Export of Dissolved Organic Carbon, Nitrogen and Phosphorus Following Clear-Cutting of Three Norway Spruce Forests Growing on Drained Peatlands in Southern Finland

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The effect of clear-cutting on the concentrations of dissolved organic carbon (DOC), organic nitrogen (DON), NH_4^+, NO_3^-, and P in outflow water from three productive, Norway spruce dominated drained peatlands (R_{CC}, $V_{CC\text{-}1}$, $V_{CC\text{-}2}$) were studied. Changes in runoff and transport loads (concentration × runoff) at two of the catchments during the frost-free period are also presented. Approximately 40% of the area was cut at R_{CC} and $V_{CC\text{-}2}$, and 72% at $V_{CC\text{-}1}$. The volume removed was 250 $m^3\,ha^{-1}$ at R_{CC}, 259 $m^3\,ha^{-1}$ at $V_{CC\text{-}1}$, and for $V_{CC\text{-}2}$, 317 $m^3\,ha^{-1}$. The mean annual increase in outflow concentrations of DOC during the first four years after clear-cutting was 9.0 $mg\,l^{-1}$ at R_{CC}, 22.8 $mg\,l^{-1}$ at $V_{CC\text{-}1}$ and 8.4 $mg\,l^{-1}$ at $V_{CC\text{-}2}$. Corresponding increases in the forms of nitrogen were: 0.23, 0.51 and 0.16 mg $DON\,l^{-1}$; 0.06, 0.31 and 0.04 mg $NH_4^+\text{-}N\,l^{-1}$; and 0.05, 0.12 and 0.22 mg $NO_3^-\text{-}N\,l^{-1}$. Clear-cutting did not significantly ($p > 0.05$) increase P concentrations. The increase in non-frost season runoff over the first three years after clear-cutting was 107 mm at R_{CC} and 207 mm at $V_{CC\text{-}1}$. The export loads of DOC during the non-frost season increased by 80 $kg\,ha^{-1}$ at R_{CC} and by 184 $kg\,ha^{-1}$ at $V_{CC\text{-}1}$ over the first three years. Corresponding increases for the other studied solutes were: 1.78 and 3.98 kg $DON\,ha^{-1}$; 0.39 and 1.49 kg $NH_4^+\text{–}N\,ha^{-1}$; 0.45 and 0.48 kg $NO_3^-\text{-}N\,ha^{-1}$, and 0.09 and 0.06 kg $P\,ha^{-1}$. The study demonstrated that clear-cutting may significantly increase the export of DOC and different forms of nitrogen from drained productive peatlands while only small increases in phosphorus export may occur.

Keywords forest regeneration, hydrochemistry, leaching, nutrient losses, peatland forestry

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1 Introduction

Drainage of waterlogged sites has been part of the normal forestry practice in Fennoscandia, the Baltic countries, the British Isles and in some parts of Russia since the early 20th century (Päivänen and Paavilainen 1990). However, it was not until the 1950's and 1960's that ploughing and mechanized excavating techniques replaced manual ditching and forest drainage activity significantly increased. Currently, about 15 million ha of peatlands and wetlands have been drained for forestry in the boreal and temperate zones (Paavilainen and Päivänen 1995), and the growth of peatland forests has significantly increased. In the former Soviet Union, for example, the drainage of about 5.5 million ha has increased the wood resources by 110 million m^3 (Sabo 1988). The rate of forest clear-cutting on drained peatlands will undergo a rapid increase in the near future, when a large number of these forests approach their regeneration age. Increasing clear-cuttings on drained peatlands, the environmental consequences need to be clarified, however. Deterioration of downstream water quality due to enhanced nutrient leaching is one of the major concerns raised in connection with an increased clear-cutting of drained peatland forests.

Water quality effects of clear-cutting on mineral soil forests have long been of concern (Bormann et al. 1968, Verry 1972, Wiklander 1981, Grip 1982, Martin et al.1985, McClurkin et al. 1985, Martin and Harr 1988, Tiedemann et al. 1988, Kubin 1995). The effects of clear-cutting virgin peatland stands on water quality have also received attention (e.g. Knighton and Stiegler 1980, Ahtiainen 1992). However, although many stands have already reached their regeneration age, the effects of clear-cutting of drained peatlands on nutrient leaching has only been studied at two locations in central Sweden (Lundin 1999, 2000), and one site in southern Finland (Nieminen 2003).

Outflows of many nutrients following clear-cutting may be higher from drained peatlands than from mineral soils. This is particularly true for nitrogen, because nitrogen reserves in organic soils are much greater than in mineral soils. If mineralization of soil nitrogen increases after clear-cutting, the outflow loss of nitrogen may be high from drained peatlands. Indeed, Lundin (1999, 2000) found significant increases in nitrogen outflow following forest regeneration on drained and productive, Norway spruce dominated peatlands. However, a combination of clear-cutting and ditching decreased stream-water concentrations of nitrate and total nitrogen from one area. In a study by Nieminen (2003) on low productive, Scots pine dominated peatlands, leaching of nitrate and ammonium, in contrast, increased only at sites that were ditched after clear-cutting.

Export of phosphorus following clear-cutting may also increase more from drained peatlands than from mineral soils. This is due to the low phosphate adsorption capacity of peat (Kaila 1959, Cuttle 1983, Nieminen and Jarva 1996). Peat with low Al and Fe content, such as often occur in low productive peatlands, have particularly low phosphate adsorption capacities. Nieminen (2003) reported very high increases in outflow water phosphorus concentrations after clear-cutting of low productive, Scots pine dominated peatlands, whereas Lundin (1999, 2000) found only slight changes in productive peatlands.

Clear-cutting of drained peatlands can also increase the production and leaching of easily soluble organic substances. The processes controlling the leaching of dissolved organic carbon (DOC) from drained peatlands are poorly known, but the risk for enhanced leaching due to clear-cutting may be high, as was shown by Lundin (1999, 2000).

This paper presents the results from a study to investigate the effects of clear-cutting on the outflow of DOC, phosphorus, and different forms of nitrogen from drained and productive, Norway spruce dominated peatlands in southern Finland.

2 Material and Methods

2.1 Site Description

The study was conducted at two locations in southern Finland; at Ruotsinkylä (60°21´N, 25°03´E, 49 m a.s.l.) and Vesijako (61°23´N, 25°03´E, 125 m a.s.l.). On the basis of measure-

Table 1. Chemical characteristics of peat (0–20 cm peat layer) at each catchment area.

	Ruotsinkylä		Vesijako		
	R_{CC}	R_{UC}	V_{CC-1}	V_{CC-2}	V_{UC}
N_{tot}[a], %	1.87	1.40	1.99	2.08	2.21
P_{tot}[b], $mg\,kg^{-1}$	948	624	804	648	1047
Ca_{tot}[b], $mg\,kg^{-1}$	4848	4251	8854	4510	6272
Fe_{tot}[b], $mg\,kg^{-1}$	5927	2353	4507	2500	7011
Al_{tot}[b], $mg\,kg^{-1}$	3340	1878	2187	1990	3002

Methods used:
[a] LECO CHN-1000 analyzer
[b] Dry ashing + digestion in HCI (Halonen et al. 1983); ICP/AES

ments by the Finnish Meteorological Institute at nearby weather stations (Climatological statistics in Finland… 1991), the long-term (1961–1990) mean annual precipitation at Ruotsinkylä was 650 mm and at Vesijako 620 mm. Mean annual temperature at Ruotsinkylä is +4.5 °C, with means of –6.8 °C in February and +16.6 °C in July. At Vesijako, the corresponding temperatures are +3.6, –8.3, and +16.0 °C. The average duration of the growing season, defined as the number of days with a mean temperature >+5 °C, is 172 days at Ruotsinkylä and 166 days at Vesijako. The average depth of the snow pack at the end of February is 27 cm at Ruotsinkylä and 42 cm at Vesijako.

There was a control and treatment catchment at Ruotsinkylä (R_{UC} and R_{CC}) and a control and two treatment catchments at Vesijako (V_{UC}, V_{CC-1}, V_{CC-2}) (Fig. 1). The sizes of catchments were: R_{CC} 6.5 ha, R_{UC} 3.7 ha, V_{CC-1} 4.3 ha, V_{CC-2} 7.8 ha, and V_{UC} 6.9 ha. Productive peatland forest stands covered the lowest parts of the catchments and mineral soil forests the surrounding uplands. The peatland and upland forests were mature and dominated by Norway spruce (*Picea abies* Karst.) except for the upland forest at R_{UC}, where Scots pine (*Pinus sylvestris* L.) was dominant. The proportion of peatlands from the total catchment area was: R_{CC} 29%, R_{UC} 38%, V_{CC-1} 58%, V_{CC-2} 39%, and V_{UC} 89%. The peatland areas at Vesijako had been drained for forestry purposes in 1914. At Ruotsinkylä, the control catchment (R_{UC}) was drained in 1932 and the clear-cut area (R_{CC}) in 1927. According to the classification of old drainage areas used in Finland (Heikurainen and Pakarinen 1982), the peatland forests at R_{CC} and V_{CC-2} were of the Herb-rich type and of the *Vaccinium myrtillys* type at the other catchments. The upland forests were *Vaccinium myrtillus* type (R_{CC}, V_{CC-1}, V_{CC-2}, V_{UC}) or *Vaccinium vitis-idaea* type (R_{UC}) according to the site type classification for upland forests (Cajander 1926).

On the basis of chemical analysis, the peatland area at the Ruotsinkylä control catchment (R_{UC}) was less fertile than the peat at the other catchments, particularly concerning nitrogen (Table 1). The depth of the peat layer at R_{UC} and V_{CC-1} was about 0.5 m and over 1 m at the other catchments. The mineral soils were podzolic and at Ruotsinkylä mainly developed in sandy-silty till and in silty till at Vesijako.

Clear-cutting was carried out in January–February 1994 at R_{CC} and V_{CC-1} and in January 1996 at V_{CC-2}. The areas were cut using conventional stem-only harvesting in which only stems down to a diameter limit of 7 cm were removed. Approximately 40% of the area of R_{CC} and V_{CC-2} was clear-cut and 72% of V_{CC-1}. The volume removed was 250 $m^3\,ha^{-1}$ at R_{CC}, 259 $m^3\,ha^{-1}$ at V_{CC-1} and 317 $m^3\,ha^{-1}$ at V_{CC-2}. The ground was frozen and covered by snow during cuttings, and the heavy harvesting machinery therefore caused no significant damage to the soil. In November 1997, the clear-cut areas at Vesijako were prepared for planting using a method known as ditch-mounding. It is done in such a way that the excavator digs shallow ditches (40–50 cm deep) at 12–15 m spacings and creates small mounds from the soil removed from the ditches. Norway spruce seedlings were planted on mounds in May 1999

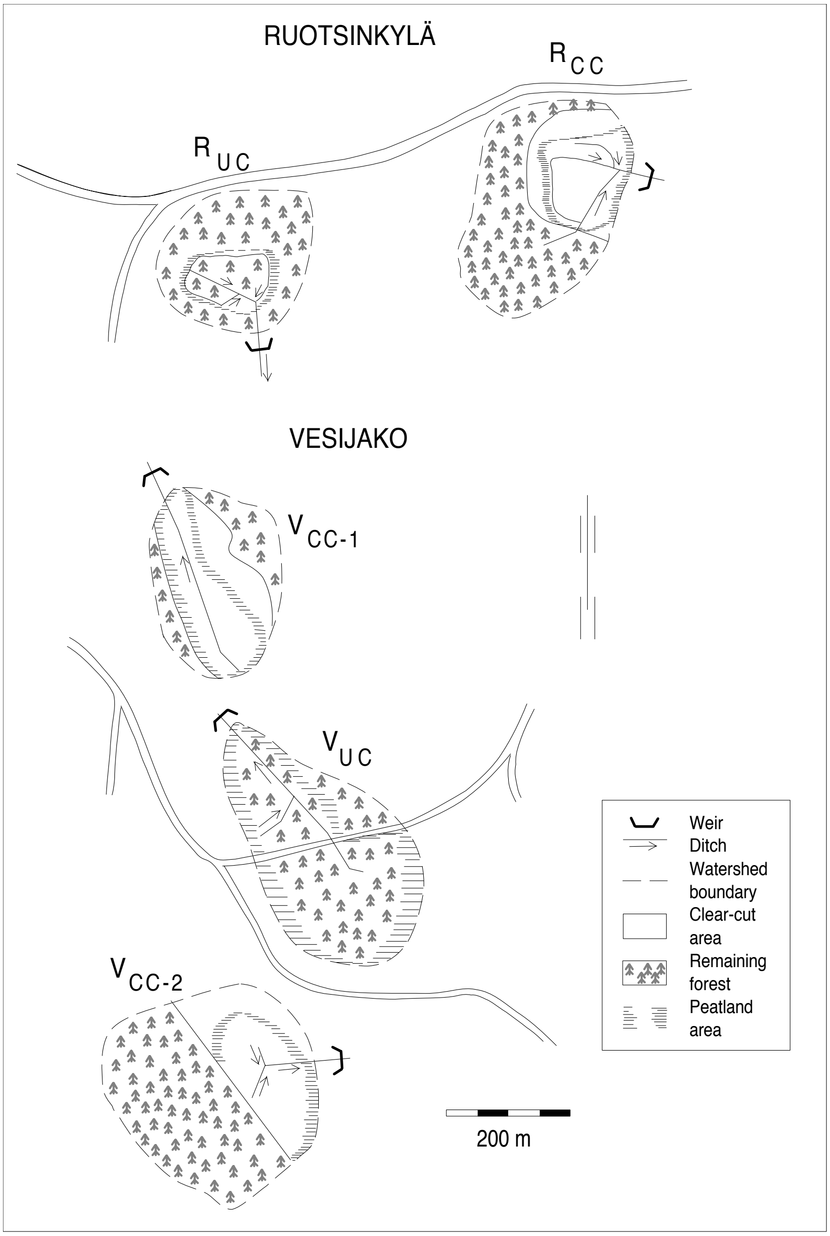

Fig. 1. The experimental layouts at Ruotsinkylä and Vesijako.

at V_{CC-1} and in September 1998 at V_{CC-2}. No artificial regeneration operations were performed at R_{CC}, where a dense cover of birch (*Betula pendula* Roth and *B. pubescens* Ehrh.) seedlings developed soon after clear-cutting.

2.2 Sampling and Analyses

Outflow water sampling was started in November 1992 at catchments R_{CC}, R_{UC}, V_{CC-1}, and V_{UC} and in June 1994 at V_{CC-2}. Outflow water was

Table 2. Regression equations and correlation coefficients for mean mothly runoff and outflow concentrations of DOC, DON, NH_4^+-N, NO_3^--N, and P between the areas to be clear-cut and control areas during the calibration period.

	Ruotsinkylä	Vesijako	
	R_{CC}/R_{UC}	$V_{CC\text{-}1}/V_{UC}$	$V_{CC\text{-}2}/V_{UC}$
Runoff, $l\ s^{-1}\ ha^{-1}$	$y = 0.532x + 0.022$ $r = 0.96^{**}$ (n = 6)	$y = 1.000x - 0.002$ $r = 0.86^{*}$ (n = 6)	-- --
DOC, $mg\,l^{-1}$	$y = 1.099x - 2.768$ $r = 0.89^{***}$ (n = 61)	$y = 0.677x + 9.993$ $r = 0.72^{***}$ (n = 49)	$y = 0.390x + 3.731$ $r = 0.67^{**}$ (n = 76)
DON, $mg\,l^{-1}$	$y = 1.074x - 0.030$ $r = 0.90^{***}$ (n =61)	$y = 0.716x + 0.192$ $r = 0.79^{***}$ (n = 48)	$y = 0.405x + 0.090$ $r = 0.43^{***}$ (n = 76)
NH_4^+-N, $mg\,l^{-1}$	$y = 0.490x + 0.020$ $r = 0.20^{n.s.}$ (n = 61)	$y = 0.185x - 0.006$ $r = 0.59^{***}$ (n = 49)	$y = -0.018x + 0.003$ $r = -0.16^{n.s.}$ (n = 76)
NO_3^--N, $mg\,l^{-1}$	$y = 1.520x + 0.007$ $r = 0.76^{***}$ (n = 58)	$y = 0.377x + 0.014$ $r = 0.37^{**}$ (n = 49)	$y = 1.076x + 0.018$ $r = 0.46^{***}$ (n = 76)
P, $mg\,l^{-1}$	$y = 0.859x + 0.005$ $r = 0.76^{***}$ (n = 61)	$y = 0.735x + 0.009$ $r = 0.71^{***}$ (n = 49)	$y = 0.709x + 0.007$ $r = 0.73^{***}$ (n = 76)

n.s. = non-significant, * = signifigant at 5 % level, ** = significant at 1 % level, *** = significant at 0.1 % level
-- runoff not measured at $V_{CC\text{-}2}$

sampled manually from the overflow of the V-notched weir in the outlet ditch of the catchment (Fig. 1). The sampling interval was 3–4 days during the snowmelt period in spring and weekly (1992–1997) or fortnightly (1998–1999) during other seasons.

Water sampling continued until the end of 1998 at R_{UC} and R_{CC}, and until the end of 1999 at the other catchments.

Runoff was monitored at all catchments except $V_{CC\text{-}2}$. Runoff was recorded for one year before clear-cutting and for the first three years after cutting using a continuous water-stage recorder. Due to freezing of the weirs and ditches, runoff was monitored only during the frost-free period (May–September or May–October).

The outflow water samples were analysed at the Finnish Forest Research Institute according to procedures described by Jarva and Tervahauta (1993). The samples were first filtered through 1.0 μm glass fibre filters (Schleicher & Schull Rundfilter 589^3). The filtrates were then analysed for dissolved organic carbon (DOC) with a Shimadsu carbon analyzer and for NO_3^- by ion chromatography. Total dissolved N (N_{tot}) and NH_4^+ were determined with a Tecaton FIA-analyzer and total dissolved P with plasma emission spectrophotometry (ICP-AES, ARL 3580). Dissolved organic N (DON) was calculated as the difference between N_{tot} and inorganic nitrogen. Results concerning nitrogen concentrations in water outflow from R_{CC} and $V_{CC\text{-}1}$ during the first growing season following clear-cutting have been presented previously (Nieminen 1998).

Changes in runoff and outflow concentrations of DOC, DON, NH_4^+-N, NO_3^--N, and P resulting from clear-cutting were studied using the paired-catchment method. On the basis of measurements made during the pre-treatment calibration period, a linear regression equation was calculated for the relationship between measured values in the area to be cut and respective values from control area. After clear-cutting, values were predicted for the area as if it had not been cut using this equation and measured values from the control area. The effect of clear-cutting on runoff and outflow concentrations is the difference between measured values after cutting in the clear-cut area and the predicted values. Regression equations used for prediction are given in Table 2. Except for NH_4^+, the correlations between clear-cut areas and control areas during calibration period were high and statistically significant ($p < 0.05$).

As can be seen from the regression equation for runoff between $V_{CC\text{-}1}$ and V_{UC} (Table 2), a negative value is predicted for $V_{CC\text{-}1}$ with V_{UC} mean monthly runoff values of $<0.002\ l\ s^{-1}\ ha^{-1}$. Negative values for NH_4^+ at $V_{CC\text{-}1}$ were also predicted. Such negative values were always substituted with zero in subsequent analysis of the data.

Monthly export loads ($kg\ ha^{-1}$ or $g\ ha^{-1}$) were simply calculated as the product of the monthly runoff and monthly mean concentration, and the changes in export loads due to clear-cutting as the difference between measured and predicted loads. The non-parametric Wilcoxon signed-rank t-test was used to test if the measured and predicted uncut outflow concentrations after cutting were significantly different. The BMDP (1990) software package was used.

3 Results

3.1 Changes in Concentrations

Outflow concentrations of DOC and DON following clear-cutting increased at all three clear-cut areas although measured and predicted concentrations from $V_{CC\text{-}2}$ differed significantly ($p<0.05$) only during the first two years after cutting (Tables 3–5). The average annual increase in DOC concentrations during the first four years after clear-cutting was 9.0 $mg\ l^{-1}$ at R_{CC}, 22.8 $mg\ l^{-1}$ at $V_{CC\text{-}1}$ and 8.4 $mg\ l^{-1}$ at $V_{CC\text{-}2}$. Corresponding increases for DON were 0.23, 0.51 and 0.16 $mg\ l^{-1}$.

Outflow concentrations of NH_4^+ and NO_3^- also increased at all three clear-cut areas, but there were large differences between areas. The average annual increase in NH_4^+-N concentrations during the first four years after clear-cutting was 0.06 $mg\ l^{-1}$ at R_{CC}, 0.31 $mg\ l^{-1}$ at $V_{CC\text{-}1}$ and 0.04 $mg\ l^{-1}$ at $V_{CC\text{-}2}$. Corresponding increases for NO_3^--N were 0.05, 0.12, and 0.22 $mg\ l^{-1}$. There were no significant ($p>0.05$) changes in P concentrations due to clear-cutting.

3.2 Changes in Runoff and Export Loads

The total increase in non-frost season runoff during the first year following clear-cutting was 52 mm at both R_{CC} and $V_{CC\text{-}1}$ and 49 mm and 85 mm during the second year. While the increase in runoff remained high at $V_{CC\text{-}1}$ during the third year, it had almost disappeared at R_{CC}. Over the entire three-year study period, the increase in runoff was 107 mm at R_{CC} and 207 mm at $V_{CC\text{-}1}$ (Table 6).

Clear-cutting increased the export loads of DOC and DON at both R_{CC} and $V_{CC\text{-}1}$. The increases were similar during the first year fol-

Table 3. Mean annual concentrations ($mg\ l^{-1}$) of DOC, DON, NH_4^+-N, NO_3^--N, and P in outflow water from R_{CC} 1–5 years after clear-cutting. An asterisk indicates significant ($p<0.05$) difference between measured (M) and predicted (P) values. ± = standard deviation.

		Time				
		+ 1	+ 2	+ 3	+ 4	+ 5
DOC	M	25.2 ± 11.3	23.0 ± 11.4	26.8 ± 15.7	19.3 ± 9.8	32.3 ± 16.2
	P	14.0 ± 5.1*	13.9 ± 4.5*	17.6 ± 9.8*	12.8 ± 3.8*	20.6 ± 7.9*
DON	M	0.57 ± 0.21	0.50 ± 0.21	0.64 ± 0.32	0.48 ± 0.25	0.63 ± 0.29
	P	0.34 ± 0.10*	0.30 ± 0.08*	0.37 ± 0.18*	0.26 ± 0.10*	0.36 ± 0.12*
NH_4^+-N	M	0.07 ± 0.12	0.15 ± 0.14	0.09 ± 0.16	0.03 ± 0.04	0.02 ± 0.03
	P	0.02 ± 0.00	0.02 ± 0.00*	0.02 ± 0.00	0.03 ± 0.04	0.02 ± 0.00
NO_3^--N	M	0.06 ± 0.11	0.10 ± 0.15	0.13 ± 0.15	0.04 ± 0.06	0.04 ± 0.06
	P	0.03 ± 0.12*	0.02 ± 0.03*	0.04 ± 0.05	0.04 ± 0.05	0.03 ± 0.05
P	M	0.01 ± 0.02	0.04 ± 0.04	0.04 ± 0.04	0.03 ± 0.03	0.00 ± 0.00
	P	0.01 ± 0.01	0.03 ± 0.03	0.02 ± 0.02	0.02 ± 0.02	0.01 ± 0.00

Table 4. Mean annual concentrations (mg l^{-1}) of DOC, DON, NH_4^+-N, NO_3^--N, and P in outflow water from V_{CC-1} 1–6 years after clear-cutting. An asterisk indicates significant ($p<0.05$) difference between measured (M) and predicted (P) values. ± = standard deviation.

		Time					
		+ 1	+ 2	+ 3	+ 4	+ 5	+ 6
DOC	M	54.0 ± 15.4	52.1 ± 11.3	56.3 ± 12.2	53.6 ± 18.0	47.9 ± 18.5	42.9 ± 8.8
	P	32.3 ± 9.8*	28.0 ± 8.0*	28.3 ± 11.2*	36.1 ± 8.7*	40.7 ± 8.1	32.6 ± 7.1*
DON	M	1.11 ± 0.31	1.09 ± 0.28	1.25 ± 0.30	1.13 ± 0.32	0.97 ± 0.36	0.68 ± 0.24
	P	0.67 ± 0.21*	0.56 ± 0.13*	0.60 ± 0.24*	0.70 ± 0.16*	0.78 ± 0.15	0.60 ± 0.12
NH_4^+-N	M	0.08 ± 0.13	0.46 ± 0.18	0.49 ± 0.37	0.29 ± 0.21	0.15 ± 0.11	0.45 ± 0.34
	P	0.02 ± 0.02	0.01 ± 0.01*	0.01 ± 0.02*	0.03 ± 0.01*	0.03 ± 0.02*	0.03 ± 0.02*
NO_3^--N	M	0.03 ± 0.06	0.07 ± 0.09	0.32 ± 0.34	0.17 ± 0.18	0.23 ± 0.25	0.46 ± 0.49
	P	0.02 ± 0.01*	0.02 ± 0.01*	0.04 ± 0.05*	0.02 ± 0.02	0.02 ± 0.02	0.03 ± 0.02*
P	M	0.03 ± 0.04	0.04 ± 0.04	0.05 ± 0.04	0.05 ± 0.04	0.03 ± 0.03	0.04 ± 0.04
	P	0.02 ± 0.02	0.03 ± 0.03	0.03 ± 0.02	0.03 ± 0.02	0.01 ± 0.00	0.01 ± 0.00

Table 5. Mean annual concentrations (mg l^{-1}) of DOC, DON, NH_4^+-N, NO_3^--N, and P in outflow water from V_{CC-2} 1–4 years after clear-cutting. An asterisk indicates significant ($p<0.05$) difference between measured (M) and predicted (P) values. ± = standard deviation.

		Time			
		+ 1	+ 2	+ 3	+ 4
DOC	M	26.4 ± 12.6	28.4 ± 14.3	28.3 ± 16.3	21.5 ± 11.3
	P	14.3 ± 6.5*	18.8 ± 5.0*	21.4 ± 4.7	16.7 ± 4.1
DON	M	0.53 ± 0.24	0.55 ± 0.28	0.58 ± 0.35	0.41 ± 0.23
	P	0.32 ± 0.14*	0.38 ± 0.09*	0.42 ± 0.08	0.32 ± 0.07
NH_4^+-N	M	0.02 ± 0.04	0.05 ± 0.09	0.04 ± 0.10	0.04 ± 0.14
	P	0.00 ± 0.00*	0.00 ± 0.00	0.00 ± 0.00*	0.00 ± 0.00*
NO_3^--N	M	0.13 ± 0.19	0.24 ± 0.24	0.36 ± 0.45	0.37 ± 0.54
	P	0.08 ± 0.14	0.04 ± 0.07*	0.05 ± 0.05*	0.05 ± 0.06*
P	M	0.02 ± 0.02	0.02 ± 0.03	0.03 ± 0.03	0.02 ± 0.04
	P	0.02 ± 0.02	0.03 ± 0.02	0.01 ± 0.00	0.01 ± 0.00

lowing clear-cutting, but the increases from V_{CC-1} were substantially higher during the second and third years. The total increase in the export of DOC over the first three years after clear-cutting was 80 kg ha^{-1} at R_{CC} and 184 kg ha^{-1} at V_{CC-1} (Table 6). The corresponding increase in the export load of DON was 1.78 kg ha^{-1} at R_{CC} and 3.98 kg ha^{-1} at V_{CC-1}.

The export loads of NH_4^+ and NO_3^- also significantly increased as a result of clear-cutting. The increases in export loads were particularly high in autumn 1994 and 1995, and spring 1995 and 1996, when runoff was high and the concentrations from the clear-cut areas significantly increased. The total increase in export of NH_4^+-N over the first three years after cutting was 0.39 kg ha^{-1} at R_{CC} and 1.49 kg ha^{-1} at V_{CC-1}. The corresponding increase for NO_3^--N was 0.45 and 0.48 kg ha^{-1}. The changes in loads of P due to clear-cutting were small; the total increase at R_{CC} was 0.09 kg ha^{-1} and 0.06 kg ha^{-1} at V_{CC-1}.

Table 6. Measured (M) and predicted (P) non-frost season [a)] runoff and export load of DOC, DON, NH_4^+-N, NO_3^--N, and P from R_{CC} and V_{CC-1} during the first three years after clear-cutting.

		R_{CC}			V_{CC-1}		
		1994	1995	1996	1994	1995	1996
Runoff, mm	M	196	139	126	165	202	192
	P	144	90	120	113	117	122
DOC, kg ha^{-1}	M	62	38	36	89	110	107
	P	22	12	22	42	38	42
DON, g ha^{-1}	M	1305	850	841	1825	2304	2327
	P	491	285	438	868	739	870
NH_4^+-N, g ha^{-1}	M	166	142	159	89	771	685
	P	29	19	26	30	8	17
NO_3^--N, g ha^{-1}	M	155	196	130	41	152	346
	P	10	6	20	16	17	26
P, g ha^{-1}	M	44	42	66	41	54	60
	P	14	23	26	25	34	31

[a)] = May–October (1994, 1995) or May–September (1996)

4 Discussion

The effect of clear-cutting on runoff and outflow concentrations and export loads of DOC, DON, NH_4^+, NO_3^- and P from drained and productive, Norway spruce dominated peatlands were studied using a paired-catchment approach. The correlations between clear-cut areas and control areas during the calibration period were usually high and statistically significant (Table 2). However, the correlations for NH_4^+ concentrations between R_{CC} and R_{UC} and between V_{CC-2} and V_{UC} were low. The predicted uncut concentrations for NH_4^+-N may therefore be less reliable than those for the other solutes. The predicted monthly runoff values for the Vesijako clear-cut area V_{CC-1} may also be somewhat less accurate than those for the Ruotsinkylä clear-cut area (R_{CC}). This is because the non-frost season monthly runoff at the Vesijako control area (V_{UC}) varied more during the post-treatment period in 1994–1996 (0–90 mm) than during the calibration period in 1993 (4–46 mm). Ideally, when using the paired-catchment approach, the calibration period and the post-treatment period should be hydrologically similar (Seuna 1988). Nevertheless, the results for both Vesijako and Ruotsinkylä concerning changes in runoff due to clear-cutting are in good agreement with previous studies from wetland forests (Seuna 1988, Lundin 1999, 2000).

The export loads and outflow concentrations of DOC and DON from this study significantly increased as a result of clear-cutting. Lundin (1999, 2000) also found high increases in their concentrations in water outflow after clear-cutting of drained and productive, Norway spruce dominated peatlands, and increased leaching also occurred after shelterwood-cutting. Thus, forest regeneration on drained productive peatlands appears to be an important source of DOC and DON to watercourses. However, ditching of peat soils has been shown to significantly decrease the leaching of soluble organic substances (Joensuu et al. 2001), and the overall effect of peatland forestry on DOC and DON may therefore be small.

In the study by Lundin (1999) on Norway spruce dominated peatlands such as in this study, the outflow concentrations of nitrate decreased from the area that was ditched after clear-cutting. This contrasts with the results of this study, where the highest nitrate concentrations at the two ditched (ditch-mounded) clear-cut areas (V_{CC-1} and V_{CC-2}) occurred after ditching. In

Scots pine dominated peatlands of low fertility, nitrate leaching only increased from areas that were ditched after clear-cutting (Nieminen 2003). Decreased leaching of nitrate due to clear-cutting and ditching is thus unlikely to be a general pattern. Indeed, although nitrate leaching decreased from one ditched clear-cut area in the previously mentioned study by Lundin (1999), there was also an area where nitrate leaching increased after clear-cutting and ditching.

Ditching of pristine mires for forestry and maintenance of ditch networks in old drainage areas (ditch cleaning and/or complementary ditching) are generally significant sources of NH_4^+ to water courses (Hynninen and Sepponen 1983, Joensuu et al. 2002). The present study and the results reported by Lundin (1999) indicate that clear-cutting of drained productive peatlands stands may also enhance NH_4^+ leaching. In drained unproductive, Scots pine dominated peatlands, minor NH_4^+ leaching may occur unless ditching operations are performed in connection with forest regeneration (Nieminen 2003). Significantly higher NH_4^+ and NO_3^- concentrations in percolating soil water following clear-cutting were observed under piles of cutting residues than respective residue-free areas (Rosén and Lundmark-Thelin 1987). Whole-tree harvesting might thus be an effective means of decreasing NH_4^+ and NO_3^- leaching.

In the study by Lundin (2000), phosphorus concentrations in streamwater increased by 3–12 $\mu g\,l^{-1}$ after clear-cutting. In this study, the outflow concentrations of phosphorus from the clear-cut areas also increased slightly. The changes in concentrations were not significant ($p > 0.05$) however. The risk for enhanced leaching of phosphorus following clear-cutting is likely to be significantly higher from nutrient poor mires than from productive Norway spruce mires because of low phosphate adsorption capacities (Cuttle 1983, Nieminen and Jarva 1996). Thus, Knighton and Stiegler (1980) reported higher phosphorus concentrations in outflow water following clear-cutting of a nutrient poor, ombrotrophic peatland than a minerotrophic peatland area. Very high phosphorus concentrations (>400 $\mu g\,l^{-1}$) in outflow water following clear-cutting of drained, low productive Scots pine dominated peatlands were also shown by Nieminen (2003).

The study demonstrated that clear-cutting may significantly increase the export of DOC and different forms of nitrogen from Norway spruce forests growing on drained productive peatlands, but only small increases in phosphorus export may occur. The results from this investigation are generally similar to those reported from Sweden (Lundin 1999, 2000). Future research should be directed towards the development of methods to reduce leaching from drained peatlands. Uncut riparian buffer zones between clear-cut areas and water courses might be an effective means of decreasing leaching. The effect of alternative cutting methods, such as whole-tree harvesting, on nutrient leaching should also be investigated.

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