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Changes in nitrogen cycling following the clearcutting of drained peatland forests in southern Finland

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The effects of forest clearcutting on the leaching of organic N, NH_4^+-N and NO_3^--N and the processes likely to influence them were studied in two Norway spruce (*Picea abies*) dominated catchments located on nutrient-rich old peatland drainage areas in southern Finland. The concentrations of NH_4^+-N in precipitation reaching the ground increased after clearcutting. Those of NO_3^--N increased in the area where the atmospheric N deposition was average, but decreased in the area subjected to higher than average N deposition. Ammonium-N concentrations in percolation water passing through the surface peat increased, both under slash-piles and in slash-free areas. Gaseous N_2O and N_2 emissions or leached amounts of N_2O were not influenced by clearcutting. Organic N concentrations in runoff increased immediately after clearcutting, whereas the concentrations of NH_4^+-N and NO_3^--N only increased after the first growing season after cutting. The causes for increased runoff nitrogen concentrations are discussed.

Introduction

The effects of forest clearcutting on leaching of elements from mineral soils have long been of great concern, e.g. in North America (Bormann *et al.* 1968, Verry 1972, Martin *et al.* 1985, Martin and Harr 1988, Tiedemann *et al.* 1988) and Sweden (Wiklander 1981, Grip 1982, Rosén and Lundmark-Thelin 1987). Recognition of the effects of clearcutting on nutrient losses from mineral soils in Finland has also increased in recent years (Kubin 1995, Lepistö *et al.* 1995). However, the effects of clearcutting on leaching of nutrients from peatlands has received little attention (cf. Knighton and Stiegler 1980, M. Ahtiainen and P. Huttunen unpubl.). Results concerning leaching from clearcutting old drainage areas have not been published.

The area of peatlands in Finland is about 10 million hectares, covering one third of the total land area. About half of this area has been drained for forestry purposes. The ability to predict the response of nitrogen leaching to clearcuttings on drained peatlands would thus be important for

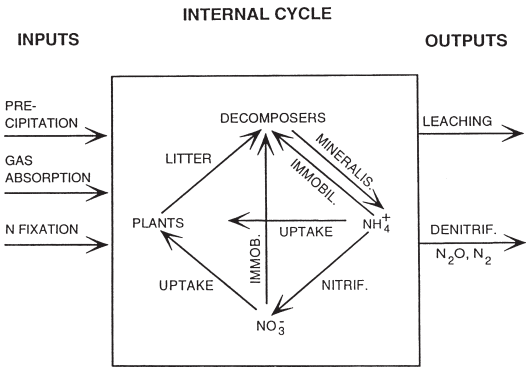

Fig. 1. A simplified model of nitrogen cycle in forest ecosystems. Redrawn according to Vitousek (1981).

water quality planning and protection. Achieving such a predictive capability requires an understanding of the effects of clearcutting on all the processes controlling the nitrogen cycle (Fig. 1), including nitrogen inputs (precipitation, gas absorption, N fixation), internal transformations (mineralization, nitrification, denitrification, immobilization, plant uptake and litter production), and nitrogen outputs (leaching of organic and inorganic nitrogen, gaseous nitrogen emissions and leaching of dissolved N_2O).

Clearcutting has the immediate effect of removing the large absorptive surface of the forest stem, branches and canopy. This would have the effect of decreasing nitrogen inputs by gas absorption but increasing the amount of wet deposition nitrogen at the soil surface. The adsorption of N from wet depositon by tree canopies in the boreal zone has been shown in a number of studies (e.g. Hyvärinen 1990). Regardless of the extent of change in wet and gaseous nitrogen deposition, the effect of clearcutting on the leaching of nitrogen from clear-cut basins may be most pronounced in areas subjected to higher than average N deposition, particularly if N deposition exceeds the demand by ground vegetation and micro-organisms and the adsorption capacity of the soil (i.e. "nitrogen saturated" systems). The importance of atmospheric nitrogen fixation to the nitrogen budget of peatlands is poorly known.

The most immediate effect of clearcutting on the internal cycle of nitrogen is the tremendous reduction in plant uptake. According to Finér (1989), the annual uptake of nitrogen in well-developed peatland forests varies from 26 to 49 kg ha^{-1}. Because of the climatic conditions prevailing in Finland, the re-establishment of nitrogen

Table 1. Basic information on study areas.

	Ruotsinkylä		Vesijako	
	Clear-cut	Control	Clear-cut	Control
Catchment area, ha	7.8	3.7	4.3	5.5
Clear-cut area, ha	2.6	–	3.1	–
Peatlands, ha	1.9	1.4	2.5	4.9
Peatland site type[1)]	Rhtkg	Mtkg	Mtkg	Mtkg
Peat depth, m	1.0	0.5	0.5	1.0
Basic drainage year	1927	1932	1914	1914
Stand volume, $m^3\,ha^{-1}$	234	250	259	249
Tree species, % of volume				
Pinus sylvestris	0	0	4	10
Picea abies	100	100	90	85
Betula spp.	0	0	6	5

[1)] According to Heikurainen and Pakarinen (1982): "Herb-rich type (Rhtkg) is usually spruce-dominated with an admixture of hardwoods. It has developed after the drainage of peatlands of the highest fertility. The ground vegetation is characterized by an abundance of ferns, shrubs and herbs, both in number and in coverage (e.g. *Rubus idaeus, Oxalis ecetosella, Athyrium filix-femina*)."
"*Vaccinium myrtillus* type (Mtkg) has developed from moderately fertile peatlands. Spruce is usually the dominant tree species; however, sites which have developed from the most fertile pine swamps may be dominated by pine, but in this case birch is also usually frequent. The ground vegetation is characterized by the occurrence of *Vaccinium myrtillus* and *V. vitis idaea*, whilst in the bottom layer, *Hylocomium splendens* is conspicuous. The frequent occurrence of certain herbs (*Melampyrum* spp., *Trientalis europaea, Orthilia secunda*) is also typical of this site."

uptake after clearcutting may take a long time. At the same time that plant uptake is reduced, conventional cutting adds live needles, leaves and branches to the soil surface. If this material is rapidly mineralised, the loss of nitrogen from clearcut areas may sharply increase. Because of the high C/N ratio of slash, nitrogen immobilization will be greater than mineralization at first. Decomposition and immobilization gradually reduce the C/N ratio of the substrate until net nitrogen mineralization occurs. Thus, there may be a substantial delay before any net nitrogen mineralization and leaching of nitrogen from slash occurs.

Compared to mineral soils, nitrogen reserves in organic soils are much greater. If mineralization of soil nitrogen increases considerably after clearcutting, the loss of nitrogen to water cources may thus be expected to be much higher on drained peatlands than for mineral soils. Due to its high adsorption to exchange sites, mineralized ammonium is effectively retained by the soil. Therefore, if there is any enhanced leaching of inorganic nitrogen from drained peatlands after clearcutting, it is most probably due to nitrification and the production of nitrate (Vitousek *et al.* 1982). Nitrification rates of drained peatlands are poorly known. However, it is a well established fact that nitrification and nitrate production is reduced or prevented in anaerobic, acid, nutrient-poor and cold soil conditions such as typify peats. Consequently, the potential for increased leaching of inorganic N from forested peatlands after clearcutting is greatest in the most nutrient-rich, well-drained minerotrophic peatlands in the southernmost Finland.

Increased nitrification after clearcutting does not necesserily lead to leaching of nitrate from clearcut areas, however, because the production of nitrate may stimulate the production of N_2O and N_2, which are emitted to the atmosphere. However, N_2O is highly soluble in water, and it has been suggested that N_2O could be transported by soil water to streams and seeps where it degasses to the atmosphere (Bowden and Bormann 1986).

Clearcutting can also increase production and leaching of soluble organic N compounds from drained peatlands. The processes controlling the leaching of organic N from drained peatlands are also poorly known. However, the risk for high leaching losses of organic N after clearcutting is probably greatest from the same areas as the risk for enhanced leaching of inorganic N, i.e. from the most nitrogen-rich minerotrophic peat soils.

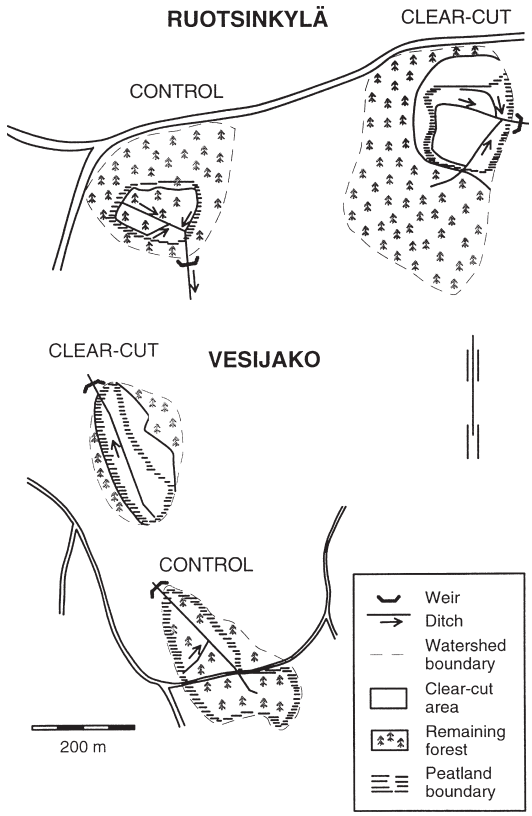

Fig. 2. The experimental layouts at Ruotsinkylä and Vesijako.

The aim of this study was to investigate the effects of clearcutting on leaching of nitrogen from nutrient-rich drained peatland forests. In particular, the effect of clearcutting on the different processes involved in the cycling of nitrogen are examined and their relative importance in controlling the loss of nitrogen to water courses are evaluated.

Study sites

The calibration period and control basin method was used 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.). A control and treatment basin were selected at each location (Fig. 2). The study areas are described in Table 1. The average temperature in January 1993

at Ruotsinkylä was –1.9 °C and – 4.2 °C in 1994. Average temperatures for July in 1993 and 1994 were +15.7 °C and +19.9 °C, respectively. At Vesijako, the average temperatures for January 1993 and 1994 were – 2.8 °C and –5.8 °C, and for July they were +15.7 °C and +19.3 °C. The rainfall at Ruotsinkylä for 1993 totalled 602 mm and for 1994, 743 mm. At Vesijako, the corresponding amount of rainfall were 501 and 583 mm. The measurements of the Finnish Environment Institute at the nearby permanent sample plots showed that nitrogen deposition at Ruotsinkylä (about 8.0 kg ha^{-1}) is much higher than at Vesijako (4.5 kg ha^{-1}) (Järvinen and Vänni 1996).

According to the classification of drained peatlands used in Finland (Heikurainen and Pakarinen 1982), the study areas had reached the final stage of drainage succession. At this stage the ground vegetation and the tree stand resemble the corresponding fertility levels on mineral soils. On the basis of a visual inventory, all the ditches in the different study areas had maintained their drainage effect. On the basis of peat analysis, the Ruotsinkylä control basin was less fertile than the other basins, particularly concerning nitrogen (Table 2). Except for the low nitrogen content at the Ruotsinkylä control basin, nutrient contents were as high or higher than those described by Kaunisto and Paavilainen (1988) for nutrient-rich peatland sites on old drainage areas. The peat layer at Ruotsinkylä was underlain mainly by sandy till, and clay at Vesijako.

Conventional clearcutting was carried out during two days in the winter of 1994. Because of the flat topography and frozen surface peat during the cuttings, erosion of the peat was negligible and only a little logging slash was found in the ditches after the cuttings.

Material and methods

Nitrogen deposition and the runoff of nitrogen, as well as gaseous nitrogen emissions from the peat were measured in all the catchment areas. Nitrogen mineralisation from peat and slash was inferred on the basis of percolate chemistry collected using zero tension lysimeters.

Nitrogen deposition to the forest floor was monitored prior to clearcutting in 1993 and after the cuttings in 1994. Ten precipitation collectors were located systematically under the tree canopy in a square (4×16 m) at intervals of four meters in each catchment area prior to clearcutting in 1993. After clearcutting in 1994, the collectors in the clear-cut areas were left in the open, whereas the collectors in the control areas were still under trees. It is to be noted here that the samples collected after clearcutting in the open should be named as bulk precipitation, while those sampled under the tree canopy are usually referred to as throughfall samples (Päivänen 1974). In this study, however, both the samples collected under the tree canopy and in the open are referred to as "precipitation reaching the ground".

The collectors consisted of a PVC funnel connected to a 1-litre polyethene collection bottle. The collection surface of the funnel (surface area

Table 2. Nutrient concentrations in the 0–20 cm peat layer in different study areas.

		Ruotsinkylä		Vesijako	
		Clear-cut	Control	Clear-cut	Control
N %	0–10 cm	1.70	1.37	1.85	1.92
	10–20 cm	2.04	1.43	2.12	2.50
P mg kg^{-1}	0–10 cm	939	742	804	894
	10–20 cm	957	505	803	1200
K mg kg^{-1}	0–10 cm	500	566	512	625
	10–20 cm	200	232	271	173
Ca mg kg^{-1}	0–10 cm	4 334	4 241	7 912	5 297
	10–20 cm	5 361	4 260	9 795	7 246
Mg mg kg^{-1}	0–10 cm	547	485	756	553
	10–20 cm	480	389	981	504

201 cm^2) was at a height of 1 m. Precipitation samples were collected weekly during the frost-free period. The weekly collected samples from each catchment area were combined for analysis.

From the autumn of 1992, runoff water samples were taken in each catchment area twice a week during the snow-melt period in spring and once a week during other seasons. The samples were taken from the overflow of the V-notched weir.

Eight percolation water samplers (Fig. 3) were installed in the clearcut areas and four samplers in the control areas. After clearcutting, four of the eight lysimeters in the clear-cut areas were left under slash-free areas and four lysimeters under representative piles of slash. The lysimeters were installed by first removing an intact soil core down to the required depth, inserting the lysimeter, and then carefully replacing the upper part of the soil core. At Ruotsinkylä, a vacuum pump was used to empty the collectors weekly during the frost-free periods in 1993 and in 1994. Samples were composited on the basis of treatment (control, below slash, without slash). At Vesijako, lysimeters were not installed until the summer of 1994. Sampling was then as described for Ruotsinkylä.

All the water samples were transported in styrox boxes to the Central Laboratory of the Finnish Forest Research Institute, where analysis could be started within 48 hours of sampling. Prior to analysis, the samples were kept at + 4 °C. The pretreatment of the samples and all the nutrient analysis were done according to Jarva and Tervahauta (1994). The water samples were at first filtered (Schleicher & Schull Rundfilter 589 (3)). The run-off and precipitation samples were analysed for N_{tot} and NH_4^+-N by flow injection analysis and for NO_3^--N by ion chromatography. The lysimeter samples were analysed for all the nitrogen compounds (N_{tot}, NH_4^+-N and NO_3^--N) by flow injection analysis. Organic N was calculated as the difference between N_{tot} and NH_4^+-N plus NO_3^--N.

N_2O-N and N_2 fluxes were measured four times in 1994 using two static chambers per catchment area according to the method of Crill *et al.* (1988) and Martikainen *et al.* (1993). Cylinder-shaped chambers (volume 20 l, height 35 cm) with an open bottom were pushed against the soil surface so that the lower edge of the chamber sank about 5 cm below the peat surface. N_2O was always sampled first. Nitrous oxide emissions from the soil to the chamber were measured by sucking gas samples from the chambers with the polypropylene syringes (60 ml) at four time intervals (5, 15, 25, 35 min) after placing the chambers. The height from peat surface to the upper edge of the chamber and the temperature inside the chamber were measured. The gas samples were transported to the National Public Health Institute (NPHI), where analysis was started within 24 hours of sampling. In order to determine the amount of nitrous oxide that was transported from catchment areas with the run-off water, two run-off water samples per each catchment area were also taken at the same time as the autumn gas collection and also sent to NPHI for analysis. One sample was taken from the overflow of the weir and the other about 100 m upstream from the weir.

N_2O produced by either nitrification or denitrification can be reduced to N_2 and emitted. The acetylene-inhibition method was used to evaluate the

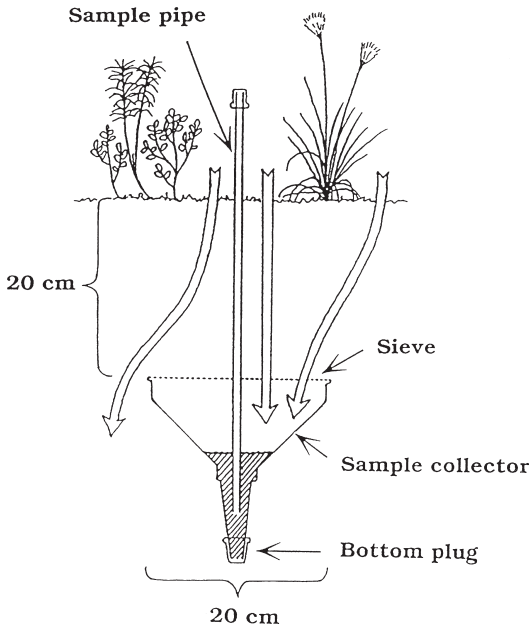

Fig. 3. Diagram showing the construction of lysimeter. The arrows depict the potential ways of percolation water movement. During the wettest periods of year the collectors may also be filled due to the rise of the ground water level.

amount of N_2 in gaseous nitrogen emissions. Acetylene is used to prevent N_2O from reducing to N_2 and, consequently, the total nitrogen emissions can be measured by just analysing for N_2O (Balderston *et al*. 1976, Yoshinari and Knowles 1976, Yoshinari *et al*. 1977, Tiedje *et al*. 1989). The chamber was thus filled to 10% volume with acetylene prior to taking the gas samples. The samples were taken 5, 60, 120 and 180 minutes after placing chambers and loading them with acetylene.

The gas samples were analysed for N_2O-N by a HP 5890 Series II gas chromatograph (Nykänen *et al*. 1995). Nitrous oxide concentrations in runoff water were determined according to McAullife (1971).

Using the equation for ideal gases and the linear regression describing the relationship between the concentration of N_2O inside the chamber and sampling time, N_2O-N emissions were calculated using the following formula:

$$E = \frac{\frac{P}{R} \times 10^{-6} M \times t \times A}{\mathrm{T}} \times h \times k \qquad (1)$$

where E = N_2O-N (μg m^{-2} d^{-1}), P = standard pressure (atm), R = gas standard (l atm K^{-1} mol^{-1}), M = molecular weight (g mol^{-1}), t = time dimension for which E is calculated, A = area dimension for which E is calculated, T = temperature inside the chamber (K), h = mean height from the peat surface to the upper edge of the chamber (cm), k = regression coefficient from the linear regression equation for the relationship between the concentration of N_2O inside the chamber and sampling time.

The correlation between the concentration of N_2O inside the chamber and sampling time was usually high and statistically significant (r > 0.85***). If not statistically significant, the N_2O-N emission was not calculated for that sampling occasion.

Changes in the nitrogen concentrations of precipitation and runoff resulting from clearcutting were studied using the calibration period and control area method. On the basis of the measurements during the calibration period (1992–1993), a linear regression equation was calculated for the relationship between measured values in the area to be clear-cut and respective values from control area. After clearcutting 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 clearcutting on water quality is the difference between measured values following clearcutting in the clear-cut area and the predicted values. If the relationship between values in the clear-cut area and respective values in the control area during the calibration period was not statistically significant, the average ratio of values in the clear-cut area to respective values in the control area was used to calculate the predicted values.

Non-parametric Wilcoxon signed-rank t-test (either two-group or matched pairs t-test) was used to calculate statistical differences between years or between treatments (also between observed and predicted values) using BMDP (1990) software package. In a few cases, 95% confidence intervals were calculated for differences between the means of the different treatments.

Results

Precipitation reaching the ground

Prior to clearcutting the mean organic nitrogen concentration in precipitation reaching the ground from the area to be clear-cut was 1.5 mg l^{-1} at Ruotsinkylä and 1.6 mg 1^{-1} at Vesijako. Corresponding ammonium concentrations were 0.99 mg 1^{-1} and 0.38 mg l^{-1}, and nitrate concentrations, 0.62 mg 1^{-1} and 0.09 mg l^{-1}.

Clearcutting did not increase the organic nitrogen concentrations of precipitation reaching the ground (Figs. 4 and 5). Ammonium-N concentrations of precipitation increased significantly in both clear-cut areas. The response of precipitation NO_3^--N differed between the two areas. At Vesijako, nitrate concentrations significantly increased after clearcutting, while at Ruotsinkylä, nitrate concentrations decreased.

Percolation

Prior to clearcutting the mean organic nitrogen concentration of percolation water was 2.0 mg l^{-1} in the area to be clear-cut and 1.7 mg 1^{-1} in the control area (Fig. 6). Ammonium concentrations were 0.6 mg 1^{-1} and 1.0 mg l^{-1} and nitrate concentrations, 2.9 mg l^{-1} and 0.1 mg l^{-1}.

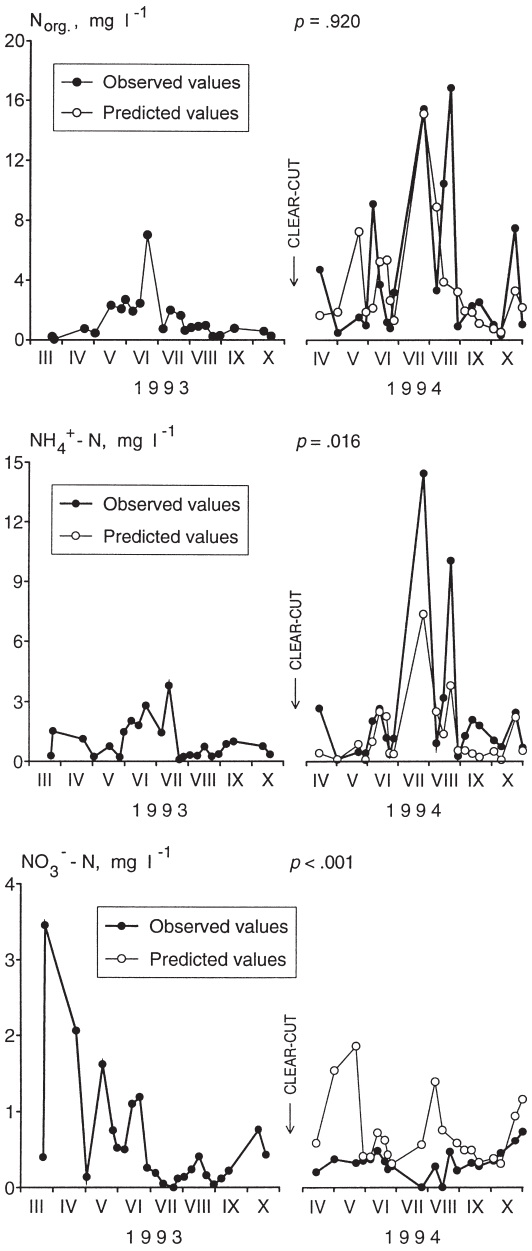

Fig. 4. The effect of clearcutting on the organic N, NH_4^+-N and NO_3^--N concentrations of precipitation reaching the ground at Ruotsinkylä. The *p*-values for statistical difference between observed and predicted values are also given.

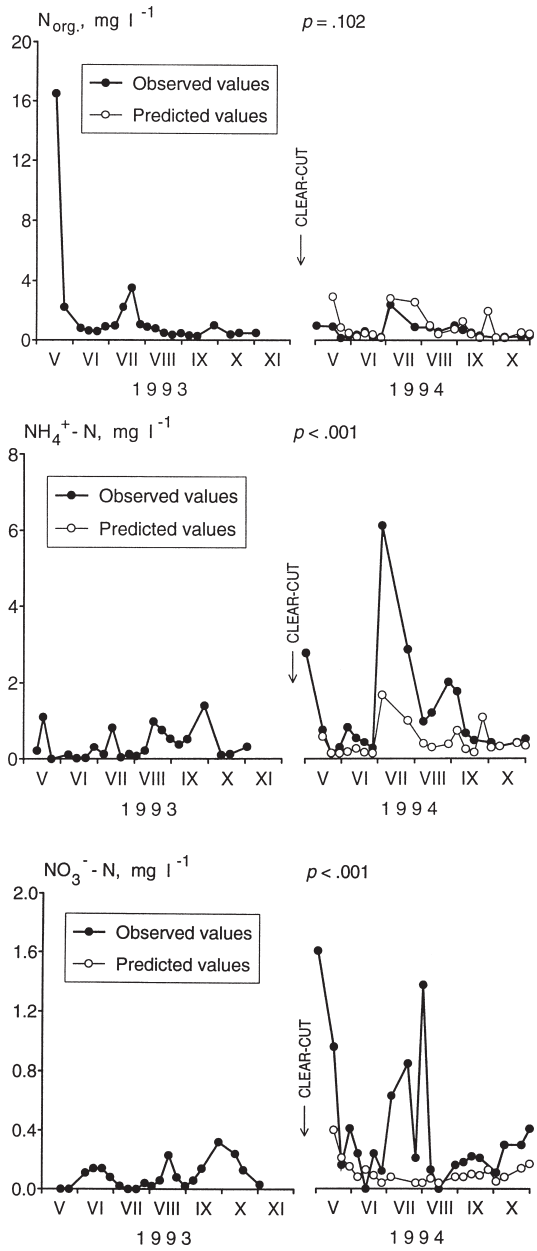

Fig. 5. Same as Fig. 4 but for Vesijako.

The concentrations of organic nitrogen and nitrate did not change statistically significantly between 1993 and 1994 either in slash free sites or under the piles of slash at Ruotsinkylä. Ammonium concentrations of percolation water increased significantly after clearcutting both in slash free areas ($p = 0.009$) and under the piles of slash ($p = 0.043$), and decreased in the control plots ($p = 0.003$). Ammonium concentrations at Vesijako were also higher from the clear-cut area than from the control area (Table 3). However,

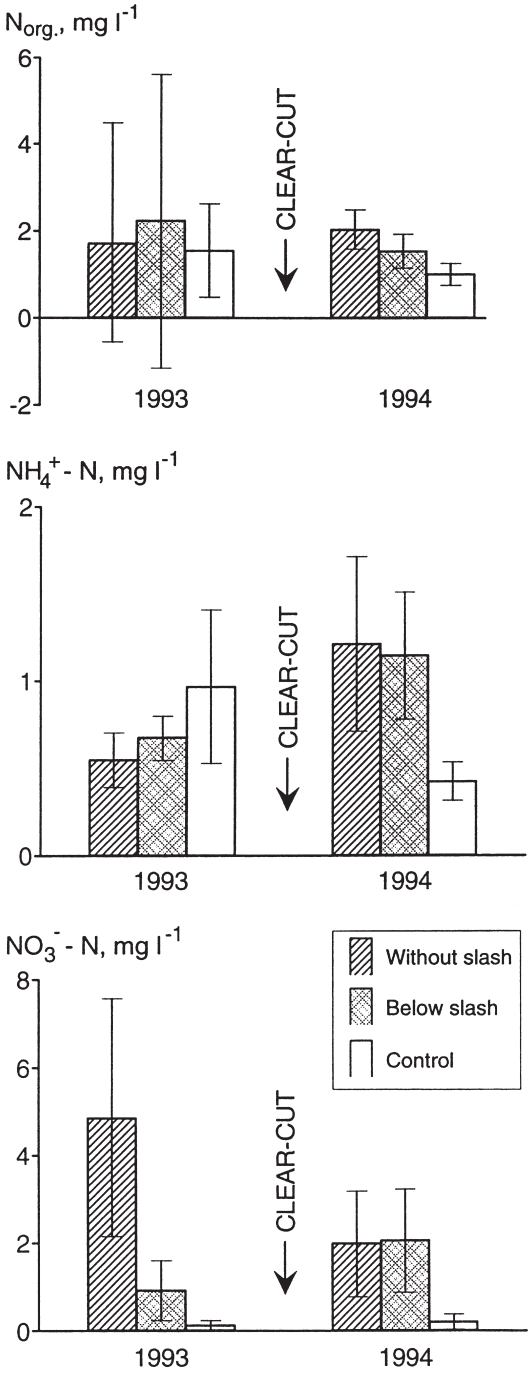

Fig. 6. Mean yearly concentrations of organic N, NH_4^+-N and NO_3^--N in percolating soil water at Ruotsinkylä. 95% confidence intervals are also given.

little ammonium was found in the percolate from the slash-free sites, while nitrate concentrations were low under the slash piles.

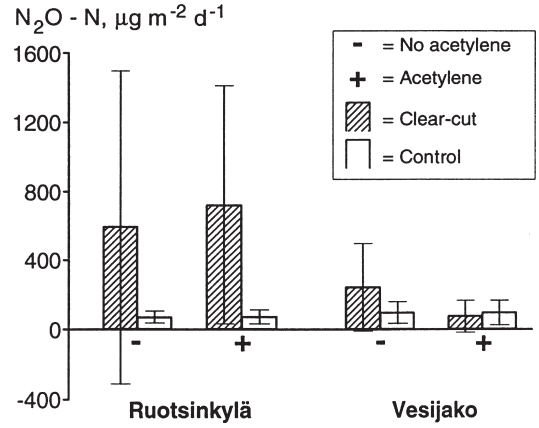

Fig. 7. Mean emissions of nitrous oxide after clear-cutting in 1994. 95% confidence intervals are also given.

Gaseous nitrogen fluxes

There were no significant between-method (acetylene-inhibition versus no acetylene) or between-treatment (control versus clear-cut) differences in the emission rates of N_2O-N (Fig. 7). The mean N_2O-N emission in the presence of acetylene was 259 µg m^{-2} d^{-1} and in the absence of acetylene 239 µg m^{-2} d^{-1}. Assuming that N_2O is emitted only during the frost-free period (about 200 days per year), the mean emissions presented here correspond to a total N_2O-N flux of well less than 1.0 kg ha^{-1} a^{-1}.

At Ruotsinkylä, the average concentration of dissolved N_2O-N (n = 2) in the runoff water from the clear-cut area was 2.0 µg l^{-1} and from the control area, 0.5 µg l^{-1}. At Vesijako, the concentrations were 1.1 and 4.5 µg l^{-1}, respectively. Assuming an average runoff of 300 mm y^{-1} in Finland, concentrations of N_2O-N in runoff water correspond to a total N_2O-N load of only 1.5–13.5 g ha^{-1} a^{-1}.

Runoff

The mean organic nitrogen concentration in runoff water from the clear-cut area during the calibration period was 0.24 mg l^{-1} at Ruotsinkylä and 0.62 mg l^{-1} at Vesijako. Nitrate concentrations were 0.01 and 0.02 mg l^{-1}, respectively. Ammonium concentrations were 0.02 mg l^{-1} from both clear-cut areas.

Organic nitrogen concentrations in runoff increased significantly after clearcutting at both Ruotsinkylä and Vesijako (Figs. 8 and 9). The concentrations for the clear-cut areas were two-threefold compared to those of the control areas in the autumn of 1994. The observed values of ammonium differed significantly from those predicted only at Ruotsinkylä, and those of nitrate at Vesijako. However, when the differences were calculated only for autumn (September and October) of 1994, statistically significant differences were observed also for nitrate at Ruotsinkylä (p = 0.031) and ammonium at Vesijako (p = 0.021).

Discussion

Precipitation reaching the ground

Both ammonium and nitrate are absorbed from bulk precipitation by tree canopies (Hyvärinen 1990). Higher ammonium and, in the case of Vesijako, also nitrate concentrations in precipitation reaching the ground were to be expected after clearcutting (Figs. 4 and 5). However, the distinct decrease in the nitrate concentrations at Ruotsinkylä was surprising. Ruotsinkylä is situated close to the Helsinki-Vantaa airport and near to a major arterial road and the dry deposition of oxidized N to forest canopies in the area is probably significant. During rainfall events the different forms of oxidized N attached to tree canopies might be converted into nitrate and added to forest canopy throughfall. Clearcutting resulted in the loss of this additional canopy-filtered dry deposition of oxidized N.

The results presented here are in accordance with Hyvärinen's (1990) study, where higher precipitation nitrate concentrations were found in the open than under the tree canopy in other parts of Finland, besides at Ruotsinkylä.

Precipation collectors of the type used in this study have been widely used in deposition studies. However, as stated by Hyvärinen (1990): "The sampling technique is an obvious source of error. In addition to wet precipitation, the open funnels collect an unknown amount of dry deposition and leachate from litterfall that accumulates in the collector funnel." In this study, the funnels were not equipped with loops to retard evaporation. Even if the sampling interval was only one week, the throughfall chemistry may also have been influenced by evaporation.

Percolate

The interpretation of the effects of clearcutting on the percolation water chemistry is difficult because there were no (at Vesijako) or only a few (at Ruotsinkylä) samples from the calibration period. This contrasted with the situation after clearcutting when samples could be collected almost every week. Lysimeters of the type used in this study probably better depict the real situation in the soil than the filled-in type of lysimeters used by Rosén and Lundmark-Thelin (1987). With the filled-in lysimeters, horizontal water movement and uptake of water and nutrients from the soil above the collector are excluded. However, the sample chemistry may have been affected by mineralization, which may well have been stimulated as a result of installation. The aerobic conditions prevailing in the lysimeters may also have resulted in the mineralization and possible nitrification of the collected sample.

Except for the control area at Ruotsinkylä, the percolate showed high sporadic nitrate concentrations, which suggests that the study areas had a potential for high leaching losses of nitrogen af-

Table 3. Mean nitrogen concentrations of percolation water in 1994 in Vesijako. 95% confidence intervals in parentheses.

	Without slash (n = 7)	Under slash (n = 7)	Control (n = 3)
$N_{org.}$, mg l^{-1}	1.76 (1.16–2.36)	2.18 (1.63–2.73)	1.14 (0.99–1.28)
NH_4^+-N, mg l^{-1}	0.33 (0.17–0.48)	1.50 (1.21–1.79)	0.11(– 0.20–0.42)
NO_3^--N, mg l^{-1}	1.12 (0.03–2.20)	0.16 (0.01–0.31)	1.88 (1.06–2.70)

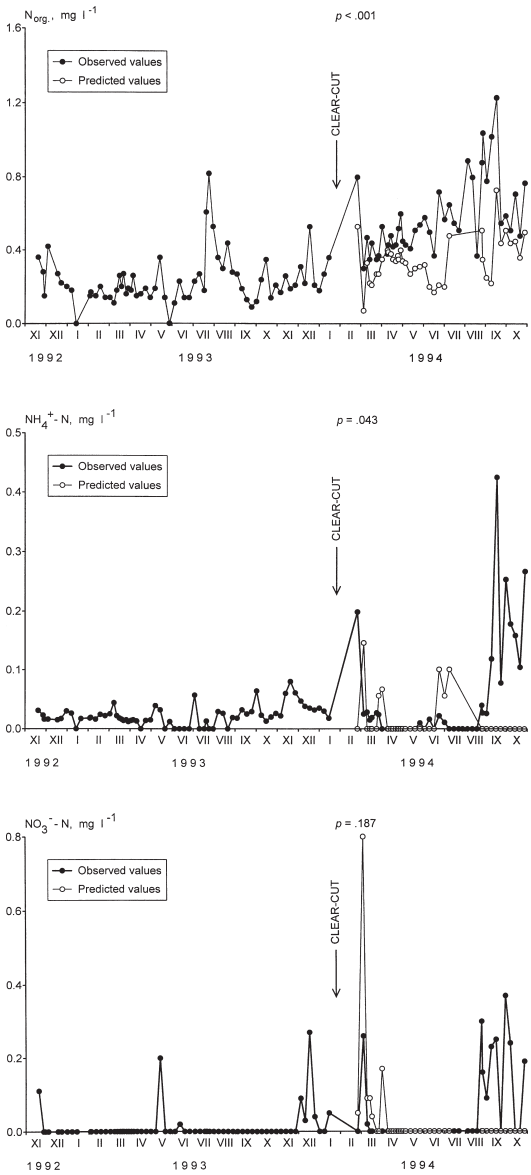

Fig. 8. The effect of clearcutting on the organic N, NH_4^+-N and NO_3^--N concentrations of runoff water at Ruotsinkylä. The *p*-values for statistical difference between observed and predicted values are also given.

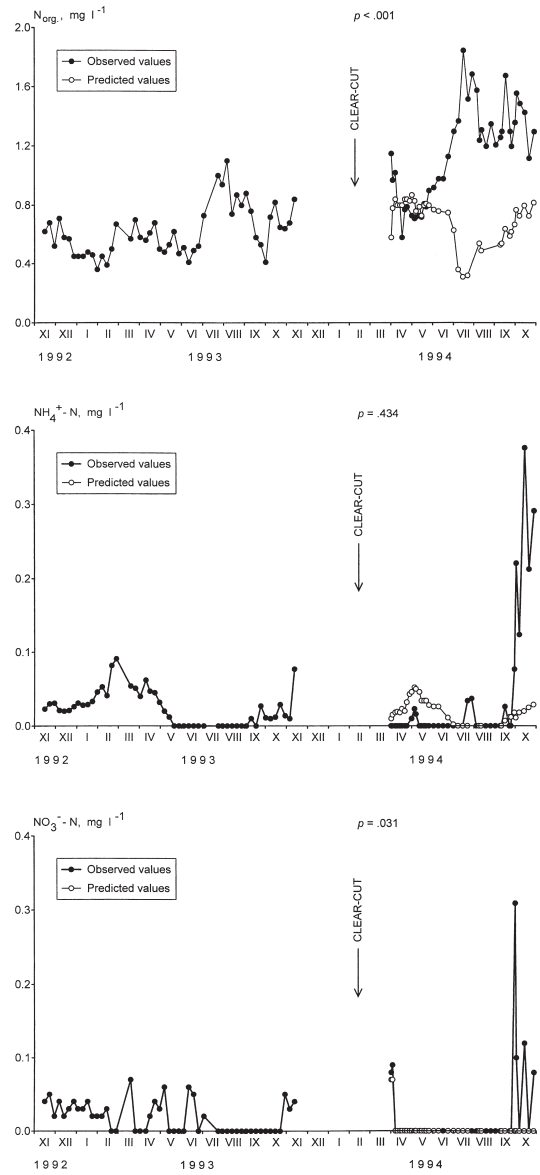

Fig. 9. Same as Fig. 8 but for Vesijako.

ter clearcutting (Vitousek 1981). Clearcutting did not, however, significantly affect the nitrate concentrations of the percolation water (Fig. 6). At Vesijako, nitrate concentrations were even lower in the clear-cut area than in control area (Table 3). Ammonium concentrations, in contrast, clearly increased after clearcutting. At Vesijako, ammonium concentrations were higher under piles of slash than in the slash-free areas, while there were no difference between the two lysimeter positions at Ruotsinkylä. Rosén and Lundmark-Thelin (1987) found both high nitrate and ammonium concentrations of percolation water under slash-piles on mineral soils during the second and third growing season after clearfelling. Nitrate and ammonium concentrations collected from spots between the piles of slash were at the same level as could be expected from a forested area.

Gaseous nitrogen fluxes

The gaseous nitrogen emissions were not influenced by clearcutting (Fig. 7), indicating no increases in denitrification after clearcutting. Denitrification is positively correlated with the amount of nitrate, available carbon and denitrifying bacteria in soil (Christensen *et al.* 1990). Denitrifying bacteria are favoured by anaerobic conditions. Clearcutting raises the water table which results in anaerobiosis. Because of the decomposing slash, the amount of available carbon can also increase. On these bases, clearcutting may be expected to increase denitrification. However, an increase in water availability will decrease the production of nitrate, which does not favour denitrification. Because the interaction between different site-specific factors affecting denitrification is poorly known, it is difficult to predict the emission rates of N_2O-N after clearcutting. As regards the importance of N_2O-N fluxes (< 1 kg ha^{-1} a^{-1}) and leached amounts of N_2O-N (< 20 g ha^{-1} a^{-1}) in the nitrogen cycle on drained peatlands or in the global atmospheric budget of greenhouse gases, the values measured in this study must be regarded as very low. Nitrous oxide emissions presented here were lower than those presented by Martikainen *et al.* (1993) for the drained minerotrophic peatlands.

The theoretical equilibrium concentration of N_2O-N in water with the atmosphere (based on water temperature, an assumed atmospheric N_2O concentration of 310 ppb and the theoretical solubility of N_2O at zero salinity) varies normally from 0.20 to 0.40 μg l^{-1} of N_2O-N (Bowden and Bormann 1986). The measured values from this study are somewhat higher than the theoretical equilibrium concentration. This would indicate that part of the N_2O-N produced during either nitrification or denitrification is really transported by the runoff water.

Runoff

The concentration of organic nitrogen in runoff water increased significantly in both clear-cut areas after the clearcuttings (Figs. 8 and 9). The organic nitrogen concentrations of percolate passing through the 0–20 cm peat layer did not change after clearcutting either in the slash-free areas or representative piles of slash. Therefore, the increase in runoff organic nitrogen is probably not due to leaching of nitrogen from decomposing slash or from surface peat, but due to leaching of nitrogen from deeper peat profiles.

Clearcutting increased the ammonium concentrations of both precipitation and percolate. The increase in runoff ammonium concentrations was thus expected. There were also sporadic high runoff nitrate concentrations from both clear-cut areas during the first autumn after clearcuttings. The causes for increased runoff nitrate concentrations are difficult to explain. This is particularly true in the case of Ruotsinkylä because nitrate concentrations of precipitation reaching the ground decreased after clearcutting, and percolate samples showed no indications of increased nitrification. The increase in the ammonium concentrations of runoff water after clearcutting was similar to that reported by Ahtiainen (1990), but smaller than that reported by Grip (1982) for clear-cut areas in Sweden. According to the results from Ahtiainen's study (1990), increased nitrate leaching did not occur until three years after clearcutting. In this study high nitrate concentrations occurred sporadically during the first year after cuttings.

Conclusions

Considering the limited number of study sites and the short period covered by the results, the following conclusions can be drawn:

— The concentrations of ammonium in the precipitation reaching the ground are increased after clearcutting. Nitrate concentration increased in an area where N deposition was average for Finland, but decreased in an area where deposition was higher than average.

— Ammonium concentrations in percolating soil water increased after clearcutting both under slash-piles and in slash-free areas. There were no significant changes in the concentrations of organic nitrogen or nitrate.

— Clearcutting did not increase gaseous nitrogen emission. As regards the importance of the gaseous nitrogen emissions in the nitrogen cycle on drained peatlands or in the global atmospheric budget of greenhouse gases, the emissions measured here must be considered as low.

— The runoff organic nitrogen concentrations increased significantly after clearcutting. The increased organic nitrogen in runoff appears to come from deep peat profiles. The causes for sporadic increases in nitrate concentrations remained unexplained. Because of the increase in ammonium deposition and ammonium concentrations in percolation water, the increase in runoff ammonium concentrations after clearcutting was logical.

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