Effects of forest clear-cutting on the sulphur, phosphorus and base cations fluxes through podzolic soil horizons

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Abstract. Clear-cutting considerably alters the flow of nutrients through the forest ecosystem. These changes are reflected in soil solution concentrations and fluxes. The effects of clear-cutting (stems only) on the fluxes of water soluble phosphorus (P), sulphur (S) and base cations (Ca, Mg and K) through a podzolic soil were studied in a Norway spruce dominated mixed boreal forest in eastern Finland. Bulk deposition, total throughfall (throughfall + stemflow) and soil percolate from below the organic (O), eluvial (E) and illuvial (B) horizons were collected for 4 years before and for 3 years after cutting. Annual deposition loads ($kg\,ha^{-1}$) to the forest floor were less after clear-cutting, averaging 1.7 S, 0.84 Ca, 0.14 Mg, 0.64 K and 0.10 P. Before cutting, the loads were 4.6 S, 2.7 Ca, 0.70 Mg, 6.2 K and 0.20 P. Annual fluxes of total S and sulphate $\left(SO_4^{2-}\right)$ from below the O-horizon were also lower (33%) after clear-cutting, total S averaging $2.0\,kg\,ha^{-1}$, the flux from below the B-horizon also diminished after clear-cutting. The flux of total P (mainly inorganic) from below the O-horizon increased threefold ($6.9\,kg\,ha^{-1}$; sum over the 3-year period) compared to period before cutting. The fluxes of base cations from below the O-horizon increased twofold. The flux of K^+ from below the O- and E-horizons was most strongly correlated with that of phosphate (PO_4^{3-}) and those of Ca^{2+} and Mg^{2+} with the DOC flux. Increased fluxes of P and base cations to the mineral soil generated only slightly increased fluxes from below the B-horizon. The retention of base cations and P in the mineral soil indicates there was little change in leaching to ground and surface waters after clear-cutting.

Introduction

Clear-cutting eliminates the interaction between canopy and deposition, diminishes uptake from the soil by trees, replaces the continuous flux of litterfall to the soil by a sudden and large input of dead organic matter in the form of logging residues, and may increase the water flux through the soil. All these changes increase the potential risk for increased nutrient leaching from the soil.

Base cations, especially K^+ may be released rapidly from logging residues (Titus and Malcolm 1992; Staaf and Olsson 1994; Stevens et al. 1995; Robertson et al. 2000). But solutes released from logging residues may also be immobilised, at least temporarily, in the expanding microbial population or taken up by the developing

ground vegetation, adsorbed by the soil through ion exchange or precipitation reactions, or they may leach to ground and surface waters.

Large leaching losses of base cations accompanied by nitrate (NO_3^-) anions from clear-cut areas have been reported for temperate forests (Likens et al. 1969; Dahlgren and Driscoll 1994; Homann et al. 1994; Titus et al. 1997). However, studies carried out in the boreal zone with both low N deposition and low potential for nitrification are lacking. Since the leaching of cations must be accompanied by an equivalent amount of anions (Johnson and Cole 1980), and NO_3^- concentrations in soil water from such sites are low, anions other than NO_3^- must be involved in the transport of base cations. Carbonate/bicarbonate (CO_3^{2-}/HCO^{3-}) concentrations are low in acid forest soils (Bohn et al. 1985) and chloride (Cl^-), being conservative and highly mobile, is unlikely to be markedly altered by clear-cutting. Although sulphate (SO_4^{2-}) deposition is reduced after clear-cutting concentrations in soil solution can increase due to leaching from logging residues (Cortina and Vallejo 1994). Others studies have, however, found the logging residues act as a sink for S (Gosz et al. 1973). Deposition fluxes of phosphate (PO_4^{3-}) are little affected by clear-cutting because the dry deposition is negligible and interaction of P in the canopy is small (e.g. Parker 1983). But PO_4^{3-} is readily released from dead organic matter, when the C/P ratio is low enough as to not limit mineralisation (Berg and Staaf 1980). However, the adsorption of SO_4^{3-} and PO_4^{3-} ions by Al and Fe oxides can be expected to be efficient in podzolic soils (Singh et al. 1980; Gustafsson and Jacks 1993; Gobran et al. 1998) and for PO_4^{3-}, partly irreversible (Stevenson and Cole 1999). Phosphate can also form insoluble complexes with Ca and Mg (Johnson and Cole 1980).

Incomplete mineralisation of organic matter, which is typical for podzolic soils, produces soluble and, under low pH conditions, negatively charged organic ions. Organic acid anions may therefore be involved in cation leaching from boreal podzolic soils (e.g. Dijkstra et al. 2001). However, the leaching of dissolved organic matter (DOM) to streams is not markedly increased by clear-cutting (see review by Hope et al. 1994) and much of the DOM leaching from the O-horizons is retained or mineralised in the upper mineral soil of podzols (Piirainen et al. 2002b).

Besides the loss of base cations nutrients from the soil and associated decline in site productivity, it is important to know whether clear-cutting increases inputs, especially those of P, to surface waters, which can cause eutrophication. Increased fluxes of P to ground water (Kubin 1995) and surface waters (Ahtiainen and Huttunen 1999) have been reported to occur in the boreal zone after cuttings.

In this paper, we present results concerning the effects of clear-cutting (stems only) on the fluxes of base cations and water soluble P and S through the soil at a mixed, Norway spruce dominated boreal forest in eastern Finland. This area receives low levels of N deposition and the soil has low nitrification potential (Piirainen et al. 2002b). We hypothesise that, even after such a major disturbance of the ecosystem, the mineral soil is able to effectively retain any increased nutrient fluxes, resulting in small leaching loss increases. The study is a part of an ongoing research project evaluating the effects of clear-cutting and site preparation on nutrient fluxes through the soil and on stream water quality and yield (Finér et al. 1997).

Material and methods

Study area

The data presented were collected from three adjacent $50\,m \times 50\,m$ sample plots located on a south-easterly facing slope in the Kangasvaara catchment in eastern Finland (63°51′N, 28°58′E, 220 m a.s.l.) (Finér et al. 1997). The boreal forest was an old-growth mixed coniferous stand dominated by Norway spruce (*Picea abies* Karsten). Scots pine (*Pinus sylvestris* L.), white and silver birch (*Betula pubescens* Ehrh. and *Betula pendula* Roth) and European aspen (*Populus tremula* L.) were also present (Table 1). Clear-cutting was done at two of the plots in September 1996 and one plot left uncut to serve as a control. Only stems (with bark) were removed; the logging residues (branches, leaves and tree tops $<8\,cm$ stem diameter) being left, evenly distributed over the surface.

According to the Finnish site type classification (Cajander 1949; Mikola 1982), the site was classified as a *Vaccinium–Myrtillus* type. Accordingly, the field layer was dominated by dwarf shrubs (*Vaccinium vitis-idaea* L. and *V. myrtillus* L.) and the bottom layer by feather mosses (*Pleurozium schreberi* Brid. and *Hylocomium splendens* (Hedw.) B. S. and G.). The forest floor consisted of a litter and mor humus layer with an average thickness of 3 cm. The soil, derived from sandy till material, was a weakly developed iron-podzol (according to the classification of Kubiëna, 1953), with a clay content of $<2\%$. The stone content of the upper 30 cm layer, determined by the rod penetration method of Viro (Tamminen and Starr 1994), was 28% by volume. Further characteristics of the soil are presented in Table 2.

The mean annual air temperature averaged $+0.7\,°C$ and the annual temperature sum (sum of daily mean temperature exceeding $+5\,°C$) was $903\,°C$ for the period 1993–1999. The long-term (1971–2000) mean annual air temperature for the region is between $+1\,°C$ and $+2\,°C$ and mean annual precipitation between 600 and 650 mm (Climatological Statistics of Finland 1971–2000). A more detailed description of the study area has been presented elsewhere (Finér et al. 1997).

Deposition and soil water sampling

Bulk precipitation in a nearby clearing and throughfall at the sample plots were collected during the 4-year period prior to clear-cutting (1993–1996) and for 3 years afterwards (1997–1999) using permanently open bulk precipitation collectors. For bulk precipitation, five plastic collectors (each $131\,cm^2$) were used during the snow-free period and three bigger ones (each $299\,cm^2$ during 1992–1993 and $1146\,cm^2$ thereafter) during the winters. The collectors were placed 0.6 m above ground level during the snow-free period and at 1.5 m in winter. Throughfall was collected at each sample plot using 16 collectors during the snow-free period and 8 collectors for snow in winter. The same type of collectors as for bulk precipitation in the open were used and placed systematically at equal distances along the border of the plots (4 collectors each side). After clear-cutting, throughfall was collected

Table 1. Tree stand characteristics of the uncut plot and clear-cut plots 1 and 2 and annual litterfall elemental fluxes before clear-cutting in 1996, and logging residue elemental pools.

	Uncut plot	Plot 1	Plot 2
Before cutting			
Stem volume with bark, $m^3 ha^{-1}$	260	230	290
Spruce, %	78	50	33
Pine, %	11	36	51
Deciduous, %	11	14	16
P in above ground litterfall, $kg ha^{-1}$	1.6	1.6	1.9
S in above ground litterfall, $kg ha^{-1}$	1.1	0.9	1.1
Ca in above ground litterfall, $kg ha^{-1}$	16.0	10.6	14.4
Mg in above ground litterfall, $kg ha^{-1}$	2.0	1.6	2.2
K in above ground litterfall, $kg ha^{-1}$	4.7	2.8	3.8
After clear-cutting			
P in above ground logging residues, $kg ha^{-1}$	–	20	21
S in above ground logging residues, $kg ha^{-1}$	–	15	15
Ca in above ground logging residues, $kg ha^{-1}$	–	144	138
Mg in above ground logging residues, $kg ha^{-1}$	–	17	18
K in above ground logging residues, $kg ha^{-1}$	–	69	75

Table 2. Some chemical properties and elemental pools in soil horizons at the uncut plot and clear-cut plots 1 and 2 before cutting.

	O-horizon			E-horizon			B-horizon		
	Uncut	Plot 1	Plot 2	Uncut	Plot 1	Plot 2	Uncut	Plot 1	Plot 2
Thickness of horizon, cm	3.0	3.5	2.8	7.1	6.0	7.2	12.8	13.7	15.3
pH_{H_2O}	4.22	3.84	3.93	4.22	4.24	4.22	4.95	4.98	5.20
C, %[a]	38.8	49.8	47.8	1.5	1.6	1.1	2.2	2.2	1.4
P, %[b]	0.06	0.07	0.08	0.01	0.02	0.01	0.03	0.06	0.08
P, $kg ha^{-1}$ [b]	30.7	38.0	32.4	43.3	75.5	76.3	229.6	526.3	942.4
S, $kg ha^{-1}$ [b]	50.0	58.8	45.5	31.9	60.7	23.9	302.5	379.5	516.5
Ca, $kg ha^{-1}$ [b]	164.1	148.5	132.3	139.8	153.0	337.0	494.0	474.6	2218.3
Mg, $kg ha^{-1}$ [b]	42.6	26.7	27.1	174.7	409.7	159.9	1716.6	1639.2	3026.4
K, $kg ha^{-1}$ [b]	61.5	63.7	58.7	63.6	77.0	88.9	244.8	283.8	625.3
CEC, $kmol_c ha^{-1}$ [c]	12.8	14.5	11.0	17.8	16.6	19.1	15.1	10.9	8.8
Base saturation, %	69	61	69	13	9	9	17	15	32

[a]Determined with Leco CHN analyser.
[b]O-horizon: nitric acid + H_2O_2 digest; E- and B-horizons: nitric + hydrochloric acid digest.
[c]Effective cation exchange capacity (0.1 M $BaCl_2$ extraction).

only at the uncut plot and deposition to the ground at the cut plots was assumed to be that of the bulk deposition. Stemflow was collected during 1993–1995 at two of the plots. For the following years, stemflow fluxes were taken as the average of the measured years. At each plot, five white or silver birches, Scots pines and Norway

spruces representing different breast height diameter classes (>6 cm) were fitted with a spiral type stemflow collector made of silicon tubing.

The bulk precipitation and throughfall collectors were emptied once a week during the snow-free period and once a month during winter. On each sampling occasion the volume collected was recorded. Weekly or monthly bulk precipitation and throughfall samples were pooled by plot for chemical analyses. Stemflow was collected weekly and only during the snow-free period, and pooled by tree species for chemical analysis.

Soil water (percolate) was sampled at each sample plot using nine zero-tension lysimeters installed in the plots at each of three depths: below the organic (O), below the eluvial (E) (14, 11 and 11 cm depths from the soil surface at the uncut plot and cut plots 1 and 2, respectively), and below the upper part of the illuvial (B) horizon (36, 37 and 32 cm depths from the soil surface, respectively). Particular care was taken during installation to avoid damage to the field layer vegetation and roots. The three lysimeters below the B-horizon in the cut plot 2 and two lysimeters below the O-horizon in the cut plot 1 did not collect water or only did so before July 1998, and all data from these five lysimeters therefore have been excluded from subsequent calculations. The lysimeters below the O-horizon were of the Jordan type (Jordan 1968); namely a plexiglass gutter, closed at the ends with a collecting area of 420 cm^2. The lysimeters installed below the E- and B-horizons were made of a polythene plastic funnel, filled with quartz sand, with a collecting area of 299 cm^2 fitted to a 2 L sample collection bottle. The particle size of the quartz sand used varied from 0.8 to 1.2 mm. The main particle size fraction in the E- and B-horizons was also sand (41 and 39%, respectively), allowing free water flow from the soil into the lysimeters (Piirainen et al. 2002a). When not frozen (usually from April to October), the lysimeters were emptied on the same day as the precipitation and throughfall collectors and each lysimeter sample was analysed separately. Care was taken during the clear-cutting operations not to disturb the lysimeter installations.

We use the term *total throughfall* to mean throughfall plus stemflow, *leaching* to mean output of percolate in excess of input for a soil horizon and *retention* when inputs are greater than outputs. *Base cations* refer to Ca^{2+}, Mg^{2+} and K^+ ions.

Laboratory analyses and calculations

All the samples were kept cold and transported to laboratory the day after sampling. After measuring the volume of water collected from lysimeters, pH was measured (Radiometer PHM92 pH-meter) from all water samples and thereafter the samples were filtered (Schleiche and Schuell no. 589[1] filter paper and in the case of soil percolate samples a Schleiche and Schuell no. GF 52 glass wool filter). All the filtrates were then stored in a freezer ($-18\,°C$) until further analyses. Sulphate and PO_4^{3-} concentrations were determined by ion chromatography (Dionex series 100 or 300 or 500) and Ca^{2+}, Mg^{2+} and K^+ concentrations by flame atomic absorption spectrophotometer (Perkin-Elmer 5000). Total S and P concentrations in a representative number of samples were measured with an ICP emission spectrometer

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Table 3. Linear regression models ($p < 0.01$) for estimating weekly total S (y) concentrations from SO_4^{2-}-S (x) and for estimating total P (y) concentrations from PO_4^{3-}-P (x) ($mg\,L^{-1}$) in bulk precipitation (BP), throughfall (TF) and percolate from below different soil horizons before (1993–1996) and after (1997–1999) clear-cutting.

	Before clear-cutting	After clear-cutting
BP	S: $y = 1.15x$ ($R^2 = 0.94$, $n = 93$ in 1993–1999)	
	P: $y = 1.12x$ ($R^2 = 0.97$, $n = 93$ in 1993–1999)	
TF	S: $y = 1.10x$ ($R^2 = 0.96$, $n = 22$)	
	P: $y = 1.53x$ ($R^2 = 0.79$, $n = 22$)	
O-horizon	S: $y = 0.32 + 1.29x$ ($R^2 = 0.78$, $n = 122$)	S: $y = 0.54 + 1.21x$ ($R^2 = 0.79$, $n = 129$)
	P: $y = 1.45x$ ($R^2 = 0.93$, $n = 123$)	P: $y = 1.25x$ ($R^2 = 0.99$, $n = 130$)
E-horizon	S: $y = 0.65 + 1.24x$ ($R^2 = 0.50$, $n = 138$)	S: $y = 1.85 + 0.98x$ ($R^2 = 0.05$, $n = 178$)
	P: $y = 1.43x$ ($R^2 = 0.93$, $n = 123$)	P: $y = 0.03 + 1.14x$ ($R^2 = 0.99$, $n = 130$)
B-horizon	S: $y = 1.27 + 0.71x$ ($R^2 = 0.35$, $n = 36$)	S: $y = 2.11x$ ($R^2 = 0.79$, $n = 26$)
	P: $y = 1.21x$ ($R^2 = 0.98$, $n = 37$)	P: $y = 1.13x$ ($R^2 = 0.96$, $n = 26$)

(ARL 3580 in 1993–1996 and TJA Iris Advantage thereafter). These data were used to derive linear regression equations to estimate total S and P concentrations to the whole study period using the measured $SO_4^{2-}-S$ and $PO_4^{3-}-P$ concentrations (Table 3).

The detection limits (DL) for $SO_4^{2-}-S$, $PO_4^{3-}-P$, Ca^{2+}, Mg^{2+} and K^+ were 0.07, 0.05, 0.10, 0.02 and 0.05 $mg\,L^{-1}$, respectively. For samples collected during 1993–1995, the DL of Ca^{2+} was 0.30 $mg\,L^{-1}$ and that of $PO_4^{3-} - P$ 0.02 $mg\,L^{-1}$ in 1996–1997. Detection limits of total S and total P were 0.07 and 0.15 $mg\,L^{-1}$ in 1993–1996 and 0.03 and 0.02 $mg\,L^{-1}$ thereafter. If the concentration was less than DL, a value of half DL was used in further calculations. Some 80% of Ca^{2+} bulk precipitation concentrations collected in 1993–1995 were less than DL and 13% thereafter. The percentage of bulk precipitation samples with concentrations below DL was 76% for PO_4^{3-}, 56% for total P, 14% for Mg^{2+} and 6% for K^+. For PO_4^{3-} concentrations in soil percolate, 30% of samples collected from below the O- and E-horizons were below DL and 80% of samples from below the B-horizon.

Monthly and annual deposition and fluxes in the soil for plots were calculated from mean concentrations (volume weighted by contribution of individual collectors), the volume of water collected and the total collection area of all contributing collectors. Significant differences in concentrations between uncut and cut plots were tested using the SAS MULTTEST procedure with bootstrap p-value adjustment [SAS for Windows 6.12 (SAS® 1997)]. This procedure does not assume normal distribution and takes into account the problem of multiple comparisons (Westfall and Young 1993). A critical probability level of 0.05 was used to indicate significance of differences. The statistical testing was done on annual and seasonal (spring, summer, autumn) values before and after clear-cutting. The monthly concentrations values were first logarithmically transformed for each season. Seasons before and after clear-cutting were analysed separately and if no differ-

ences were found between the plots before clear-cutting, differences thereafter were considered to be the result of clear-cutting. The spring season included the months April and May starting from snowmelt (first sampling in March in 1994), summer June through August, and autumn September through October (November in 1994 and 1999 and December in 1996). Correlations between solute concentrations were calculated from monthly plot data without logarithmic transformation.

Results

Water fluxes

The results of the water fluxes have been reported in more detail earlier (Piirainen et al. 2002b). Annual bulk precipitation during the entire study period averaged 493 mm. Total throughfall averaged 92% of this value (only uncut plot data for 1997–1999). From November to April, the precipitation fell mainly as snow and accounted for 39% of the annual bulk precipitation value. Of the annual amount of throughfall collected at the cut plot 1 before clear-cutting 84, 48 and 4% on average passed through the O-, E- and B-horizons, respectively. The corresponding values at the cut plot 2 were 57, 20 and 5%. After cutting, the proportion of the annual incident precipitation passing through the O-horizon remained similar to these before cutting values, except in 1999 at cut plot 1 when it decreased to 67%. The relative amount of percolation from the E-horizon (percentage of incident precipitation) also did not change after cutting, but that below the B-horizon increased, being 7% at cut plot 1 in 1999 and 9 and 6% at cut plot 2 in 1997 and 1998.

pH

The pH of the precipitation reaching the forest floor increased after clear-cutting. The mean annual bulk precipitation pH (4.72 for the period 1993–1996 and 4.99 for the period 1997–1999) was a little higher than that of the total throughfall (4.49 and 4.54 for the same two periods). While clear-cutting did not change the pH of the soil percolate from below the O-horizon, it did significantly increase that of the soil percolates from below the E- and B-horizons in 1998 and in the E-horizon in 1999 at cut plot 2 compared to the uncut plot (Figure 1). There were also individual elevated monthly pH values in the soil percolates collected at cut plot 1 after cutting, but these changes were not significant.

Sulphur and phosphorus fluxes and concentrations

The proportion of estimated organic S from total S in throughfall and bulk deposition and that of estimated organic P to total P in bulk deposition was small, but the proportion of estimated organic P to total P in throughfall was considerable
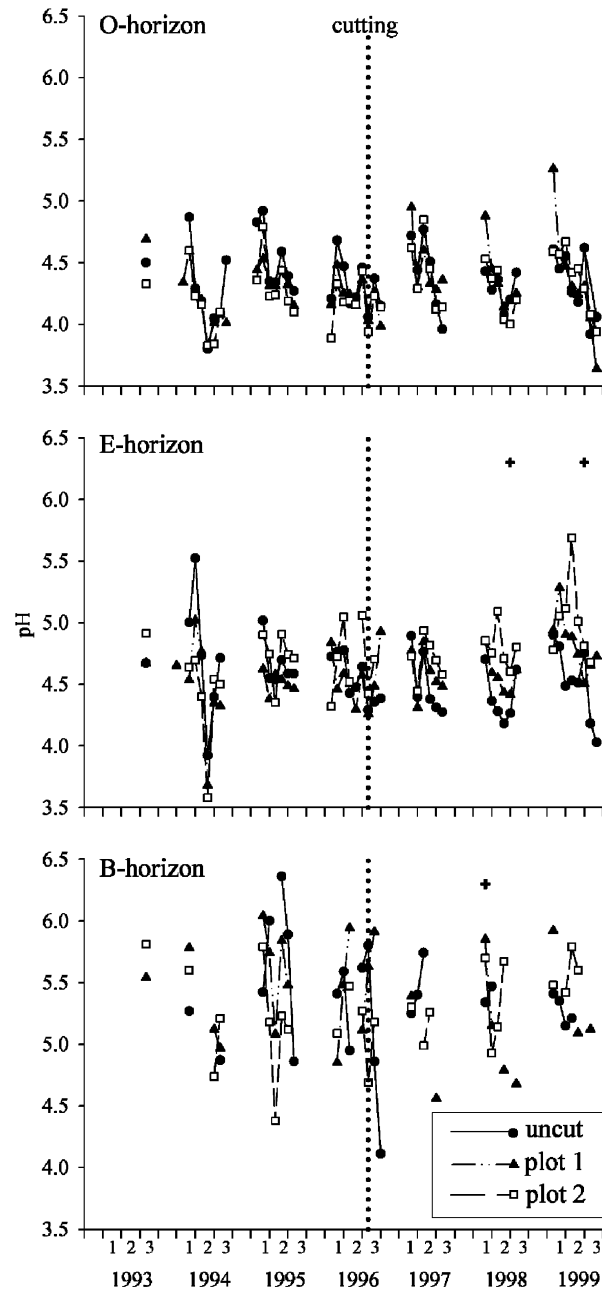
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Figure 1. Mean monthly pH in the soil percolate from below each horizon at the uncut plot and the cut plots 1 and 2 in 1993–1999. Clear-cutting was done in September 1996. 1 = April–May, 2 = June–August, 3 = September–October. Significant differences ($p < 0.05$) between the uncut and cut plot 1 (logarithm transformed values) are indicated with $^+$ and those between the uncut and plot 2 with *.
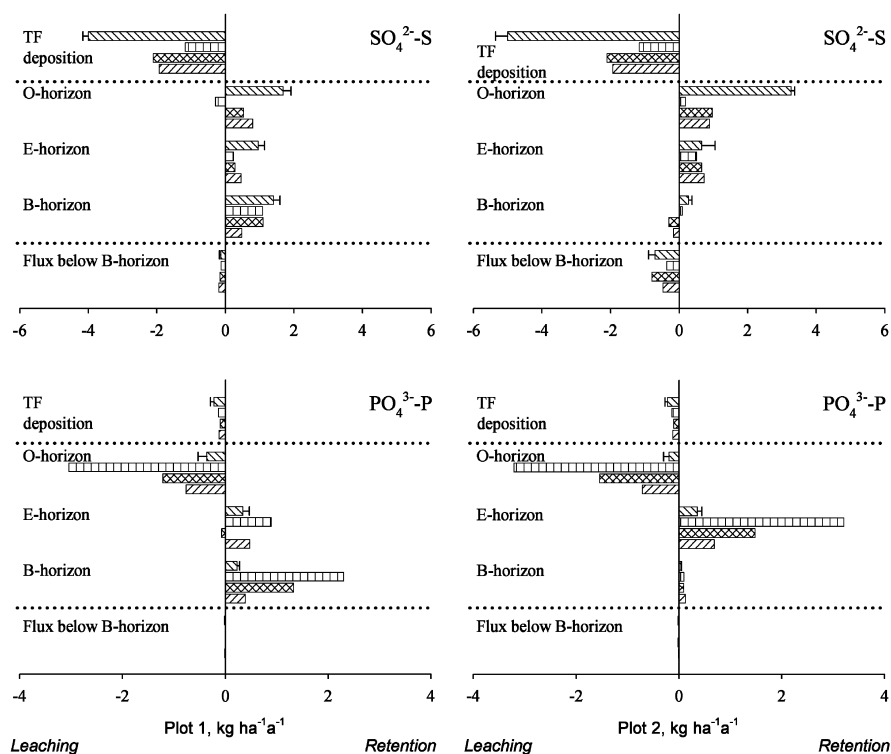
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Figure 2. Mean annual total throughfall deposition (TF), flux below the B-horizon and the leaching from or retention in the different soil horizons of SO_4^{2-} and PO_4^{3-} before (1993–1996) and after (1997–1999) clear-cutting at the cut plots. The error bars are the standard error of the mean, $n = 4$.

(Table 3). The annual deposition of SO_4^{2-} to the forest floor decreased after clear-cutting by more than 60% to an average of 1.72 ($\pm$0.49) kg S ha^{-1} in 1997–1999 and that of PO_4^{3-} decreased somewhat less (52%) to 0.10 ($\pm$0.04) kg P ha^{-1} (Figure 2). The annual deposition of organic S and P (total S – SO_4^{2-} –S; total P – PO_4^{3-} –P) to the forest floor also decreased, being 0.46 kg S and 0.11 kg P ha^{-1} in throughfall during 1993–1996 and 0.26 kg S and 0.01 kg P ha^{-1} (in bulk precipitation) in 1997–1999.

The overall influence of clear-cutting on soil water SO_4^{2-} concentrations was small, although there were a few clear-cut plot seasonal values that were significantly smaller than uncut plot values (Figure 3). Meanwhile the PO_4^{3-} concentrations increased considerably in the percolate from below the O- and E-horizons after cutting, although some elevated concentrations on the cut plots were also observed in the period before cutting. However, in the percolate from below the B-horizon PO_4^{3-} concentrations remained low also after cutting.

Even though the deposition input of SO_4^{2-} to the forest floor and leaching output from below the O-horizon decreased in absolute terms after clear-cutting, a greater
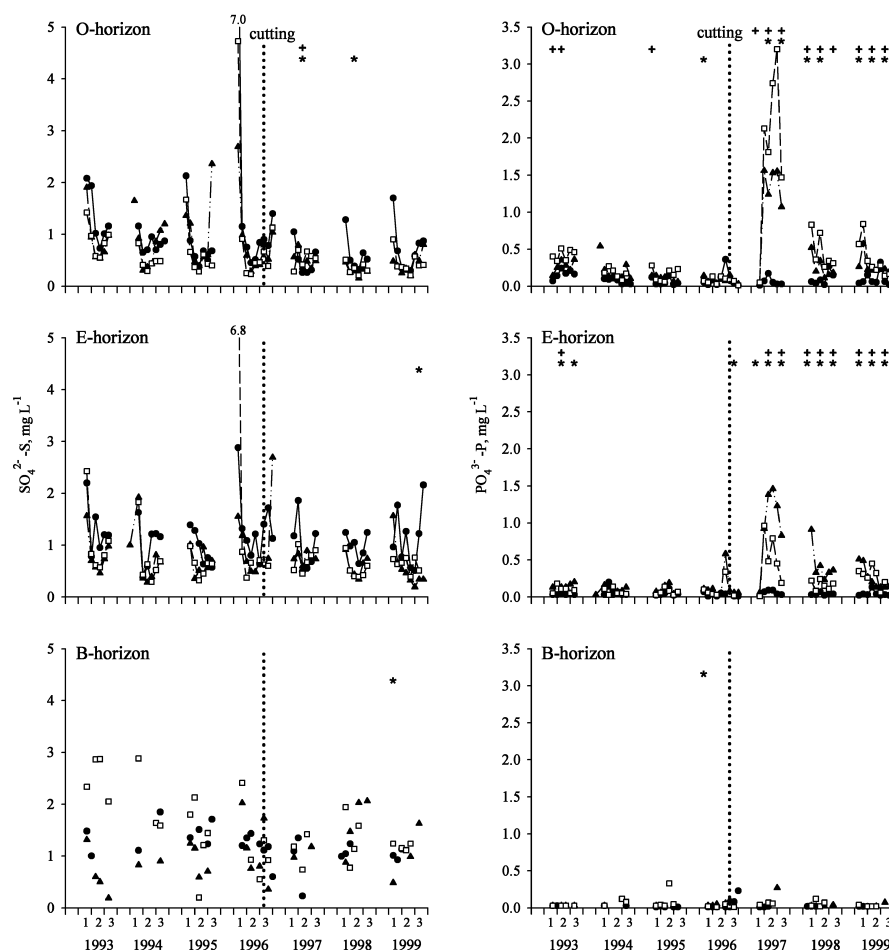
Figure 3. Mean monthly SO_4^{2-} and PO_4^{3-} concentrations $(mg\,L^{-1})$ in the soil percolate from below each horizon at the uncut plot and the cut plots 1 and 2 in 1993–1999. Clear-cutting was done in September 1996. For abbreviations and symbols see Figure 1.

proportion of the inputs leached from below the O-horizon at cut plots in the first year after cutting (Figure 2). Before clear-cutting, 40 (±9)% of the annual SO_4^{2-} input at cut plot 1 and 67 (±8)% at cut plot 2 was retained by the O-horizon. The degree of SO_4^{2-} retention by the O-horizon partly recovered over the harvested period, reaching 42 and 46% of the annual deposition input at cut plots 1 and 2, respectively, in 1999. The annual flux of SO_4^{2-} from below the O-horizon therefore decreased over the harvested period (30%). In 1999, the annual flux of SO_4^{2-}-S from below the O-horizon was $1.38\,kg\,S\,ha^{-1}$ at cut plot 1 and $1.04\,kg\,S\,ha^{-1}$ at cut plot 2. The estimated annual organic S flux from below the O-horizon also decreased after cutting, dropping from 0.92 to $0.79\,kg\,S\,ha^{-1}$. However, the

proportion of the total S flux as organic S increased slightly from 31 to 39% (Table 3).

In the case of PO_4^{3-}, clear-cutting increased the leaching from below the O-horizon, reaching a peak in 1997 when the leaching fluxes were eightfold at cut plot 1 and 17-fold at cut plot 2 (Figure 2). In the following years, PO_4^{3-} leaching decreased but remained twofold (cut plot 1) and threefold (cut plot 2) higher than the level before cutting in 1999. The estimated annual flux of organic P from below the O-horizon also increased after cutting, changing from 0.32 to 0.46 kg P ha^{-1} (Table 3). However, in contrast to organic S, the proportion of organic P decreased from 45 to 25% of total P.

Changes in the retention of SO_4^{2-} by the mineral soil horizons occurred but they were not as clear as those by the O-horizon. Before clear-cutting, the retention of SO_4^{2-} by the E-horizon averaged 38 ($\pm$13)% of the percolate input (that leaving the O-horizon) at cut plot 1 and 31 ($\pm$36)% at cut plot 2 (Figure 2). After cutting, retention decreased to 17% but increased to its initial level in 1999 at cut plot 1. At cut plot 2, no such reduction was observed and in 1999 the retention remained as high as 70%. The annual flux of estimated organic S from below the E-horizon averaged 0.95 kg ha^{-1} before cutting and retention by the E-horizon was negligible (Table 3). However, after cutting both the absolute (1.72 kg ha^{-1}) and relative annual organic S fluxes increased, but the estimate of organic S should be viewed with caution as the R^2-value of the model was low (Table 3). The relative retention of PO_4^{3-} by the E-horizon was somewhat higher than that of SO_4^{2-} before cutting. The E-horizon retained 54 ($\pm$25)% at cut plot 1 and 86 ($\pm$7)% at cut plot 2 of the annual O-horizon input. In 1997, in the first year after cutting, retention decreased to 29% at cut plot 1 and increased slightly to 96% at cut plot 2. In the following years, occasional increased leaching of PO_4^{3-} from the E-horizon at cut plot 1 occurred, but the retention returned to the same level as before cutting at cut plot 2. The estimated organic P annual flux from below the E-horizon also increased after cutting, changing from 0.06 to 0.13 kg ha^{-1}, but decreased as a proportion of the total P fluxes (Table 3).

The retention of SO_4^{2-} by the B-horizon before cutting was, on average, 90 ($\pm$7)% and 32 ($\pm$24)% of the input (that leaving the E-horizon) at cut plots 1 and 2, respectively. The corresponding retention values for PO_4^{3-} were 98 ($\pm$1)% and 74 ($\pm$13)%. After cutting, the annual retention of SO_4^{2-} by the B-horizon compared to inputs decreased year by year at cut plot 1 from 90% in 1997 to 71% in 1999. At cut plot 2 there was no retention of SO_4^{2-} anymore by 1998 but rather a leaching loss instead. The retention of PO_4^{3-} in contrast, remained very high at cut plot 1 (99%) and actually increased a little at cut plot 2 to 90% in 1999.

In spite of these changes in retention and leaching compared to inputs, the absolute fluxes of SO_4^{2-} or PO_4^{3-} from below the B-horizon at both cut plots did not change markedly after clear-cutting. Before cutting, the annual SO_4^{2-} and PO_4^{3-} fluxes from below the B-horizon averaged 0.13–0.70 kg S and 0.01 kg P ha^{-1} at the cut plots. After cutting, the corresponding values were 0.16–0.54 kg S and 0.01 kg P ha^{-1} a^{-1}. The estimated annual organic S (0.39 kg ha^{-1}) and organic P (0.001 kg ha^{-1}) fluxes from below the B-horizon also remained small after cutting.
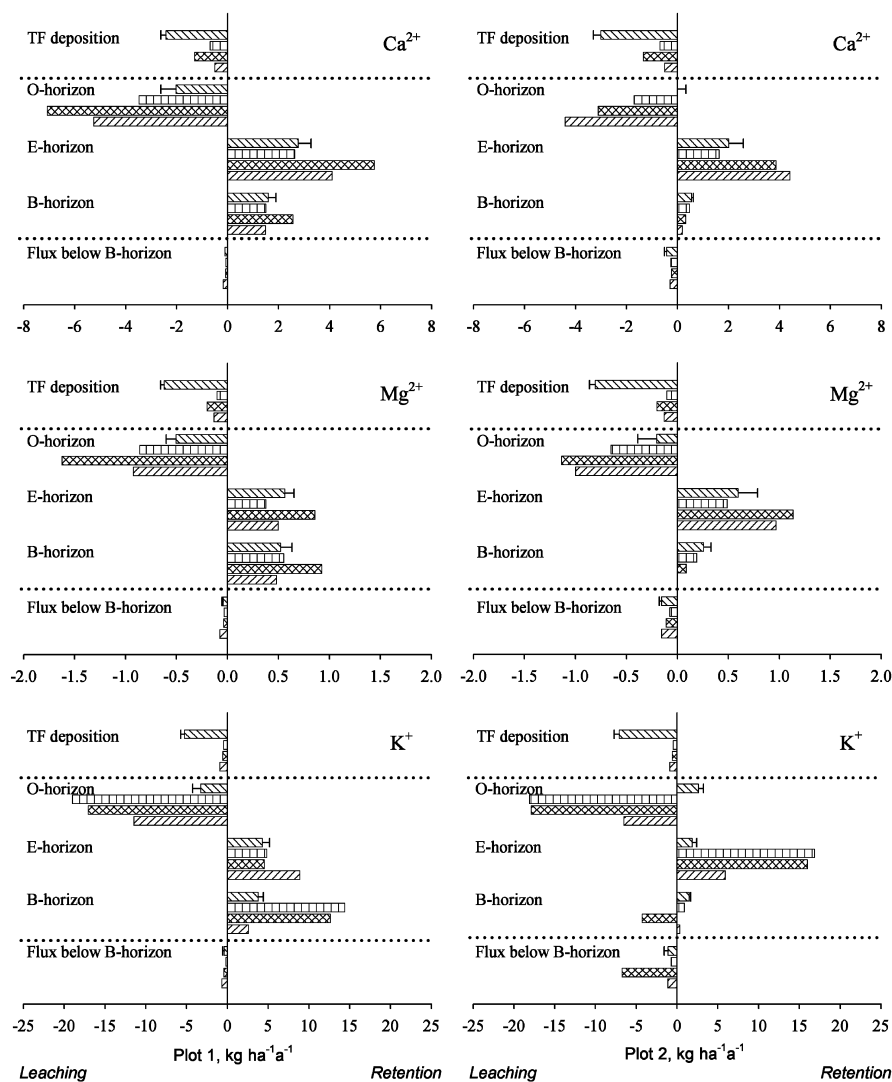
Figure 4. Mean annual total throughfall deposition (TF), flux below the B-horizon and the leaching from or retention in the different soil horizons of Ca^{2+}, Mg^{2+} and K^+ before (1993–1996) and after (1997–1999) clear-cutting at cut plots. For abbreviations and symbols see Figure 2.

The annual SO_4^{2-} flux from below the B-horizon compared to the annual total throughfall deposition input showed an increase from 3 (± 2)% (average of the years before cutting) to 9 (± 1)% (average of the years after cutting) at cut plot 1 and from 15 (± 9)% to 31 (± 7)% at cut plot 2 after cutting (Figure 2). Correspondingly, the annual PO_4^{3-} flux from below the B-horizon increased from 3 (± 1) (cut plot 1) and 6 (± 2)% (cut plot 2) to a maximum of 8% in 1999 (cut plot 1) and to 29% in 1998 (cut plot 2). Over the 3-year harvested period (1997–1999), 3.7 (cut
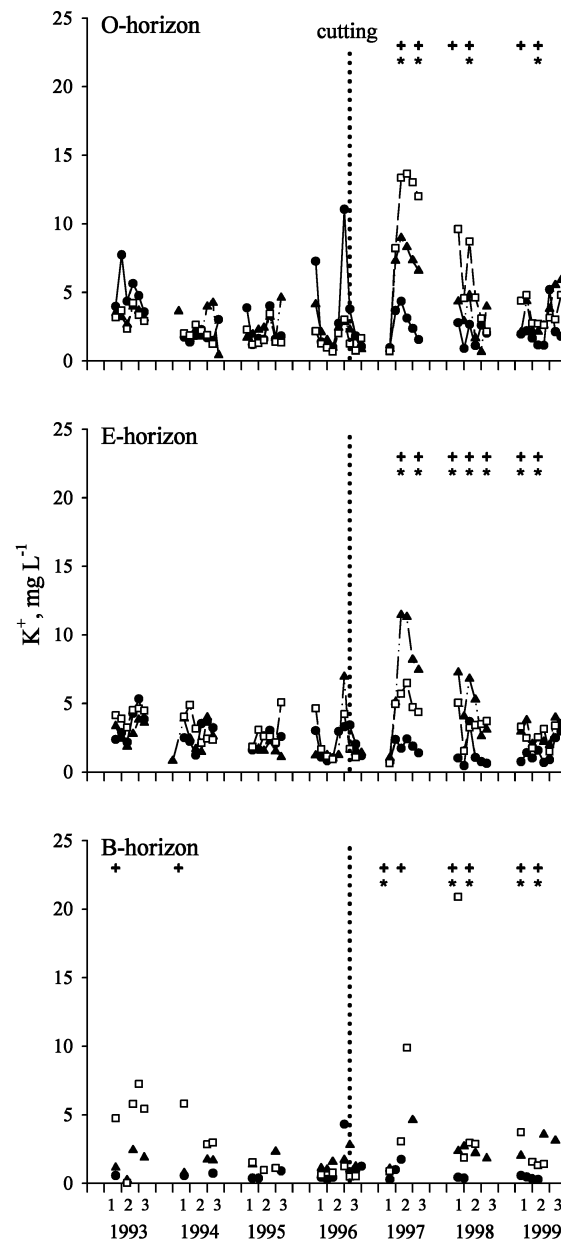
Figure 5. Mean monthly K concentrations $(mg\,L^{-1})$ in the soil percolate from below each horizon at uncut plot and cut plots 1 and 2 in 1993–1999. Clear-cutting was done in September 1996. For abbreviations and symbols see Figure 1.
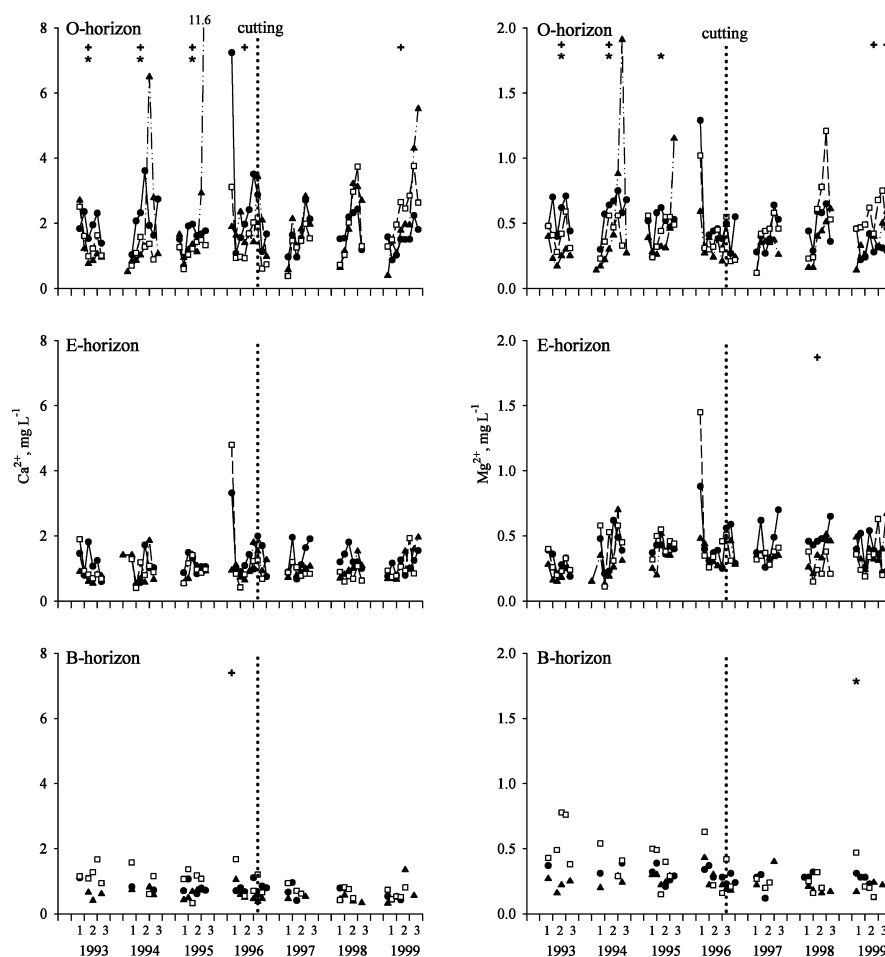
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Figure 6. Mean monthly Ca and Mg concentrations (mg L^{-1}) in the soil percolate from below the different soil horizons in 1993–1999 at uncut plot and cut plots 1 and 2. Clear-cutting was done in September 1996. For abbreviations and symbols see Figure 1.

plot 1) and 4.5 kg ha^{-1} (cut plot 2) more PO$_4^{3-}$ was retained in the mineral soil, primarily in the B-horizon compared to the period before cutting.

Calcium, magnesium and potassium

The annual deposition fluxes of base cations to the forest floor decreased after clear-cutting (Figure 4). Potassium deposition decreased the most, over 80% compared to the period before cutting. However, K$^+$ concentrations increased immediately after clear-cutting in the percolates from below the soil horizons (Figure 5). Occasional increased concentrations of Ca^{2+} and Mg^{2+} in the soil percolates were also observed after clear-cutting, but the changes were much smaller than those of K$^+$ (Figure 6).

The observed increases in base cation concentrations in soil percolate after clear-cutting resulted in increased leaching of Ca^{2+}, Mg^{2+} and K^+ from below the O-horizon (Figure 4). The average increase in the annual Ca^{2+} leaching was threefold at both cut plots over the harvested period (1997–1999). The corresponding values for Mg^{2+} were twofold at cut plot 1 and fivefold at cut plot 2 and those for K^+, fivefold (cut plot 1) and 14-fold (cut plot 2). The increased flux of all base cations to the mineral soil was mostly retained by the E-horizon at cut plot 2. At cut plot 1, the E-horizon retained most of the Ca^{2+} and the B-horizon most of the K^+ and Mg^{2+} annual fluxes (Figure 4). Some increased annual fluxes of Mg^{2+} in 1999 (cut plot 1) and K^+ in 1998 (cut plot 2) from below the B-horizon were observed after cutting, but the fluxes were much smaller than the corresponding input fluxes to mineral soil.

After cutting, monthly concentrations of PO_4^{3-} and K^+ were significantly correlated in the percolate from below the O- ($r = 0.87$, $n = 40$) and E- ($r = 0.87$, $n = 39$) horizons, but not so in the percolate from below the B-horizon. Correlations between percolate PO_4^{3-} and other base cations concentrations were negligible as were those between SO_4^{2-} and base cations.

Discussion

Changes in S, P and cations fluxes

The amounts of nutrients in logging residues left the study site after clear-cutting were much greater than those in litterfall or deposition before cutting (Table 1, Figures 2 and 4). Nutrient in dead organic matter can leach directly or after decomposition and mineralisation deeper into the soil. In this study the fluxes of total P, Ca^{2+}, Mg^{2+} and K^+ increased from below the O-horizon and that of total S decreased after clear-cutting. The leaching of P increased immediately after clear-cutting (Figure 2) and most probably originating from logging residues, since the C/P ratio of logging residues averaged 866 (Table 1). The threshold value for P net mineralisation has been shown to be 2000 (Berg and Staaf 1980). The increased dominance of PO_4^{3-} (75%) in the percolate from below the O-horizon, also observed in other studies after cutting (Qualls et al. 2000), also suggests the increased mineralisation of organic P. Before clear-cutting, PO_4^{2-} accounted for less than 55% of the total P flux from below the O-horizon, which is similar to the proportion reported by Qualls et al. (2000) and Yavitt and Fahey (1986) for undisturbed forests. The flux of total P from below the O-horizon was $6.9 \, kg \, ha^{-1}$ over the harvested period (1997–1999), which was about third of the amount bound in the logging residues.

The increased annual fluxes of base cations are probably also attributable to the decomposition and mineralisation of logging residues (Titus and Malcolm 1992; Staaf and Olsson 1994; Stevens et al. 1995; Robertson et al. 2000), but some leaching of cations, especially that of K^+, can occur directly from dead needles (Tukey 1970; Ukonmaanaho and Starr 2001). The increased leaching of Ca^{2+} is probably due to leaching also from the organic matter in the O-horizon itself (Hendrickson et al. 1989).

Probably the release of SO_4^{2-} from logging residues also occur since the C/S ratio of logging residues averaged 1184, which was less than the threshold value for net mineralisation of 1500 reported by Berg and Staaf (1980). Some direct leaching of S from dead organic matter can also occur (Ukonmaanaho and Starr 2001). However, the amount of released SO_4^{2-} was not large enough to compensate the loss of throughfall deposition and litterfall inputs on an annual basis (Table 1), since the flux of SO_4^{2-} from below the O-horizon was less than before cutting. The increased retention level of SO_4^{2-} by the O-horizon during the harvested period probably indicated recovered S uptake by the understorey vegetation and microbial immobilisation and/or reduced mineralisation of organic S.

Reduced uptake probably also explains the observed decrease in the proportion of SO_4^{2-} inputs retained by the E-horizon. The decrease in the proportion of SO_4^{2-} retained by the B-horizon, however, can be due to an input of earlier adsorbed SO_4^{2-} from the B-horizon itself as observed by Likens et al. (2002). The adsorption of SO_4^{2-} by acidic soils is an anion exchange process and is controlled by the amount and degree of the saturation of amorphous Al and Fe hydroxides (Nodvin et al. 1986, 1988; Harrison and Johnson 1992) and, depending on pH, is partly reversible (Harrison and Johnson 1992; Karltun 1995; Gobran et al. 1998). By definition, the B-horizon in podzolic soils is enriched in Al and Fe hydroxides and the soil at Kangasvaara was no exception (Piirainen et al. 2002a). The increase in percolate pH following clear-cutting could indicate an increase of soil pH, which could have resulted in desorption of SO_4^{2-} from this pool and enriching the percolate. The increased nitrification after cutting can result in enhanced SO_4^{2-} adsorption capacity due to lower soil pH as observed by Likens et al. (2002), but in the study site it was negligible (Piirainen et al. 2002b). However, the flux of SO_4^{2-} from below the B-horizon did not increase after clear-cutting at our study site. Neither have studies in temperate forests reported increased SO_4^{2-} leaching after cutting (Likens et al. 1970, 1977; Fuller et al. 1987).

The retention of PO_4^{3-} by acidic mineral soils is much stronger than that of SO_4^{2-}. Phosphate anions and soluble organic P complexes are known to precipitate with Al and Fe in solution to the form of highly insoluble Al and Fe-phosphate complexes and to be strongly adsorbed onto the surfaces of Al and Fe of hydrous oxides (Schnitzer 1969; Wood et al. 1984; Stevenson and Cole 1999). Strong PO_4^{3-} sorption by mineral soil, observed also in this study, would explain why the increased leaching of P from clear-cut areas to watercourses generally does not occur (Stevens et al. 1995; Yanai 1998; Briggs et al. 2000). However, increased stream water total P concentrations after cutting have been reported (Adamson and Hornung 1990; Ahtiainen and Huttunen 1999). This probably happens when runoff takes place mainly through the organic horizon, as during snowmelt, or if the ground-water table raises resulting in anaerobic conditions under which P becomes soluble (Armstrong 1982).

Leaching of cations and accompanied anions

Before clear-cutting, the flux of the sum of base cations from below the O-horizon was correlated with the flux of SO_4^{2-} (Piirainen et al. 2002a). After cutting, the role

of other ions such as PO_4^{3-} and soluble organic matter measured as dissolved organic carbon (Piirainen 2002) became more important. Because the retention of PO_4^{3-} was very effective in the mineral soil horizons its importance as a counter ion decreased in the percolate from below the B-horizon and that of organic anions and NO_3^- increased (Piirainen 2002). However, the fluxes of base cations and measured anions below the B-horizon were small.

Before clear-cutting, the forest ecosystem acted as a sink for deposition inputs of K^+ and Ca^{2+}, but for Mg^{2+} the deposition inputs and outputs from below the B-horizon were in balance (Piirainen et al. 2002a). After clear-cutting, the deposition inputs of base cations decreased, resulting in less positive annual mass balances (Figure 4). However, the difference between input and output fluxes for the mineral soil (E + B-horizon) indicates that the soil pool of base cations increased after clear-cutting and that there was little additional base cations leaching from below the B-horizon.

Conclusions

The deposition inputs of SO_4^{2-}, Ca^{2+}, Mg^{2+} and K^+ to the forest floor decreased immediately after clear-cutting while there was little change in PO_4^{3-} inputs. Although there was increased leaching inputs of Ca^{2+}, Mg^{2+}, and especially PO_4^{3-} and K^+, to the mineral soil over the first 3 years after clear-cutting, the source being the logging residues and organic horizon, most was retained in the mineral soil and there was no significant change in the leaching fluxes from below the B-horizon. It remains to be determined if these nutrients will continue to be retained on-site, either in the soil or in circulation within developing vegetation in the long-term, or whether they will eventually leach to ground and surface waters.

Acknowledgements

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