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REPORT

Nitrogen, Phosphorus, Carbon, and Suspended Solids Loads from Forest Clear-Cutting and Site Preparation: Long-Term Paired Catchment Studies from Eastern Finland

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Abstract The long-term impacts of current forest management methods on surface water quality in Fennoscandia are largely unexplored. We studied the long-term effects of clear-cutting and site preparation on runoff and the export of total nitrogen (total N), total organic nitrogen (TON), ammonium (NH_4-N), nitrate (NO_3-N), total phosphorus (total P), phosphate (PO_4-P), total organic carbon, and suspended solids (SS) in three paired-catchments in Eastern Finland. Clear-cutting and soil preparation were carried out on 34 % (C34), 11 % (C11), and 8 % (C8) of the area of the treated catchments and wide buffer zones were left along the streams. Clear-cutting and soil preparation increased annual runoff and total N, TON, NO_3-N, PO_4-P, and SS loads, except for SS, only in C34. Runoff increased by 16 % and the annual exports of total N, TON, NO_3-N, and PO_4-P by 18, 12, 270, and 12 %, respectively, during the 14-year period after clear-cutting. SS export increased by 291 % in C34, 134 % in C11, and 16 % in C8 during the 14, 6, and 11-year periods after clear-cutting. In the C11 catchment, NO_3-N export decreased by 12 %. The results indicate that while current forest management practices can increase the export of N, P and SS from boreal catchments for many years (>10 years), the increases are only significant when the area of clear cutting exceeds 30 % of catchment area.

Keywords Catchment · Final cutting · Leaching · Soil preparation · Water quality

INTRODUCTION

Some 26.3 million ha (86 %) of Finland's land area is covered by forests, and most (90 %) of them are managed for wood production (Ylitalo 2010). Annually 130 000–150 000 ha of forests are clear-cut and mechanical soil preparation is carried out on 120 000–130 000 ha (Ylitalo 2010). Clear-cutting can considerably change water and nutrient fluxes of forested catchments (Kreutzweiser et al. 2008). The removal of trees reduces interception and transpiration, which, in turn, increase ground water levels, runoff, and peak flows (Lundin 1979; Bosch and Hewlett 1982; Rosén et al. 1996; Sørensen et al. 2009; Schelker et al. 2013). Nutrients are susceptible to leaching after clear-cutting because nutrient uptake by vegetation is minor (Finér et al. 2003; Palviainen et al. 2005), large amounts of nutrients are released from logging residues (Palviainen et al. 2004) and nitrification and mineralization in the soil may increase (Paavolainen and Smolander 1998; Smolander et al. 2001). Soil preparation further increases the risk of nutrient leaching because it accelerates decomposition (Lundmark-Thelin and Johansson 1997), destroys ground vegetation (Palviainen et al. 2007) and disturbs soil structure which may affect soil hydrological properties, water flow paths and thereby influence runoff generation mechanisms (Mäkitalo 2009).

Increased carbon (C), nitrogen (N), phosphorus (P), and suspended solids (SS) export to watercourses have often been observed after the clear-cutting of boreal forests (Grip 1982; Rosén et al. 1996; Ahtiainen and Huttunen 1999; Lamontagne et al. 2000; Laudon et al. 2009; Schelker et al. 2012). This is due to increased runoff, elevated concentrations or both. Exports are usually the greatest during the first years after clear-cutting but it can take up to 10–20 years until loads return to pre-cutting levels (Rosén et al. 1996; Ahtiainen and Huttunen 1999). The leaching of N, P, and SS can deteriorate the quality of surface waters by increasing eutrophication, turbidity, silting, algal blooms, and hypoxia (Kreutzweiser et al. 2008). The leaching of organic C influences transportation of metals (Reuter and Perdue 1977; Porvari et al. 2003) and the acid-base chemistry and pH of surface waters (Mattsson et al. 2007), and represents an important pathway of C from terrestrial to aquatic ecosystems (Cole et al. 2007; Schelker et al. 2012). The occurrence, intensity, and duration of forest management impacts on stream water depends on climate, catchment topography, soil properties, and atmospheric deposition (Lepistö et al. 1995; Bredemeier et al. 1998; Akselsson et al. 2004; Kokkonen et al. 2006; Kreutzweiser et al. 2008). Intensity of harvesting and site preparation, size of harvested area and proximity to watercourses, and vegetation recovery also determine the magnitude and duration of excess leaching (Likens et al. 1970; Ahtiainen and Huttunen 1999; Kreutzweiser et al. 2008; Löfgren et al. 2009). Catchments with high atmospheric deposition, steep slope angles, and fertile soil have higher stream water N and P concentrations and export loads (Mattsson et al. 2003; Kortelainen et al. 2006; Kreutzweiser et al. 2008). In Finland stream water N and P concentrations and exports are higher in the south than in the north, reflecting differences in deposition loads and climate (Mattsson et al. 2003; Kortelainen et al. 2006). That might indicate that the element loads increase less in the north than in the south after clear-cutting and soil preparation, although the increase might last long due to the slow nutrient mineralization rates and recovery of nutrient uptake by vegetation in cold climatic conditions.

The effects of clear-cutting and soil preparation on nutrient export have been studied in only a few catchments in Fennoscandia, mainly in southern parts of Finland and Sweden (Grip 1982; Haapanen et al. 2006; Mattsson et al. 2006) and more data are needed in order to be able to generalize the results. Furthermore, most of the studies have been short-term and were carried out in the 1970s and 1980s when forestry practices were drastically different from those of today (Grip 1982; Wiklander et al. 1991; Rosén et al. 1996; Ahtiainen and Huttunen 1999; Kreutzweiser et al. 2008). Nowadays, clear-cut areas are smaller, soil preparation methods lighter (less soil disturbance), and buffer zones obligatory along watercourses. To develop water protection, improved and updated knowledge about the long-term impacts of current forest management methods on surface water quality is needed.

The aim of this study was to investigate the long-term effects of clear-cutting and soil preparation on runoff, total nitrogen (total N), total organic nitrogen (TON), ammonium (NH_4-N), nitrate (NO_3-N), total phosphorus (total P), phosphate (PO_4-P), total organic carbon (TOC), and suspended solids (SS) concentrations and loads in stream water in four catchments (one reference and three clear-cut treated catchments) in eastern Finland. The purpose of this study was to find out the magnitude, timing, and duration of possible effects. Clear-cutting and soil preparation were performed according to current forest management guidelines and buffer zones were left along the streams. We hypothesized that clear-cutting and soil preparation cause small but long-lasting increase in runoff and the concentrations and export of N, P, TOC, and SS.

MATERIALS AND METHODS

Study Areas

The study was carried out at four forested first-order catchments in eastern Finland (Table 1; Fig. 1, Finér et al. 1997) using a paired catchment approach. Porkkavaara (Ref) served as a reference catchment for Kangasvaara (C34), Iso-Kauhea (C11), and Korsukorpi (C8) treatment catchments. The catchments were all located within 30 km of each other and have similar relief with shallow slopes (2–7 %). The long-term (1971–2000) mean annual air temperature for the area is +1.9 °C and precipitation 564 mm of which 200 mm falls as snow (Drebs et al. 2002). The highest annual peak stream flow occurs during snowmelt in April–May. The mean annual atmospheric N deposition in the area is 3.8 kg ha^{-1} and P deposition 0.1 kg ha^{-1} (Piirainen et al. 1998, 2004).

The soils are rather thin, weakly developed iron podzols, peaty podzols, and shallow fibric histosols that have developed on shallow (often <2 m) stony till material. Most of the peat layers are <2 m thick. The bedrock is gneiss granite and granodiorite. The main site types on the uplands of the catchments are medium rich *Vaccinium myrtillus* and *Empetrum–Vaccinium* types (Cajander 1949). The peatland site types range from *Sphagnum fuscum* bogs and low-sedge fens to herb-rich hardwood-spruce swamps and eutrophic hardwood-spruce fens (Laine and Vasander 1990). Some 17 % of the peatland area at C11 catchment has been drained, whereas the peatlands in the other catchments are pristine. The forests are dominated by Norway spruce (*Picea abies* Karst.) but Scots pine (*Pinus sylvestris* L.) and deciduous trees, mainly white and silver birch (*Betula pubescens* Ehrh. and *Betula pendula* Roth.), are also present.

Forestry Operations

Final cutting was carried out in the upland part of C34 and C11 catchments in September–October 1996 and at C8 catchment in March 2000 using a mechanized harvester (Table 1; Fig. 1). Only merchantable stems were removed and logging residues were left on clear-cut area. Unmanaged buffer zones were left along the streams (Table 1). Soil preparation was carried out in autumn 1998 in C34 and C11 catchments and in autumn 2001 in C8 catchment. Clear-cut areas were prepared mainly by soil harrowing,

Table 1 Characteristics of the reference (Ref) and C34, C11, and C8 treatment catchments and forest management practices

	Ref	C34	C11	C8
Latitude	63°52′N	63°51′N	63°53′N	63°53′N
Longitude	29°10′E	28°58′E	28°37′E	28°40′E
Elevation (m a.s.l.)	182	187	200	198
Elevation of highest point (m a.s.l.)	226	238	231	221
Slope (%)	5	7	2	2
Area (ha)	72	56	176	69
Peatlands (%)	16	8	50	56
Total stem volume (m^3 ha^{-1})	179	275	95	60
Spruce (%)	45	54	64	50
Pine (%)	40	30	26	38
Deciduous tree species (%)	15	16	10	12
Clear-cutting and site preparation (ha) (% of catchment area)	0 (0)	19 (34)	20 (11)	5 (8)
Logged timber (m^3) (% of total stem volume on the catchment)	0 (0)	4299 (28)	3686 (22)	500 (12)
The width of buffer zone (m)		33–71	10–454	150–200

but in C11 5 ha out of the 20 ha clear-cut area was mounded. As a result of soil preparation, 46–49 % of the soil surface of the clear-cut areas was disturbed. In the spring following soil preparation, 1-year old Scots pine or Norway spruce seedlings (2200 ha^{-1}) were planted on the clear-cut areas. Porkkavaara (Ref) catchment remained unmanaged during the entire study period.

Measurements and sampling

Runoff from the catchments was measured using V-notch weirs equipped with continuous water-level recorders fitted to limnigraphs. Measurements started in all catchments in October 1991 and ended in December 2002 in C11 catchment and in December 2010 in the other catchments. Weekly limnigraph papers were used and daily runoff values calculated from the average water table level recorded at 4-h intervals. From 2002 monthly limnigraph papers were used during winter months (December–March) and thus only one value for each day could be recorded. Manual calibration measurements of stream water level were made each time the papers were changed. The condition of the weirs was checked once a year and changes in their alignment were accounted for by adjusting the weir calibration equation.

A total of 198 water samples were collected for chemical analyses from Ref, C34 and C8 catchments between January 1992 and November 2010. From C11 catchment, 118 water samples in total were taken during the period January 1992 to November 2002. The water samples were taken a few meters upstream from the weir to avoid the potential influence of water ponding above the weir. Samples were taken 3–7 times in spring (March–May) and autumn (September–November) when the flow was higher and 1–3 times in summer (June–August) when the flow was low. During the first years of the study (1992–1995), water samples were taken also once or twice during the winter (December–February). In 2000, water samples could be taken only in October and November.

The water samples were transported to the laboratory and analyzed the next day using accredited methods by the Finnish Environment Institute. Total N, NH_4-N, NO_3-N, total P, and TOC concentrations were analyzed from unfiltered samples and PO_4-P and SS concentrations from filtered samples. SS samples were filtered with 0.45 μm glass fiber filters and for PO_4-P either 0.45 μm membrane filters (1992–2000) or 0.45 μm polycarbonate filters (2001–2010) were used. Total N concentrations were determined colorimetrically after oxidization with $K_2S_2O_8$, NH_4-N was measured by a spectrophotometer, and NO_3-N by the cadmium method. Concentrations of TON were calculated as the difference between total N and inorganic N. Total P was analyzed by the molybdenum blue method after digestion with $K_2S_2O_8$. PO_4-P was measured by the molybdenum blue method. The acidified TOC samples were bubbled with nitrogen to remove inorganic carbon (CO_2) and TOC concentrations determined using high-temperature oxidation followed by infra-red gas measurements. SS concentrations were measured as the residue of ignition in 1992–2000 and afterwards as the portion retained on the glass fiber filter. The detection limits (DL) for N, NH_4-N, NO_3-N, P, PO_4-P, TOC, and SS were 40 μg L^{-1}, 2 μg L^{-1}, 5 μg L^{-1}, 3 μg L^{-1}, 2 μg L^{-1}, 0.5 mg L^{-1}, and 1 mg L^{-1}, respectively. The concentrations of NH_4-N (14 % of the samples), NO_3-N (40 % of the samples), total P (3 % of the samples), and PO_4-P (35 % of the samples) that were below DL and were substituted with half DL values.

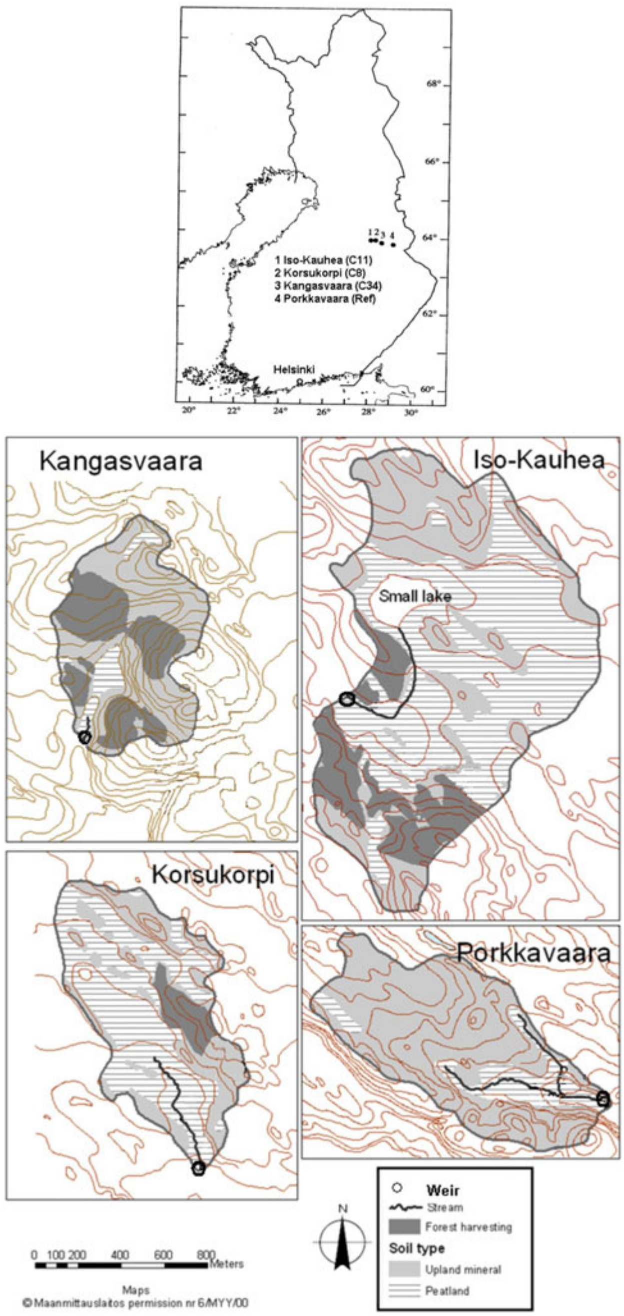

Fig. 1 Location and basic topographic map of the study catchments indicating the catchment boundaries, uplands, peatlands, clear-cut areas, outflow streams (open channels), and weirs. *Contour lines* are at intervals of 5 m

Calculations and Statistical Analyses

Daily concentrations for non-sampled periods were linearly interpolated from sequential measured values. The daily loads were calculated by multiplying daily concentrations with daily runoff and annual loads were obtained by summing up the daily values. The annual values refer to the hydrological year, which in Finland begins on November 1 and ends on October 31 of the following year.

In the paired catchment approach used in this study, two similar catchments are monitored during several years after which one of the catchment is treated and the other remains untreated. The monitoring period before treatment is called calibration period. The relationship between the catchments during the calibration period is used to predict the behavior of the treated catchment during post-treated period as if it had not been treated. The treatment effect can be determined as the difference between the measured and predicted values. Because inter-annual climatic variability can be large, the length of the calibration period should be several years so that the behavior and relationship of the catchments can be reliably predicted in different climatic conditions. In the present study, the length of the calibration period was 5 years in C34 and C11 catchments and 8 years in C8 catchment. The post-treatment period was 14 years in C34, 6 years in C11, and 11 years in C8.

To study the effect of clear-cutting on runoff, substance concentrations and loads, we used the approach of Laurén et al. (2009) and fitted the following linear regression model between reference and treatment catchments:

$$T_i = a_0 + a_1 C_i + b_1 I_1 + b_2 I_2 + b_3 I_3 + \cdots + b_m I_m + e_i, \quad i = 1, 2, 3, \ldots, n \qquad (1)$$

where i is the year index; n is the total number of years in the dataset; nc is the number of years in the calibration period; m is the number of years in the post-treatment period; k is the post-treatment year index; T_i is the observed annual runoff (mm), mean annual substance concentration (μg L^{-1}, mg L^{-1}), or load (kg ha^{-1} $year^{-1}$) for the treatment catchment in year i; C_i is the observed annual runoff (mm), mean annual substance concentration (μg L^{-1}, mg L^{-1}), or load (kg ha^{-1} $year^{-1}$) in the reference catchment in year i; a_0, a_1, b_1, b_2, …, b_m are regression coefficients; I_1, …, I_m are the dummy variables for post-treatment years. The dummy variable I connects the observation C_i to the treatment effect b_i for each year separately. The dummy variable I is assigned with a value of 1, when the year index i is equal to nc + k, else I is equal to zero. e_i is the error term.

Errors (e_i) were assumed to be uncorrelated and to have homogenous variance. The degrees of freedom of the error term depend on the number of years in the calibration period, df = nc − 2, but they do not depend on the number of years in the post-treatment period. The runoff, concentrations, and loads for the treated catchments as if they had not been treated are calculated as $a_0 + a_1 C_i$. The correlations between treatment and reference areas were high and statistically significant (Table 2). Estimates for coefficients b_1, b_2, …, b_m represent annual treatment effects. The null

Table 2 The estimates of parameters (a_0 is constant and a_1 is slope), statistical significance (p), standard errors of the estimates (SEE), and the adjusted R^2 values for annual runoff and substance concentrations and loads in C34 (Kangasvaara), C11 (Iso-Kauhea), and C8 (Korsukorpi) catchments. Porkkavaara was used as the reference catchment

	C34					C11					C8				
	a_0	a_1	p	SEE	R^2	a_0	a_1	p	SEE	R^2	a_0	a_1	p	SEE	R^2
Annual runoff	70.799	0.588	<0.001	25.33	0.994	14.456	0.907	0.001	36.28	0.990	69.62	0.874	<0.001	20.74	0.997
Concentrations															
Total N (μg L^{-1})	−34.818	0.891	0.001	12.88	0.994	515.762	−0.007	<0.001	0.45	0.999	442.672	−0.188	<0.001	31.87	0.993
TON (μg L^{-1})	−18.149	0.797	0.001	13.59	0.991	447.156	0.043	<0.001	2.54	0.999	407.728	−0.177	<0.001	36.90	0.990
NH_4-N (μg L^{-1})	0.550	0.740	0.010	0.48	0.956	14.344	0.565	0.001	1.19	0.993	19.857	−2.764	0.084	5.71	0.594
NO_3-N (μg L^{-1})	5.417	0.421	0.002	2.85	0.985	33.555	1.235	<0.001	0.56	0.999	34.739	−2.167	0.034	9.10	0.717
Total P (μg L^{-1})	−6.448	2.042	0.002	0.53	0.986	14.949	−0.244	<0.001	0.26	0.999	4.438	1.475	<0.001	1.93	0.967
PO_4-P (μg L^{-1})	0.040	0.942	0.001	0.13	0.993	−0.060	3.490	0.002	0.68	0.981	1.683	0.902	<0.001	0.70	0.951
TOC (mg L^{-1})	−4.406	1.116	<0.001	0.45	0.995	27.209	0.010	<0.001	0.08	0.999	21.388	−0.038	<0.001	2.77	0.984
SS (mg L^{-1})	0.166	−0.454	0.047	0.12	0.873	0.057	0.014	0.021	0.04	0.918	0.220	0.333	<0.001	0.12	0.988
Loads															
Total N (kg ha^{-1} $year^{-1}$)	0.226	0.275	<0.001	0.04	0.994	0.566	1.507	0.003	0.28	0.978	0.566	1.104	<0.001	0.27	0.968
TON (kg ha^{-1} $year^{-1}$)	0.225	0.257	<0.001	0.37	0.994	0.574	1.310	0.003	0.25	0.977	0.544	1.092	<0.001	0.27	0.966
NH_4-N (kg ha^{-1} $year^{-1}$)	0.002	0.525	0.034	0.002	0.898	0.017	3.018	0.004	0.01	0.974	0.022	0.285	<0.001	0.005	0.951
NO_3-N (kg ha^{-1} $year^{-1}$)	0.005	0.524	<0.001	0.002	0.998	0.071	4.021	<0.001	0.01	0.998	0.041	0.114	0.003	0.01	0.885
Total P (kg ha^{-1} $year^{-1}$)	0.013	0.135	0.006	0.003	0.969	0.017	1.268	0.006	0.01	0.963	0.016	1.157	<0.001	0.01	0.970
PO_4-P (kg ha^{-1} $year^{-1}$)	0.001	0.606	<0.001	0.0001	0.998	0.006	0.666	0.003	0.002	0.976	0.008	0.072	<0.001	0.001	0.980
TOC (kg ha^{-1} $year^{-1}$)	7.795	0.286	0.002	2.51	0.987	30.738	1.763	0.002	11.98	0.985	36.735	1.112	<0.001	16.57	0.965
SS (kg ha^{-1} $year^{-1}$)	0.225	0.013	0.041	0.36	0.883	0.269	−0.060	0.002	0.07	0.982	0.468	1.659	<0.001	0.84	0.955

Parameter estimates for the treatment effects (b_1, …, b_m) and their 95 % confidence limits are presented in Figs. 3, 4, 5, and 6

hypothesis (no treatment effect) is tested using the F test with m and $nc - 2$ degrees of freedom for parameters b_1, b_2, …, b_m. The advantage of Eq. 1 is that it allows to take into account the random variability between treatment and reference catchments during the calibration period in the interpretation of the effects observed after treatments.

The estimates of annual treatment effects or their statistical significance were not used to study the duration of treatment effects because the random variation of the annual estimates may change the sign of the effect before the real treatment effect disappears and small treatment effects are easily lost in statistical tests of annual effects (Laurén et al. 2009). To avoid underestimation of total treatment effects and their duration we calculated the sum of $b_1 + b_2 + \cdots + b_k$ to obtain cumulative treatment effects (Laurén et al. 2009). The treatment effect was assumed to cease when the cumulative effect reaches a stable level.

RESULTS

Hydrological Conditions

The mean annual temperature (2.2 °C during 1992–1996 and 2.1 °C during 1992–1999) and precipitation (557 mm during 1992–1996 and 549 mm during 1992–1999) during the calibration periods were similar to the long-term averages (1.9 °C, 564 mm) for the area (Fig. 2). The post-treatment periods were, on average, warmer than the long-term mean temperature while the amount of precipitation was similar (Fig. 2). The annual runoff was highest for C8 and smallest for C34 during the calibration period (Table 3).

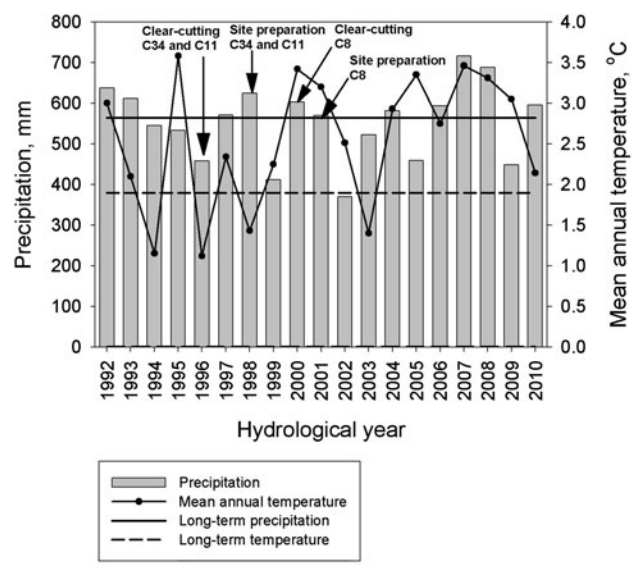

Fig. 2 Annual precipitation and mean annual temperature in the study area in the long-term (1971–2000) and during the study period (1992–2010). The *arrows* indicate the timing of clear-cutting and soil preparation in C34 (Kangasvaara), C11 (Iso-Kauhea), and C8 (Korsukorpi) catchments

Table 3 Mean (standard deviation in parenthesis), annual runoff and total nitrogen (total N), total organic nitrogen (TON), ammonium (NH_4-N), nitrate (NO_3-N), total phosphorus (total P), phosphate phosphorus (PO_4-P), total organic carbon (TOC), and suspended solids (SS) concentrations and loads in reference (Ref) and C34, C11, and C8 treatment catchments during the calibration period

Variable	Ref (1992–1996)	C34 (1992–1996)	C11 (1992–1996)	Ref (1992–1999)	C8 (1992–1999)
Total N (μg L^{-1})	210 (21)	153 (21)	514 (0.4)	205 (23)	404 (30)
TON (μg L^{-1})	200 (21)	141 (21)	456 (24)	195 (23)	373 (34)
NH_4-N (μg L^{-1})	3.5 (0.5)	3.1 (0.5)	16.3 (1.1)	3.2 (0.6)	10.9 (5.6)
NO_3-N (μg L^{-1})	7.0 (1.3)	8.4 (2.5)	42.2 (1.7)	6.8 (1.4)	20.1 (9.0)
Total P (μg L^{-1})	5.5 (0.4)	4.8 (0.9)	13.6 (0.2)	5.3 (0.5)	12.2 (2.0)
PO_4-P (μg L^{-1})	1.2 (0.2)	1.2 (0.2)	4.2 (1.0)	1.4 (0.5)	3.0 (0.8)
TOC (mg L^{-1})	9.5 (0.9)	6.2 (1.1)	27.3 (0.1)	9.7 (1.4)	21.0 (2.6)
SS (mg L^{-1})	0.15 (0.10)	0.10 (0.10)	0.06 (0.04)	0.11 (0.10)	0.26 (0.11)
Runoff (mm)	409 (72)	311 (48)	385 (73)	403 (77)	422 (70)
Total N (kg ha^{-1} $year^{-1}$)	0.94 (0.2)	0.48 (0.1)	1.98 (0.37)	0.91 (0.22)	1.57 (0.34)
TON (kg ha^{-1} $year^{-1}$)	0.90 (0.2)	0.46 (0.1)	1.75 (0.32)	0.88 (0.21)	1.50 (0.34)
NH_4-N (kg ha^{-1} $year^{-1}$)	0.02 (0.01)	0.01 (0.003)	0.06 (0.02)	0.01 (0.005)	0.03 (0.005)
NO_3-N (kg ha^{-1} $year^{-1}$)	0.02 (0.01)	0.02 (0.01)	0.16 (0.04)	0.02 (0.01)	0.04 (0.01)
Total P (kg ha^{-1} $year^{-1}$)	0.026 (0.006)	0.017 (0.003)	0.052 (0.011)	0.026 (0.006)	0.046 (0.009)
PO_4-P (kg ha^{-1} $year^{-1}$)	0.005 (0.001)	0.004 (0.001)	0.009 (0.002)	0.005 (0.001)	0.008 (0.001)
TOC (kg ha^{-1} $year^{-1}$)	42.2 (9.4)	19.9 (3.5)	105.1 (19.6)	41.7 (10.9)	83.1 (19.5)
SS (kg ha^{-1} $year^{-1}$)	0.96 (1.4)	0.24 (0.3)	0.21 (0.10)	0.61 (1.18)	1.49 (2.11)

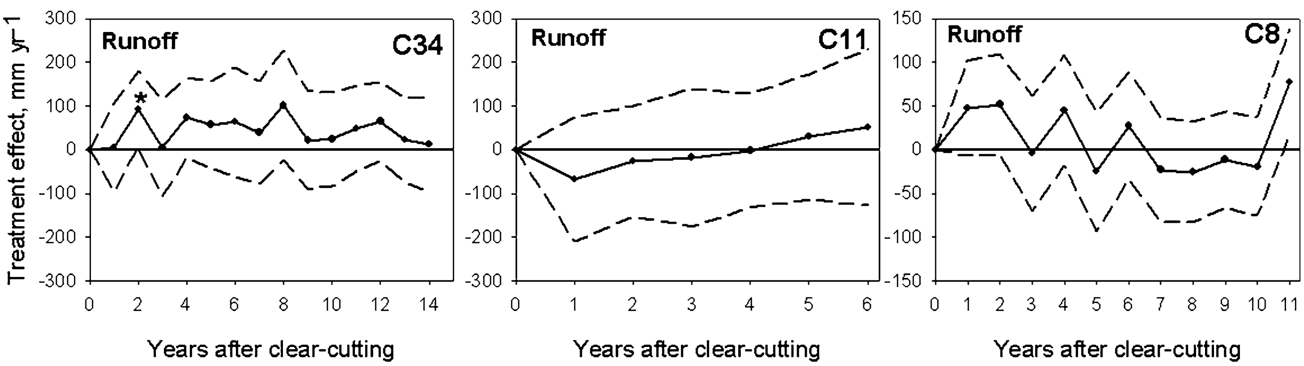

Fig. 3 Treatment effects (*solid lines*) and their 95 % confidence intervals (*dashed lines*) for annual runoff in C34 (Kangasvaara), C11 (Iso-Kauhea), and C8 (Korsukorpi) catchments. Statistically significant differences ($p < 0.05$) are indicated with *asterisk*. Note the different scales on *y*-axis

In C34, clear-cutting increased annual runoff by 4–102 mm (1–30 %). However, the increment was statistically significant only at the second year after clear-cutting (Fig. 3). The maximum cumulative treatment effect at C34 catchment was reached 14 years after clear-cutting. Altogether, clear-cutting resulted in an increase in runoff of 632 mm (16 %) over the 14 years. In C11 and C8 clear-cutting did not significantly affect annual runoff (Fig. 3).

Substance Concentrations

Mean annual substance concentrations in stream water during the calibration period were lower in C34 and Ref catchments than in C11 and C8 catchments, except those of SS (Table 3). In C34 catchment, clear-cutting and soil preparation increased stream water NO_3-N concentrations by 14–39 μg L^{-1} (182–512 %) and decreased TOC concentrations by 1.7 mg L^{-1} (17 %), on average, but did not significantly affect the concentrations of other substances (Figs. 4, 5). Nitrate concentrations peaked 4 years after clear-cutting and remained elevated until 8 years after clear-cutting.

In C11 catchment, clear-cutting increased the concentrations of TON, TOC, and SS by 4.4–12.7 μg L^{-1} (1–3 %), 0.1–0.3 mg L^{-1} (0.4–1 %), and 0.07–0.19 mg L^{-1} (127–322 %), respectively, and decreased the concentrations of total N, NH_4-N, NO_3-N, and total P by 0.8–2.2 μg L^{-1} (0.2–0.4 %), 1.5–5.2 μg L^{-1} (10–32 %), 0.7–9.6 μg L^{-1} (2–22 %), and 0.6–1.6 μg L^{-1} (5–11 %),

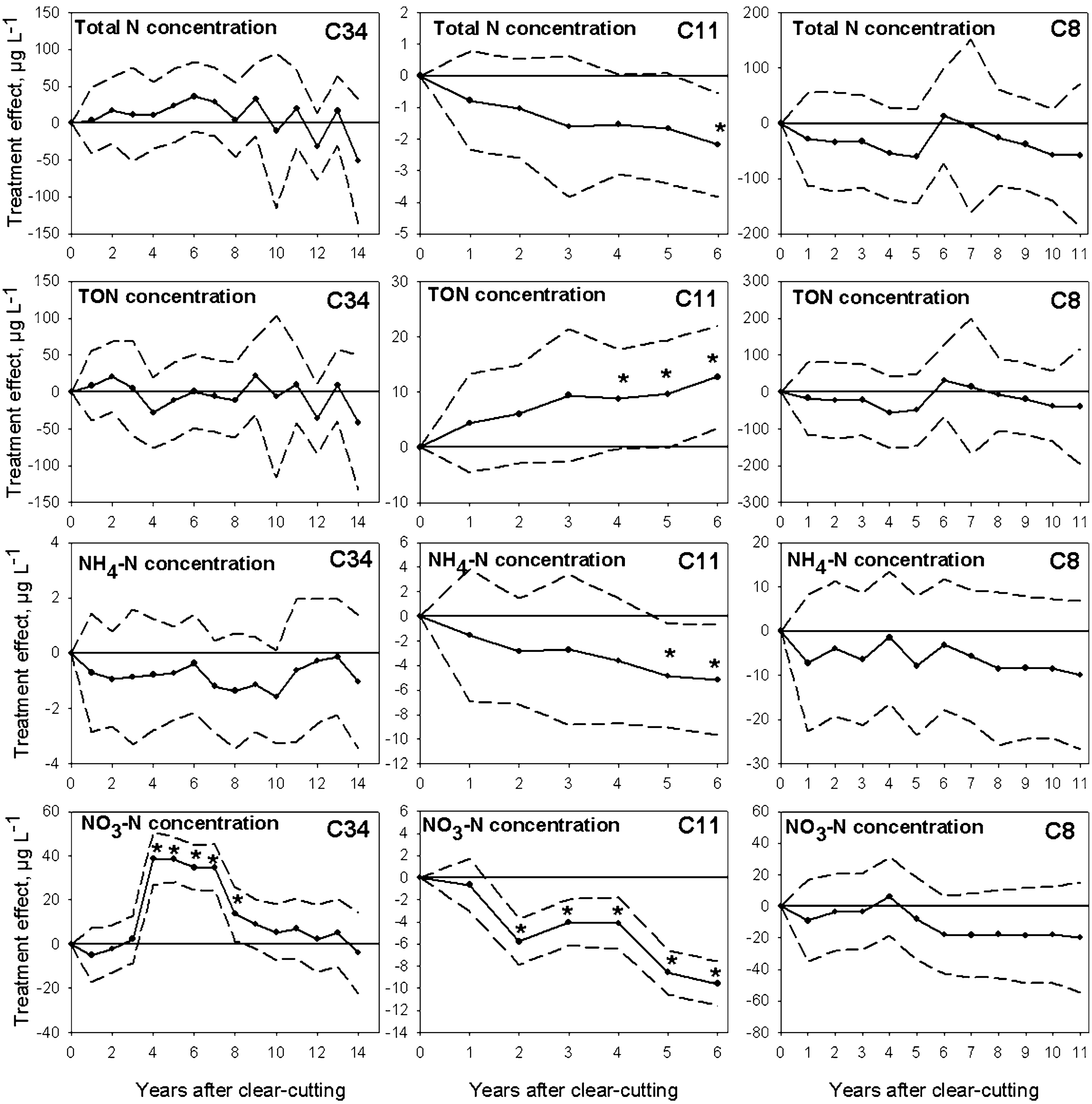

Fig. 4 Treatment effects (*solid lines*) and their 95 % confidence intervals (*dashed lines*) for total nitrogen (total N), total organic nitrogen (TON), ammonium (NH_4-N), and nitrate (NO_3-N) concentrations in stream water in C34 (Kangasvaara), C11 (Iso-Kauhea), and C8 (Korsukorpi) catchments. Statistically significant differences ($p < 0.05$) are indicated with *asterisk*. Note the different scales on *y*-axis

respectively, but did not affect PO_4-P concentrations (Figs. 4, 5). Changes in NO_3-N were significant already in the second year after clear-cutting, whereas significant changes in the concentrations of other substances were not observed until minimum 4 years after clear-cutting.

In C8, clear-cutting increased SS concentrations by 0.3–2.1 mg L^{-1} (92–435 %) but did not affect significantly the concentrations of other substances (Figs. 4, 5). The concentrations of SS remained elevated 2–10 years after clear-cutting.

Nitrogen, Phosphorus, Carbon, and Suspended Solids Loads

During the calibration period, the annual loads of all substances except SS were lower in C34 and Ref catchments

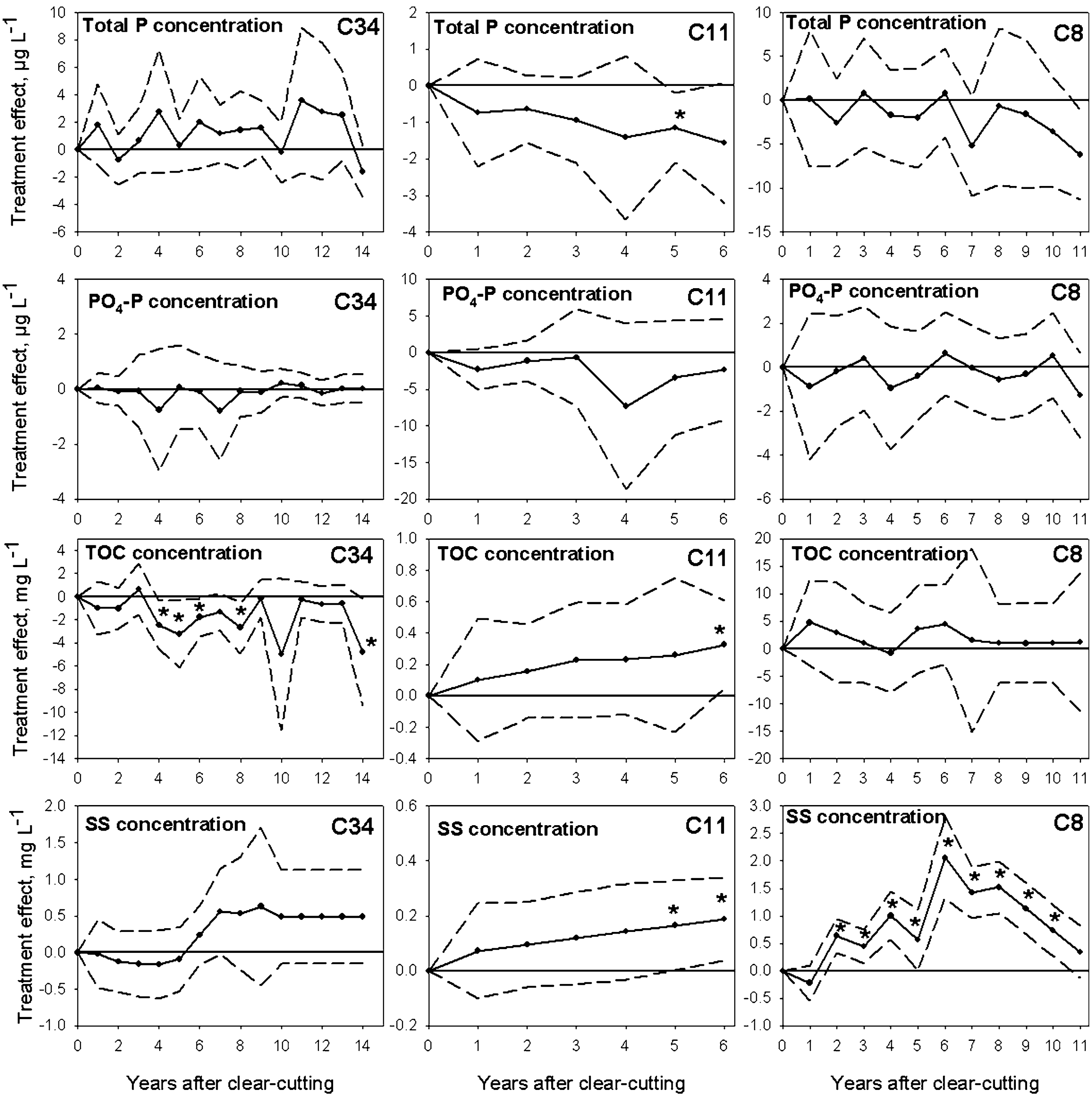

Fig. 5 Treatment effects (*solid lines*) and their 95 % confidence intervals (*dashed lines*) for total phosphorus (total P), phosphate (PO_4-P), total organic carbon (TOC), and suspended solids (SS) concentrations in stream water in C34 (Kangasvaara), C11 (Iso-Kauhea), and C8 (Korsukorpi) catchments. Statistically significant differences ($p < 0.05$) are indicated with *asterisk*. Note the different scales on *y*-axis

compared to C11 and C8 catchments (Table 3). Inorganic N accounted for only 6–11 % of the total transported N and PO_4-P constituted 16–24 % of the total dissolved P load.

In C34, clear-cutting and soil preparation increased total N, TON, NO_3-N, PO_4-P, and SS loads significantly (Fig. 6), but did not affect NH_4-N, total P, and TOC loads (data not shown). Clear-cutting increased the annual export of total N, TON, NO_3-N, PO_4-P, and SS by at most 0.36 (72 %), 0.35 (76 %), 0.15 (1056 %), 0.002 (35 %), and 2.0 (715 %) kg ha^{-1}, respectively. The increase in the export of N forms were significant already during the first few years after clear-cutting, whereas for PO_4-P and SS the increase became significant several years after clear-cutting. The export of total N increased by 18 %, TON by 12 %, NO_3-N by 270 %, PO_4-P by 12 %, and SS by 291 % during the 14-year observation period. Based on the cumulative excess load, the treatment effect lasted 11 years for TON (0.7 kg ha^{-1}), 13 years for total N (1.2 kg ha^{-1})

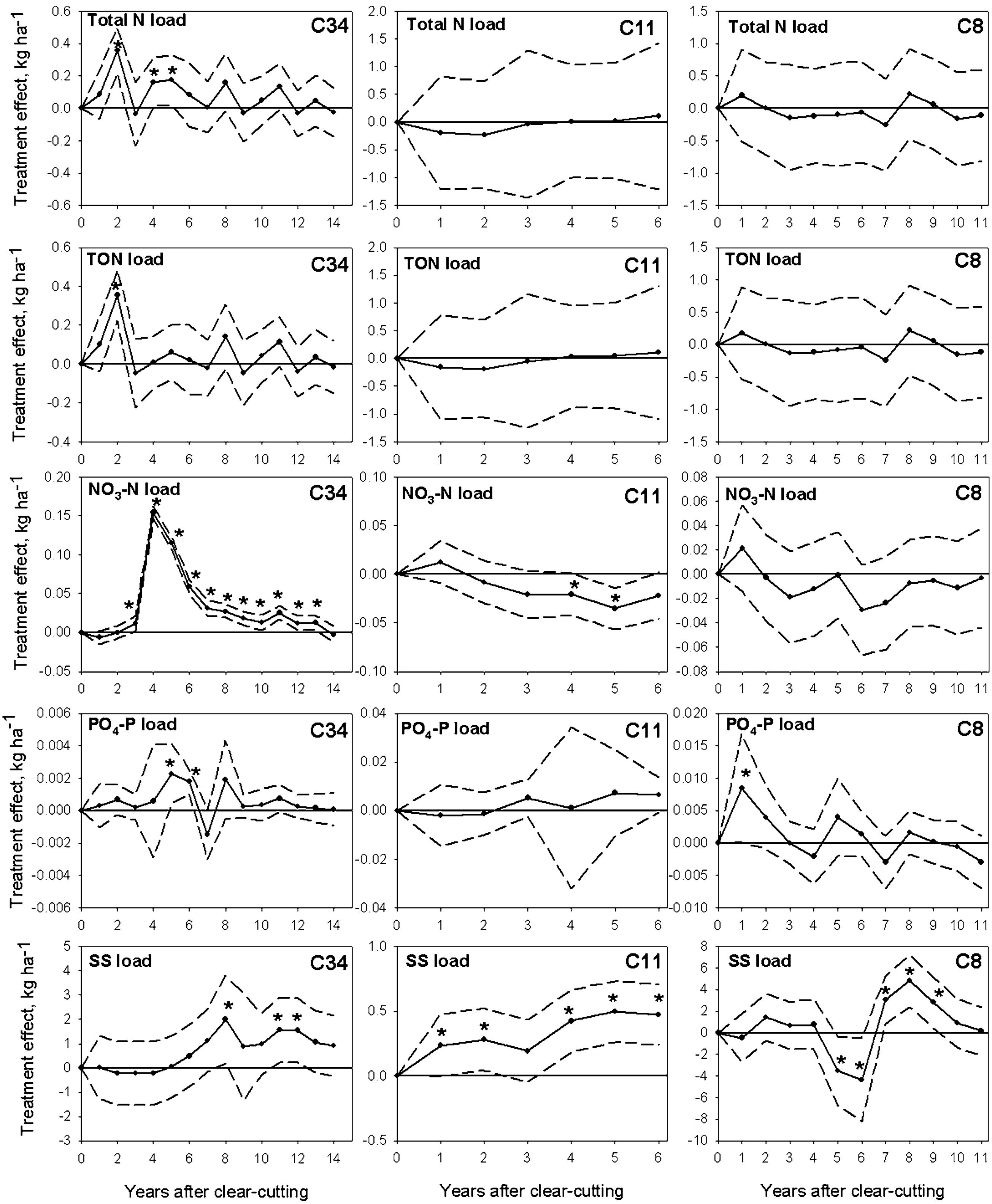

Fig. 6 Treatment effects (*solid lines*) and their 95 % confidence intervals (*dashed lines*) for annual total nitrogen (total N), total organic nitrogen (TON), nitrate (NO_3-N), phosphate (PO_4-P), and suspended solids (SS) loads in C34 (Kangasvaara), C11 (Iso-Kauhea), and C8 (Korsukorpi) catchments. Statistically significant differences ($p < 0.05$) are indicated with *asterisk*. Note the different scales on *y*-axis

and NO_3-N (0.47 kg ha^{-1}), and 14 years for PO_4-P (0.008 kg ha^{-1}) and SS (10 kg ha^{-1}). The proportion of inorganic N load out of the total N load was, on average, greater after clear-cutting (mean 10 %, range 2–29 %) than in the calibration period (mean 6 %, range 4–7 %). Also the proportion of PO_4-P load out of total dissolved P load was greater after clear-cutting (mean 35 %, range 19–70 %) than in the calibration period (mean 22 %, range 13–26 %).

In the C11 catchment, clear-cutting and soil preparation increased SS loads and decreased NO_3-N loads (Fig. 6), but did not affect the export of other substances. Clear-cutting increased the annual export of SS by 0.2–0.5 kg ha^{-1} (72–198 %) and decreased the annual export of NO_3-N by 0.01–0.04 kg ha^{-1} (6–23 %). During the 6-year study period SS export increased 2.1 kg ha^{-1} (134 %) and NO_3-N export decreased 0.1 kg ha^{-1} (12 %).

According to the statistical test clear-cutting increased the export of PO_4-P (0.008 kg ha^{-1}, 95 %) significantly in the first year after clear-cutting in C8 (Fig. 6). During the 11-year study period the cumulative increase of PO_4-P export was 0.011 kg ha^{-1} (12 %). The statistical test showed first significant decrease in annual export of SS in the fifth (4.4 kg ha^{-1}, 46 %) and sixth (3.0 kg ha^{-1}, 113 %) years after clear-cutting but increased thereafter (2.8–4.8 kg ha^{-1}, 74–118 %). The initial increase in PO_4-P export and decrease in SS export were related to the unusual loads of these substances in the reference catchment in those years and accordingly affecting the modeled loads for treatment catchment in its natural state (without treatment). During the 11 year study period the cumulative increase of SS export was 6.2 kg ha^{-1} (16 %).

DISCUSSION

Differences Between Catchments

The studied forested catchments were located in an area with low atmospheric deposition of N, with cold climatic conditions, with medium rich soils and with relatively flat terrains. Concentrations and loads of substances were low in all catchments before clear-cutting indicating closed nutrient cycling and small leaching loss from the catchments. The observed concentrations and loads during the calibration period were of the same order of magnitude as previously reported for unmanaged boreal forested catchments in Finland (Mattsson et al. 2003; Kortelainen et al. 2006). Somewhat greater total N, TON, NH_4-N, NO_3-N, total P, PO_4-P, and TOC concentrations and loads during the calibration period in C11 and C8 catchments compared to C34 and Ref catchments can be attributed to their high proportion of peatlands (Laudon et al. 2004; Kortelainen et al. 2006), smaller amount of tree stock per hectare with smaller nutrient uptake capacity (Table 1), and larger annual runoff (Table 3).

Clear-cutting significantly increased annual runoff (4–102 mm or 1–30 %) in C34 catchment only. The maximum annual treatment effect, 102 mm, its timing and duration was very similar to those reported in other Fennoscandian studies with the same proportion of clear-cut area (Ide et al. 2013 and references therein). The lack of an increase in catchment C11 and C8 runoff was most probably due to the small proportion of the clear-cut area in these catchments (Bosch and Hewlett 1982; Stednick 1996; Ide et al. 2013). Catchments can also display different runoff responses depending on topography, soil properties, configuration and timing of harvesting, location of clear-cut area in relation to the stream and the rate of regrowth (Hornbeck et al. 1997; Kreutzweiser et al. 2008; Abdelnour et al. 2011). The topography differed between C34 and C11 and C8 (Table 1). The somewhat steeper slopes in C34 than the other two catchments could contribute to the increase in runoff after clear-cutting (Kreutzweiser et al. 2008). Furthermore, in boreal catchments, where a considerable part of annual runoff takes place in spring, there are large inter-annual variations in snowmelt and streamflow responses after clear-cutting, with some years showing an increased runoff and others showing no effect (Ide et al. 2013; Schelker et al. 2013).

Clear-cutting increased the export of total N, TON, NO_3-N, PO_4-P, and SS, and except for PO_4-P and SS, in C34 only. The increase in the export of total N and TON can be attributed largely to the increased runoff because clear-cutting did not significantly affect the concentrations of total N and TON and their increase occurred simultaneously with the increase in runoff. The results are in line with previous studies indicating that inorganic N output occurs predominantly as NO_3-N rather than NH_4-N and that most of the leached N from boreal clear-cut forests is organic N (Grip 1982; Lamontagne et al. 2000; Löfgren et al. 2009, Table 4). The increases in stream water NO_3-N concentrations and loads in C34 could result from higher deposition loads due to the lack of N retention by tree canopy (Piirainen et al. 2002), greater snow accumulation on clear-cut areas (Varhola et al. 2010), reduced nutrient uptake by trees and understory vegetation (Piirainen et al. 2002; Finér et al. 2003; Palviainen et al. 2004, 2005, 2007), and increased nitrification in the litter layer and soil (Paavolainen and Smolander 1998; Smolander et al. 2000, 2001; Piirainen et al. 2007). NO_3-N is poorly retained in the soil by sorption and can easily be leached to ground and surface waters after clear-cutting (Ahtiainen 1990; Rosén et al. 1996; Kubin 1998; Kreutzweiser et al. 2008). Elevated NO_3-N concentrations were also observed in soil and ground water in the study catchments after clear-cutting and soil preparation (Piirainen et al. 2002, 2007;

Table 4 The catchments characteristics, the duration of the study, and clear-cutting induced increase in average annual total nitrogen (total N), nitrate (NO_3-N), ammonium (NH_4-N), total phosphorus (total P), phosphate (PO_4-P), and suspended solids (SS) loads (kg ha^{-1} $year^{-1}$) in Fennoscandian catchments. The increases in export as percentage in relation to reference period are presented in parentheses. Soil preparation was carried in all the other studies except in the study of Grip (1982)

Coordinates	Clear-cutting ha/%	Removed trees (m^3 ha^{-1})	Buffer zone	Peatland %	Study (years)	Total N	TON	NO_3-N	NH_4-N	Total P	PO_4-P	SS	Ref
59°54′N 15°50′E	65.4/87	176	No	2.5	3	4.94 (464 %)	3.70 (422 %)	0.58 (460 %)	0.66 (1941 %)	0.25 (500 %)	0.07 (389 %)	–	1
59°54′N 15°50′E	25.3/23	116	No	0.9	3	4.04 (380 %)	2.43 (277 %)	1.23 (976 %)	0.38 (1118 %)	0.12 (240 %)	0.04 (222 %)	–	1
59°54′N 15°50′E	55.9/40	171	No	1.4	3	1.26 (118 %)	1.13 (129 %)	0.11 (87 %)	0.02 (59 %)	0.06 (120 %)	0.04 (222 %)	–	1
63°45′N 28°29′E	286/58	168	No	50	3	2.60 (118 %)	–	0.15 (750 %)	0.17 (298 %)	0.70 (538 %)	0.50 (847 %)	4 (82 %)	2, 3
63°45′N 28°29′E	286/58	168	No	50	12	3.30 (150 %)	–	–	–	0.53 (408 %)	0.31 (525 %)	389 (7939 %)	3
63°52′N 28°39′E	36/56	177	Yes	32	3	0.70 (39 %)	–	n.s.	0.09 (310 %)	0.03 (42 %)	0.01 (63 %)	3 (115 %)	2, 3
63°52′N 28°39′E	36/56	177	Yes	32	12	0.43 (24 %)	–	–	–	0.01 (14 %)	0.01 (63 %)	1 (38 %)	3
62°02′N 16°32′E	100/50		No	12	8	1.88 (238 %)	1.19 (175 %)	0.27 (386 %)	0.18 (360 %)	–	–	–	4
62°00′N 16°33′E	38/95		No	22	8	3.29 (346 %)	1.69 (241 %)	0.78 (411 %)	0.47 (940 %)	–	–	–	4
61°51′N 23°41′E	13.1/40	220	Yes	14	3	0.84 (89 %)	–	–	–	0.53 (177 %)	–	5 (80 %)	5
61°51′N 23°41′E	2.1/40	234	Yes	13	3	0.98 (79 %)	–	–	–	0.14 (175 %)	–	5 (96 %)	5
61°52′N 23°41′E	2.8/39	301	Yes	14	3	1.10 (88 %)	–	–	–	0.08 (160 %)	–	n.s.	5
61°00′N 24°45′E	5.4/76	197	Yes	1	3	2.59 (355 %)	–	–	–	0.08 (400 %)	–	n.s.	5
60°08′N 24°16′E	5.4/30	212	Yes	6	3	4.70 (362 %)	–	1.6 (762 %)	0.66 (1345 %)	0.14 (500 %)	0.01 (227 %)	72 (720 %)	6
63°49′N 20°15′E	27/73	146	No	8	2	1.29 (89 %)	0.84 (65 %)	0.40 (444 %)	0.05 (71 %)	0.02 (33 %)	–	22.5 (47 %)	7
63°49′N 20°15′E	3.3/30	200	Yes	2	2	0.66 (52 %)	0.80 (71 %)	n.s.	n.s.	0.02 (25 %)	–	25.0 (63 %)	7
63°51′N 28°58′E	19/34	226	Yes	8	14	0.08 (18 %)	0.05 (12 %)	0.03 (270 %)	n.s.	n.s.	0.0003 (12 %)	0.71 (291 %)	This study
63°53′N 28°37″E	20/11	184	Yes	50	6	n.s.	n.s.	−0.02 (12 %)	n.s.	n.s.	n.s.	0.35 (134 %)	This study
63°53′N 28°40′E	5/8	100	Yes	56	11	n.s.	n.s.	n.s.	n.s.	n.s.	0.001 (12 %)	0.56 (16 %)	This study

References: *1* Grip (1982), *2* Ahtiainen (1990), *3* Ahtiainen and Huttunen (1999), *4* Rosén et al. (1996), *5* Haapanen et al. (2006), *6* Mattsson et al. (2006), *7* Löfgren et al. (2009); – Not determined, *n.s.* not statistically significant increase

Mannerkoski et al. 2005). NO_3-N concentrations and loads did not change in C8 and actually decreased in C11. The small proportion of clear-cut area and long distance to the stream can probably explain why there was no significant change in the leaching of NO_3-N in C8, but the decrease in NO_3-N is more difficult to explain and is not observed in earlier studies (Table 4). In C11 the clear-cut area that was closest to the stream was water-logged already before clear-cutting and the other clear-cut areas within the catchment were separated from the stream by pristine peatlands. Thus it is probable that the high ground water table and anaerobic conditions promoted denitrification and consequently decreased NO_3-N concentrations and export from the catchment (Saari et al. 2009).

The increased PO_4-P export after clear-cutting in C34 was probably due to increased runoff because there was no increase in PO_4-P concentrations. Phosphate could originate from logging residues, which released phosphorus rapidly (Palviainen et al. 2004), and decomposing understory vegetation after soil preparation (Palviainen et al. 2007). Elevated ground water levels and more superficial water flow paths after clear-cutting may also have promoted PO_4-P solubility and transport to the stream (Piirainen et al. 2004, 2007; Kreutzweiser et al. 2008). However, the export of PO_4-P did not increase in the C11 catchment even though the ground water levels were higher in catchment C11 than in catchment C34 (Mannerkoski et al. 2005). The longer average distance to the stream and presence of peat with high P retention capacity in the buffer zone (Nieminen and Jarva 1996) could explain the differences in the behaviour between catchments C11 and C34. The increase in the PO_4-P export in the first year after clear-cutting in the C8 catchment is probably due to unusually low PO_4-P loads in the reference catchment in that year (data not shown) rather than treatment effect.

Unlike in some other studies (Lamontagne et al. 2000; Laudon et al. 2009; Schelker et al. 2012), we did not find increased exports of TOC after clear-cutting and TOC concentrations even decreased after clear-cutting in C34, probably as a result of the dilution effect caused by the increased runoff (Mattsson et al. 2003). High runoff could induce more flow through the subsurface, organic-rich soil horizons and increase TOC export (Laudon et al. 2009; Schelker et al. 2012). However, clear-cutting increases runoff mainly in spring (data not shown, Ide et al. 2013) when the soil can be frozen and runoff is generated with little contact with organic soil horizons (Mattsson et al. 2003; Köhler et al. 2008).

Clear-cutting and soil preparation increased the export of SS in all treatment catchments. The machinery used for logging and soil preparation could have caused rutting and the soil preparation created long furrows forming additional flow paths and increasing erosion. The time delay in the increase in SS export in C34 and C8 could be a sign of the higher impact of soil preparation than the soil disturbance by the logging machines. The long-lasting impacts on SS load indicate that the erodible soil surfaces are only slowly vegetated so allowing the erosion to continue.

Magnitude of the Increase in Substance Loads

Irrespective of the substance, the increase in the annual loads, both in absolute (kg ha^{-1}) and in relative terms (%) were small compared to those reported in earlier Fennoscandian studies, except for SS (Table 4). The total differences could be even greater, since most of the studies report only the first 2- to 3-year impacts of clear-cutting on the substance loads. Most of the previous studies are also conducted in more southern location, where the atmospheric deposition and background loads from forested catchments are higher than in the north (Mattsson et al. 2003; Kortelainen et al. 2006), and clear-cutting can more easily induce higher absolute increase in substance export than in the north (Wiklander et al. 1991; Akselsson et al. 2004). However, also in studies conducted in northern catchments higher increase in the export of substances were observed after clear-cutting than in this study (Ahtiainen 1990; Ahtiainen and Huttunen 1999; Löfgren et al. 2009). This may be due to narrow (10–50 m) or non-existing buffer zones or higher clear-cut percentages in those earlier studies.

Responses to clear-cutting may vary also due to differences in soil texture and topography. Soil texture and topography affect the quality and movement of soil water to surface water. In coarse textured soil a large proportion of water moves as subsurface runoff and in catchments with shallow slopes water residence times are longer (Kreutzweiser et al. 2008). Consequently, subsurface water is in contact with soil layers for a longer time, facilitating the precipitation and sorption of nutrients by the soil (Laurén et al. 2005; Kokkonen et al. 2006; Kreutzweiser et al. 2008). Our study catchments were gently sloping and the soils were coarse textured. Soil water studies in C34 catchment indicated that a large part of the increased C, N, and P fluxes after clear-cutting and soil preparation were retained in the mineral soil (Piirainen et al. 2002, 2004, 2007). The rapid development of understory vegetation (Palviainen et al. 2005, 2007) and the accumulation of N in decomposing logging residues (Palviainen et al. 2004) during the first years after clear-cutting observed in C34 probably also diminished the leaching of nutrients in the study catchments. The annual exports of total N and P were smaller than the deposition loads of N and P, which indicates that N and P were retained even after clear-cutting.

Timing and Duration of the Clear-Cut on Substance Loads

The runoff, total N, and TON exports increased and peaked already in the second year after clear-cutting, whereas the export of NO_3-N and PO_4-P peaked between the third and fifth years after clear-cutting. Similar findings have been made also in other Fennoscandian studies (Grip 1982; Ahtiainen and Huttunen 1999; Haapanen et al. 2006; Mattsson et al. 2006; Löfgren et al. 2009). The immediate responses were most probably caused by the higher water and nutrient fluxes in the soil due to the cessation of the water and nutrient uptake by trees (Piirainen et al. 2002), and the delayed responses to the soil preparation and mineralization of logging residues (Palviainen et al. 2004, 2007). The increase in the substance loads after clear-cutting was long-term, depending on the substance and the estimation method from 11 to 14 years. Our findings are consistent with the results by Ahtiainen and Huttunen (1999), showing that the effects of clear-cutting and soil preparation on runoff and substance loads can continue for at least 12 years in the catchments of Eastern Finland. In another long-term study in central Sweden runoff and the export of N returned to pre-cutting levels already in 8 years (Rosén et al. 1996). Runoff and the excess load of substances can be expected to return to pre-harvest levels as the tree stands develop and water and nutrient uptake increases. That may take ≥20 years, since in similar climatic conditions seasonal runoff patterns have altered for 18 years (Ide et al. 2013), and that most probably affects also the export of substances. There are only a few studies that report long-term effects of clear-cutting on runoff and stream water quality and their results differ from those of this study due to the various climatic and site factors, which affect the responses. More long-term studies, carried out in different climatic and site conditions are therefore necessary to be able to generalize the effects of clear-cutting on nutrient leaching and surface water quality.

Reliability of the Results

Runoff was monitored continuously with the limnigraphs and the estimates can be regarded relatively reliable, although snow and ice melting time at measuring weirs can sometimes cause difficulties. Also the limited frequency of sampling and interpolation of substance concentrations may cause uncertainties in the calculated loads and the verification of treatment effects. As in other studies of this kind (Ahtiainen and Huttunen 1999; Löfgren et al. 2009; Schelker et al. 2012), load calculations were based on linear interpolation of biweekly or monthly concentration measurements. The estimated loads may differ from the true loads because in reality the concentrations do not change linearly over time and there can be short-term variation in stream water nutrient and sediment concentrations related to water flow paths, transit times and discharge, and temporal variability of biological activity (Arheimer et al. 1996). Especially N and TOC concentrations and export in the streams of boreal forested headwater catchments exhibit considerable variability during both peak and base flows (Laudon et al. 2009; Löfgren et al. 2009). In this study the sampling frequency was higher during the high flow periods in spring and autumn, which improved the accuracy of the element load estimates (Rekolainen et al. 1991). There is also uncertainty in the relationship between the treatment and reference catchments during the pre-treatment period and large natural inter-annual variation in runoff and substance loads makes discerning small treatment effects difficult. Unlike many other studies we took into account the uncertainty in the regression between the pre-treatment loads from the reference and the treatments catchments and avoided over-interpretation of the results (Laurén et al. 2009). Except for NO_3-N in C34, the confidence limits of the treatment effects were rather wide and overlapped zero values (Figs. 3, 4, 5, 6), although the coefficient of determination in the models was high (Table 2).

CONCLUSIONS

The results of this study suggest that when a small proportion (≤10 %) of the catchment is clear-cut and wide buffer zones are left along the streams the excess load of substances into watercourses is minimal from the forested catchments in central and northern parts of Finland where the atmospheric deposition is low, soils medium rich and topography of the terrain is relatively flat. The larger clear-cuts (>30 % of the catchment area) can increase total N, TON, NO_3-N, PO_4-P, and SS export to water courses for several years (>10 years).

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