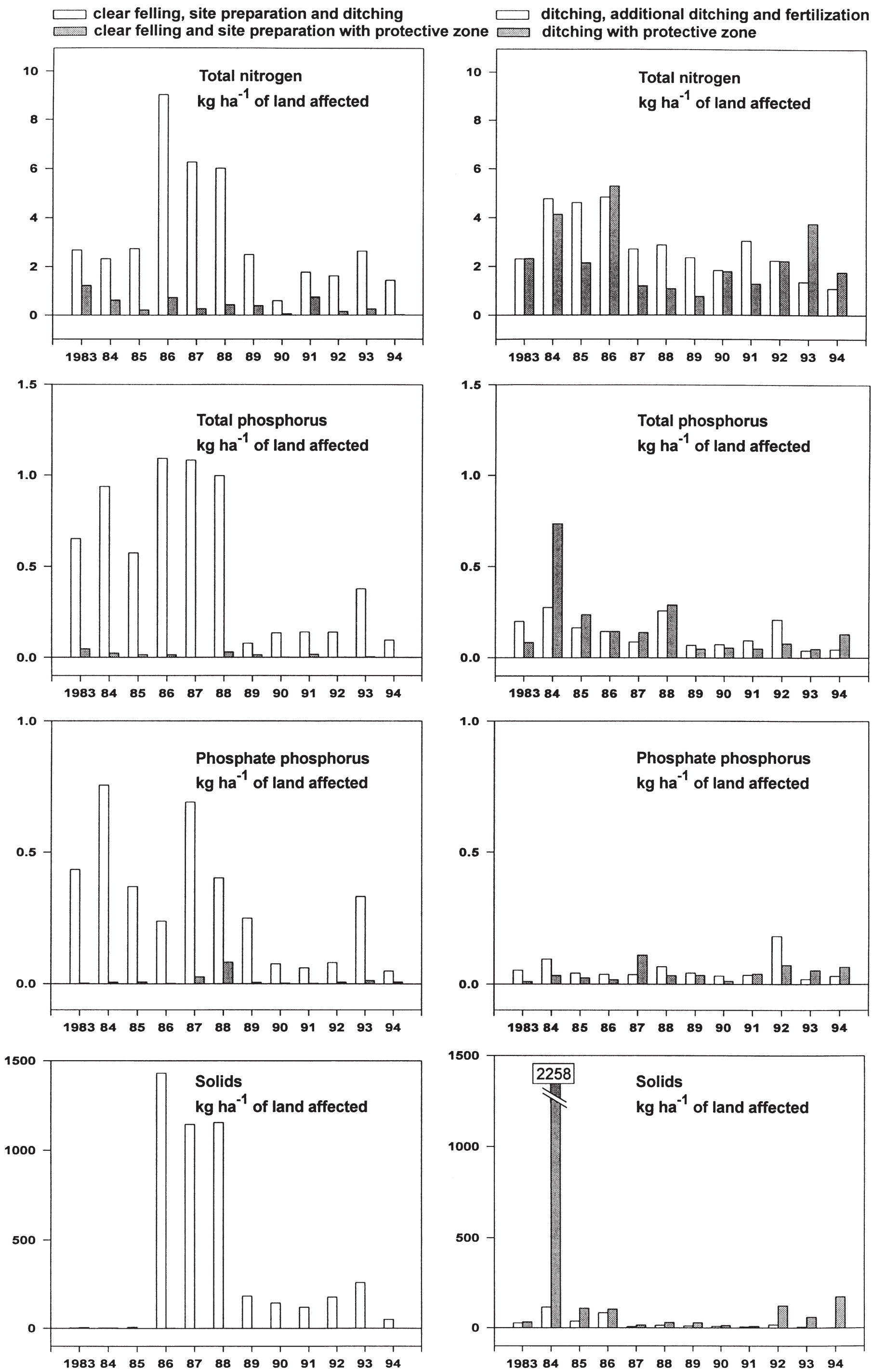

Fig. 3. Increases of annual loads due to the forestry work (specific loads, in kg ha^{-1} a^{-1} of land affected) of total nitrogen, total phosphorus, phosphate phosphorus and suspended solids in Murtopuro (M) after clear felling (1983) and after site preparation and ditching (1986), and in Kivipuro (Ki) after clear felling (1983) and ploughing (1986) with protective zone and in Koivupuro (Ko) after felling and ditching (1983), additional ditching and mounting (1986) and fertilization (1989) and in Suopuro (S) after ditching with a protective zone (1983).

the first three years was 59 kg ha^{-1} a^{-1}, decreasing to 35 kg ha^{-1} a^{-1} in the next three years and to 8 kg ha^{-1} a^{-1} for the subsequent six years. That of total phosphorus was 0.2 kg ha^{-1} a^{-1} in 1983–88 and 0.1 kg ha^{-1} a^{-1} for the next six years, and that of phosphate phosphorus in the range 0.04–0.08 kg ha^{-1} a^{-1} (Fig. 3 and Table 3).

Effects of ditching (Suopuro)

An area of 15 ha in the Suopuro basin was ditched in 1983 leaving a 10 m protective corridor between the ditched area and the brook. Suspended solids increased to almost 18 mg l^{-1} in the following three years and to 1.2 and 5.7 mg l^{-1} thereafter (Table 2). Total phosphorus increased 1.5-fold in the first period and 1.2-fold in the next, reaching more or less the reference level from 1989 onwards. Phosphate phosphorus was 1.3-fold immediately after ditching had taken place, 1.6-fold in the next three-year period and practically at the reference level in 1989–94 (Table 2). The mean concentration of total nitrogen rise by almost 200 µg l^{-1} at first and remaining at 50–100 µg l^{-1} above the reference value thereafter. Nitrate and nitrite concentrations were 1.5-fold at first and 2-fold in 1986–88, as for ammonium nitrogen. All above mentioned parameters started to decrease from 1989 onwards, however not returning to the reference levels in the course of the present monitoring.

Specific loading caused by ditching (Suopuro)

The ditching of the 15 ha of land in the Suopuro basin led to a specific loading of suspended solids of 800 kg ha^{-1} a^{-1} in the first three years, a mean of 49 kg ha^{-1} a^{-1} in the next period, 17 kg ha^{-1} a^{-1} in 1989–91 and more than 100 kg ha^{-1} a^{-1} once again in 1992–94. The specific loading of total phosphorus in the three years following ditching was 0.35 kg ha^{-1} a^{-1}, of which phosphate phosphorus accounted for 0.2 kg ha^{-1} a^{-1}, and that of total nitrogen was 2.7 kg ha^{-1} a^{-1}. The amount of total phosphorus in 1986–88 was 0.19 kg ha^{-1} a^{-1}, of which 0.06 kg ha^{-1} a^{-1} was phosphate phosphorus and in 1989–94 varied in the range 0.05–0.08 kg ha^{-1} a^{-1}. Total nitrogen was 2.5 kg ha^{-1} a^{-1} in 1986–88 and in the range 1.3–2.6 kg ha^{-1} a^{-1} until 1994.

The cumulative loading of suspended solids in the 12 years following the Suopuro ditching operation was 2953 kg per hectare of land ditched. Although the clearest rise in loading took place in the three years immediately after ditching, a considerable specific loading was observed in the early 1990s. The ditching in 1983 led to a cumulative total phosphorus load of 2.2 kg per hectare, of which something over 0.5 kg was in phosphate form, the corresponding cumulative figure for total nitrogen being over 27.1 kg ha^{-1} (Fig. 3 and Table 3).

Discussion and conclusions

General

Solid matter loads in all the brooks studied were extremely low during the calibration stage, and they remained at this level in the control brooks throughout the duration of monitoring. The nutrient cycle in an undisturbed forest ecosystem is virtually a closed system, leaching is minimal, and the circulation of the nutrients that are of importance for forest growth being particularly efficient (Likens *et al.* 1974, Melillo and Gosz 1983). The concentrations of total nitrogen and nitrate nitrogen in the brooks under natural conditions, 295–550 µg l^{-1} and 10–33 µg l^{-1} respectively, were lower than the means of 560–1 700 µg l^{-1} and 49–1 200 µg l^{-1} reported by Rekolainen (1989) for small catchments. Similarly, the range in total phosphorus concentrations was 12–33 µg l^{-1} as compared with 18–63 µg l^{-1} quoted by Rekolainen (1989) for forested catchment areas in which only minor felling had taken place.

Soil types and their nutrient content are of crucial importance for the nature of the leaching of nutrients and the washout of suspended solids and organic matter following forest management measures, and it is clear that the brooks included in the Nurmes Project differed in nutrient content from the outset. Even virtually adjacent areas can differ in their leaching properties, as demonstrated here by the difference in phosphate phosphorus loading between Murtopuro and Liuhapuro. This makes it more difficult to generalize from the results other than by examining a much larger number of sites of various kinds. Total phosphorus and total nitrogen levels in the brooks located in Sotkamo are markedly lower than those of Murtopuro and Liuhapuro in Valtimo.

Effects of clear felling and their duration

Felling effectively interrupts the nutrient cycle until the vegetation again is able to bind the majority of the nutrients contained in the precipitation and the soil, and at the same time the water content of the soil increases in response to the felling and temperatures conditions are altered. Any breaking up of the ground surface is apt to accelerate the mineralization of nutrients (Vitousek *et al.* 1979), and nutrients will also be released from the roots of the felled trees and the felling waste, causing leaching to increase many times over. Mineralization is markedly stimulated especially in alkaline soils, whereupon nitrate nitrogen concentrations in both the surface water and the groundwater have been observed in a number of investigations (Reynolds *et al.* 1992, Binkley and Brown 1994). Although an increase in phosphate phosphorus in the first year after felling has been reported by Nicolson (1988), leaching also from Murtopuro was observed to be greatest in the second year, as also found by Adamson and Hornung (1990).

The reason for the pronounced leaching of total phosphorus and phosphate phosphorus in Murtopuro is probably due to the high initial nutrient level, attributable to the nature of the soil, the increase in water content of the soil (reduction in evapotranspiration), felling wastes, the removal of a significant proportion of the tree layer, the establishment of anaerobic conditions as a consequence of the rise in the groundwater table, and changes in temperature conditions in the soil (Kubin and Kemppainen 1991, 1994). Decomposition of organic matter after felling increased total nitrogen and mineral nitrogen loads, as also observed by Martin and Pierce (1980) and Martin *et al.* (1984). One reason for minor increase in suspended solids in Murtopuro may well be the large amount of felling waste left behind (10%–20% of the volume of timber felled), which evidently prevented the washing of solid matter into the brook, as also observed by Spangenberg and McLennan (1983). On the other hand, clear felling in this nutrient-rich drainage basin, with a high proportion of mires, led to marked increases in total phosphorus and phosphate loading at least for the next three years.

The discharge and nutrient loading of Kivipuro increased for some time after clear felling, in spite of a protective zone, although this precaution did effectively reduce the alterations in water quality relative to the other basins in which forestry work was carried out. More attention should evidently be paid in the future to the correct location of felling areas and the width of the protective zone left alongside brooks and rivers. Roby *et al.* (1977), for example, note that no detrimental hydrological effects of felling could be detected at their sites if the protective zones were over 30 m in width, and Swank (1990) likewise emphasized the need for protective zones on both socioeconomic and conservational grounds.

Effects of site preparation and ditching and their duration

The ditching, ploughing and mounting operations carried out in the Murtopuro basin in summer 1986 gave rise to major washing of suspended solids into the brook, just as comparable erosion has been reported earlier as a consequence of the ploughing of felling sites, surface preparation, ditching, felling and road building (Blackburn *et al.* 1990, Sullivan 1985). In contrast, Beasley and Granillo (1988) observe that although discharge and loading with suspended solids returned to levels corresponding to those recorded in a natural state in the fourth year after both clear felling and selective felling, clear felling in combination with mechanical site preparation caused an excess sludge loading for two years and an excess discharge for only one year. According to Beasley and Granillo (1988)these low solid matter loadings were due to the even topography of the area concerned and the low discharge rate after the forestry managements. In Murtopuro the maximum increase in the washout of solid material exceeded the amount prevailing in a natural state by a factor of 180 and the natural reference level was not reached by the end of 1994. Francis and Taylor (1989) found ploughing of a forest site to increase the suspended load by a factor of 2.5–4.8 and Blackburn and Wood (1990) found the repercussions of preparation of the ground surface to cease within five years except in the case of potassium. Blackburn and Wood (1990) obtained amounts for suspended solids of 2 119 mg l^{-1} in the first year after heavy site preparation work, 167 mg l^{-1} in the second, 54 mg l^{-1} in the third and 331 mg l^{-1} in the fourth, whereas the mean amounts for the first three years calculated in the case of Murtopuro was 81 mg l^{-1}.

The ditching of 15 ha of peatland in the Suopuro basin in 1983 led to a significant increase in the amount of suspended load, especially since a small neck of dry land which was particularly susceptible to erosion was ditched by mistake. The mean increase in total phosphorus over the first three years was 0.35 kg per hectare of land ditched per year, and the effects persisted for over ten years, most notably in the case of phosphate phosphorus. At the end of 1994 the levels had still not returned to what they were before ditching. Lundin and Bergquist (1990) report an in crease in total phosphorus after ditching, but not in phosphate phosphorus. It is still quite likely in the case of the Suopuro basin that in spite of the fact that more than ten years have elapsed since ditching, substantial increases in suspended load in the brook will be encountered following heavy rain.

The sequence of forestry managements carried out in the Koivupuro basin is fairly representative for the normal pattern of forest management in Finland. The washout of suspended solids remained relatively limited, but the specific loading of total phosphorus was considerable, reaching 200 g ha^{-1} a^{-1} in the next six years and remaining at 100 g ha^{-1} a^{-1} for the following six, i.e. this parameter had not returned to the natural level by the end of the period studied here. Similarly the specific loading of total nitrogen was high for the first six years, 3.9–3.5 kg ha^{-1} a^{-1}, and remained relatively high for the rest of the monitoring period, 2.4–1.6 kg ha^{-1} (three year means).

The results obtained in the Nurmes Project indicate that clear felling in an area with predominantly meso-eutrophic peat soils will give rise to great total phosphorus loading over at least the next three years as is obtained from cultivated fields (Kauppi 1979, Rekolainen 1989). Ditching and site preparation together lead to a still greater washout of total phosphorus if erosion causes large amounts of solid material to be dislodged and no protective zone has been left alongside the brook. It should also be noted that the suspended loads and phosphorus loads quoted here are smaller than those prevailing in reality, since it has been estimated that at least 5% of the solid material suspended in a stream evades the measuring weir in the form of bed load, while the chief reason for the underestimation of the phosphorus load lies in the timing of measurement, the values recorded for the high water season being too infrequent to allow the true load to be calculated (Rekolainen *et al*. 1991).

It is common in Finland that a number of forestry managements are implemented in the same drainage basin within a short time intervals, and it is only recently that water protection aspects have been taken into account. One relevant observation to arise from the calculations of specific loads per hectare of land affected by the interventions in the Nurmes Project was the prolonged periods. On the other hand, even our results are inadequate to allow any more substantial generalizations due to the narrow range of sites in terms of soil parameters.

The results nevertheless suggest that highly significant amounts of total nutrients can be leached from areas with nutrient-rich soils in particular. Incorrect ditching and site preparation carried out without an adequate soil survey will in the worst case lead to dramatic increases in suspended loads, as observed in Murtopuro. Such effects cannot be explained by the extent of the area involved, as the ditching of only 15 ha in the Suopuro basin gave rise to very considerable suspended loads, the cumulative load there being more than half of that in Murtopuro. One interesting detail in our results is that the cumulative total nitrogen load over ten years was very similar in the Murtopuro, Koivupuro and Suopuro basins in spite of the fact that the forestry managements carried out in these basins were quite different.

The increase in the leaching of total phosphorus from the Suopuro basin was in fact surprisingly pronounced in view of the small area of land ditched. The ditching and other managements carried out in the Koivupuro basin did not extend down to the mineral soil, possibly explaining the lower outwash of suspended solids and total phosphorus. The leaching of phosphate phosphorus per hectare of land subject to forestry managements was, on the other hand virtually the same in both basins.

The results for Kivipuro confirm existing impressions of the effectiveness of protective zones in preventing the transport of nutrients and solid matter downstream, as the specific loads caused by the forestry measures in this basin were a small fraction of those received by the other brooks.

Forestry managements can bring about major changes in the quality of the groundwater, as shown here in the case of the Murtopuro basin. It is essential that more attention should be paid to the possible repercussions of forestry managements with regard to local aquifers, even though the actual pollutant concentrations recorded here did not exceed the norms laid down for drinking water supplies (Binkley and Brown 1994).

The present results can be utilized for the purposes of the practical planning of forestry work. All such planning should in future involve full determinations of soil type and more precise surveys of the topography of the drainage basin and the location of its watercourses. Similarly, more attention could be paid to the correct timing of forestry managements. If the soil investigations point to a danger of erosion, plans for ditching or site preparation in the area should not be allowed, or at least supplemented with particularly carefully designed protective managements. One essential element in the best forest management techniques is the use of protective zones to prevent the passage of suspended solids and nutrients into the nearby watercourses and to avoid any rise in temperature in these watercourses. As demonstrated in earlier work by Huttunen *et al*. (1988), Holopainen *et al*. (1991), Holopainen and Huttunen (1997) and Vuori and Joensuu (1996), these are decisive factors in the eutrophication of lakes and rivers.

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References

Adamson J.K. & Hornung M. 1990. Effects of clearfelling a Sitka Spruce plantation on solute concentrations in drainage water. *Journal of Hydrology* 116: 287–297.

Ahtiainen M. 1988. Effects of clear-cutting and forestry drainage on water quality in the Nurmes-study. *Symposium on the hydrology of wetlands in temperate and cold regions;* Joensuu, Finland 6–8 June 1988. Publications of the Academy of Finland 4/1988: 206–219.

Ahtiainen M. 1990. Avohakkuun ja metsäojituksen vaikutukset purovesien laatuun [The effects of clear-cutting and forestry drainage on water quality of forest brooks]. Vesi- ja ympäristöhallituksen julkaisuja 45: 1–110. [In Finnish with English abstract].

Ahtiainen M. 1992. The effects of forest clear-cutting and scarification on water quality of small brooks. *Hydrobiologia* 243/244: 465–473.

Ahtiainen M. 1993. The effects of forest practices on the water quality of small brooks. In: Giussani G. & Callieri C. (eds.), *Strategies for Lake Ecosystems Beyond 2000. Proceedings of the* 5th *International Conference on the Conservation and management of Lakes*; Stresa (Italy), May 17–21, 1993: 365–368.

Ahtiainen M., Holopainen A.-L. & Huttunen P. 1988. General description of the Nurmes-study. *Symposium on the hydrology of wetlands in temperate and cold regions;* Joensuu, Finland 6–8 June 1988. Publications of the Academy of Finland 4/1988: 107–121.

Ahtiainen M., Huttunen P. & Holopainen A.-L. 1993: Metsätaloustoimenpiteiden vaikutukset purovesien laatuun ja hydrobiologiaan. *Vesi- ja ympäristöhallituksen monistesarja* 455: 27–160.

Alasaarela E., Kubin E., Seuna P., Ylitolonen A. & Välitalo J. 1995. Päätehakkuun ja maanmuokkauksen vesistövaikutukset. Suomen ympäristö 2: 399–412.

Beasley R.S. & Granillo A.B. 1988. Sediment and water from managed forests on flat coastal plain sites. *Water Resources Bulletin* 24: 361–366.

Binkley D. & Brown T.C. 1994. Forest practices as nonpoint sources of pollution in North America. *Water Resources Bulletin* 29: 729–740.

Blackburn W.H., Knight R.W., Wood J.C. & Pearson H.A. 1990. Stormflow and sediment loss from intensively managed forest watersheds in East Texas. *Water Resources Bulletin* 26: 465–477.

Blackburn W.H. & Wood J.C. 1990. Nutrient export in stormflow following forest harvesting and site-preparation in East Texas. *Journal of Environmental Quality* 19: 402–408.

Bormann F.H., Likens G.E., Fisher D.W. & Pierce R.S. 1968. Nutrient loss accelerated by clear-cutting of a forest ecosystem. *Science* 159: 882–884.

Brink N. Gustafson, A. & Persson G. 1979. Losses of nitrogen, phosphorus and potassium from arable land. Swedish University of Agricultural Sciences. Division of Water Management. *Ekohydrologi* 4: 7–57. [In Swedish with English abstract].

Cassell E.A., Forcier L.K. & Shane J.B. 1982. Water quality and forestry in Vermont: a problem assessment. *Verm. Univ. Burlington, School of Natural Resources*, June 1982. 36 pp.

Finer L., Ahtiainen M., Kellomäki S., Mannerkoski H., Piirainen S., Seuna P., Starr M. & Store R. 1995. Kangasmaan päätehakkuun ja maanmuokkauksen vaikutus veden ja ravinteiden kiertoon: kalibrointijakson tuloksia. *Suomen ympäristö* 2: 383–398.

Francis I.S. & Taylor J.A. 1989. The effects of forest drainage operations on upland sediment yields. A study of two peat-covered catchments. *Earth Surf. Process. Landforms* 14: 73–83.

Heikkilä R. 1991. Influence of land use on the sedimentation of the river delta in the Kyrönjoki drainage basin. *Hydrobiologia* 214: 143–147.

Holopainen A.-L. & Huttunen P. 1992. Effects of forest clear-cutting and soil disturbance on biology of small forest brooks. *Hydrobiologia* 243/244: 457–464.

Holopainen A.-L. & Huttunen P. 1998. Impact of forestry practices on ecology of algal communities in small brooks in the Nurmes experimental forest area, Finland. *Boreal Environment Research* 3: 63–73.

Holopainen A.-L., Hovi A. & Rönkkö J. 1988. Lotic algal communities and their metabolim in small forest brooks in Nurmes area of eastern Finland. *Aqua Fennica* 18: 29–46.

Holopainen A.-L., Huttunen P. & Ahtiainen M. 1991. Effects of forestry practices on water quality and primary productivity in small forest brooks. *Verh. Int. Verein. Limnol.* 24: 1760–1766.

Hornbeck J.W., Pierce R.S., Likens G.E. & Martin C.W. 1975. Modelling the impact of contemporary forest cutting on hydrologic and nutrient cycles. *Proc. Internat. Symp. Hydrol. Char. River Basin* IAHS Publ. 117: 423–433.

Huttunen P. & Holopainen A.-L. 1993. Long-term effects of ditching on the biology of small forest brooks. In: Giussani G. & Callieri C. (eds.), *Strategies for lake ecosystems beyond 2000. Proceedings of the 5th International Conference on the Conservation and Management of lakes*; Stresa (Italy), May 17–21, 1993: 377–390.

Huttunen P., Holopainen A.-L. & Hovi A. 1988. Effects of silvicultural measures on production biology of forest brooks. *Symposium on the hydrology of wetlands in temperate and cold regions;* Joensuu, Finland 6–8 June 1988. Publications of the Academy of Finland 4/1988: 239–248.

Huttunen P., Holopainen A.-L. & Ahtiainen M. 1990. Avohakkuun ja maanmuokkauksen vaikutukset purojen veden laatuun ja vesibiologiaan [The effects of forest clearcutting and soil preparation for forestry on water chemistry and biology of small brooks]. Joensuun yliopisto, Karjalan tutkimuslaitoksen julkaisuja 91/1990. 32 pp. [In Finnish with English Abstract].

Kauppi L. 1975. Orgaanisen aineen huuhtoutuminen ja siihen vaikuttavat tekijät [The washing out of organic matter and factors affecting it]. *National Board of waters,* Finland, Rep. 84. 72 pp. [In Finnish with English summary].

Kauppi L. 1979. Effect of drainage basin characteristics on the diffise load of phosphorus and nitrogen. *Publications of the Water Research Institute* 30: 21–41.

Kauppi L., Sandman O., Knuuttila S., Eskonen K., Liehu A., Luokkanen S. & Niemi M. 1990. Maankäytön merkitys vesien käytölle haitallisten sinileväkukintojen esiintymisessä. *Vesi- ja ympäristöhallinnon julkaisuja* 48: 1–55.

Kubin E. & Kemppainen L. 1991. Effect of clear cutting of boreal spruce forest on air and soil temperature conditions. *Acta Forestalia Fennica* 225: 1–42.

Kubin E. & Kemppainen L. 1994. Effect of soil preparation of boreal spruce forest on air and soil temperature conditions in forest regeneration areas. *Acta Forestalia Fennica* 244: 1–56.

Lepistö A. & Kivinen Y. 1994. Source areas for storm runoff generation estimated by isotope methods and the TOPMODEL. In: Kanninen M. & Heikinheimo P. (eds.), *The Finnish Research Programme on Climate Change, Progress Report* 2. Publications of the Academy of Finland: 97–103.

Likens G.E. & Bormann F.H. 1974. Linkages between terrestial and aquatic ecosystems. *Bioscience* 24: 447–456.

Lundin L & Bergquist B. 1990. Effects on water chemistry after drainage of a bog for forestry. *Hydrobiologia* 196: 167–181.

Lynch J.A., Corbett E.S. & Sopper W.E. 1980. Re-evaluation of management practices on the biological and chemical characteristics of streamflow from forested watersheds. Pennsylvania State University. Institute for reseach on land and water resources. Office of Water research and technology. 99.

Martin C.W. & Pierce R.S. 1980. Clearcutting pattern affect nitrate and calsium in streams of New Hampshire. *Journal of Forestry* 78: 268–272.

Martin C.W., Noel D.S. & Federer C.A. 1984. Effects of forest clearcutting in New England on stream chemistry. *J. Environ. Qual.* 13: 204–210.

Melillo J.M. & Gosz J.R. 1983. Interactions of biochemical cycles in forest ecosystems. In: Bolin B. & Cook R.B (eds.), *The major biochemical cycles and their interactions. Scope* 21: 177–217.

National Board of Waters. 1981. *Vesihallinnon analyysimenetelmät*. Helsinki. Report 213.

National Board of Waters. 1984. Vesiviranomaisten käyttämät vesitutkimusten näytteenottomenetelmät. 2nd ed. *Publications of the National Board of Waters* 40: 56.

Nicolson J. A. 1988. Alternate strip clearcutting in upland black spruce. The impact of harvesting on the quality of water flowing from small basins in shallow-soil boreal ecosystems. *The forestry Chronicle* 64: 52–58.

Nik A.R.H., Lee R. & Helvey J.D. 1983. Climatological Watersheds calibration. *Water resources Bulletin* 19: 47–50.

Rekolainen S. 1989. Phosphorus and nitrogen load from forest and agricultural areas in Finland. *Aqua Fennica* 19: 95–107.

Rekolainen S., Posch M., Kämäri J. & Ekholm P. 1991. Evaluation of the accuracy and precision of annual

phosphorus load estimates from two agricultural basins in Finland. *Journal of Hyrdology* 128: 237–255.
Reynolds B., Stevens P.A., Adamson J., K. Hugnes S. & Roberts J.D. 1992. Effects of clearfelling on stream and soil water aluminium chemistry in three UK forests. *Environmental Pollution* 77: 157–165.
Roby K.B., Erman D.C. & Newbold D.J. 1977. Biological assessment of timber management activity impacts and buffer strip effectiveness on natural forest streams of Northern California. *Earth Resources, monograph* 1: 169.
Rosen K. 1982. Supply, loss and distribution of nutrients in three coniferous forest watersheds in central Sweden. *Swedish Univ. Agr. Sci., Dept. For. Soils, Rep. in Forest Ecology and Forest Soils Uppsala*. 41: 1–70.
Sandman O., Turkia J. & Huttunen P. 1994a. Metsätalouden pitkäaikaiset vaikutukset suurissa järvissä, Kuhmon Änättijärven ja Lentuan sedimenttitutkimus [Long-term effects of forestry practices on large lakes: a sedimentary study of the lakes Änättijärvi and Lentua in Kuhmo, Finland]. *Vesi- ja ympäristöhallituksen julkaisuja* 179: 1–56. [In Finnish with English summary].
Sandman O., Kauppi L. & Tossavainen T. 1994b. Metsäojitusten ja -lannoitusten aiheuttamien ravinnehuuhtoutumien pidättyminen järvikerrostumiin [Nutrient leaching by forestry practices and the fate of nutrients in the lake]. *Vesi- ja ympäristöhallinnon julkaisuja* 179: 59–84. [In Finnish with English summary].
Seuna P. 1983. Small basins — a tool in operational and scientific hydrology. *Publications of Water Reseach Institute* 51, 61 pp.
Seuna P. 1988. Effects of clear-cutting and forestry drainage on runoff in the Nurmes-study. *Symposium on the hydrology of wetlands in temperate and cold regions;* Joensuu, Finland 6–8 June 1988. Publications of the Academy of Finland 4/1988: 122–134.
Spangenberg N.E. & McLennan R. 1983. Effects of silvicultural practices on water quality in Northern Wisconsin. *Wisconsin Univ. Point. Coll. Of Natural Resources. Technical Report,* 17 pp.
Sullivan K. 1985. Long-term patterns of water quality in a managed watersheded in Oregon: 1 suspended sediment. *Water resources Bulletin* 21: 977–987.
Swank G.W. 1990. Streamside management units in the Pacific Northwest. *Forest Ecology and management* 33: 419–424.
Vitousek P.M., Gosz J.R., Grier C. C., Melillo J. M., Reiners W. & Todd R.L. 1979: Nitrate losses from disturbed ecosystems. Interregional comparative studies show mechanisms underlying forest ecosystems response to disturbance. *Science* 204: 469–474.
Vuori K.-M. & Joensuu I. 1996. Impacts of forest draining on the macroinvertebrates of a small boreal headwater stream: do buffer zones protect lotic biodiversity. *Biol. Conserv*. 77: 87–95.
Ziemer R.R., Lewis J., Rice R.M. & Lisle T.E. 1991. Modeling the cumulative watershed effects of forest management strategies. *Journal of Environment Quality* 20: 36–42.

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