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Hydrology & Earth System Sciences

Modelling the response of soil and runoff chemistry to forest harvesting in a low deposition area (Kangasvaara, Eastern Finland)

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Abstract

A simple dynamic soil model developed to analyse the effects of atmospheric deposition and nutrient cycling on terrestrial ecosystems, SMART 2, was applied to the Kangasvaara catchment in Eastern Finland. Given the historical deposition and forest growth patterns and reasonable values for the input parameters, SMART 2 was calibrated successfully to reproduce present-day soil and runoff water chemistry. This calibrated model was then used to investigate the impact of a partial forest removal from the Kangasvaara catchment on the soil and runoff water chemistry under a future deposition scenario (CRP scenario). These impacts were also compared to the effects of further reducing the deposition of sulphur and nitrate under the maximum feasible reduction (MFR) scenario. The model demonstrates the consequences of breaking the nutrient cycle, and predicts that final cutting results in increased leaching of inorganic nitrogen and base cations from the cut part of the catchment for about 10 years. The resulting concentrations in the stream will depend on the ability of the buffer zones surrounding the stream to capture and utilize these nutrients.

Introduction

Undisturbed forests in Northern Fennoscandia leach very few nutrients as their nutrient cycle is virtually a closed system (e.g. Lepistö *et al.*, 1995; Ahtiainen and Huttunen, 1999). Increased atmospheric nitrogen (N) deposition may lead to 'N saturation' of forest ecosystems, defined as a condition in which N availability exceeds the capacity of plants and soil microbes to accumulate N (Aber *et al.*, 1989; Gundersen, 1991). Forestry practices may, in turn, disrupt the nutrient cycle by removing some of the forest biomass responsible for maintaining the efficient N cycling and leaving some of the biomass on the forest floor available for decay and mineralisation processes. In both cases, there will be an increased leaching of N from the forest soil (Ahtiainen and Huttunen, 1999).

Forestry practices in Finland have, over the last decades included ditching of mires, thinning of young stands, final cutting with associated site preparation before replanting, fertilisation, and construction of forest roads. The forestry practices are modified continuously to respond better to the demands of environmental conservation. The effects of various forestry practices on the hydrology and runoff water quality have been studied using small catchments and reference areas for comparison (Bormann *et al.*, 1968; Finér *et al.*, 1997; Ahtiainen and Huttunen, 1999). This research has evaluated the effects of various forestry measures on surface and groundwater quality, and the effectiveness of retaining different kinds of buffer zones alongside streams and rivers to mitigate the leaching of nutrients and suspended solids to the surface waters.

The development of dynamic modelling approaches may enable an assessment of the impacts of changes in driving forces, such as deposition, climatic variables or catchment land use, on catchment soils and waters. Until the 1990s, the major environmental concern was acidification due to acidifying deposition and both steady-state (De Vries *et al.*, 1994a; Posch *et al.*, 1997) and dynamic models (e.g. Cosby *et al.*, 1985a,b; De Vries *et al.*, 1989; 1994b) have been developed to predict the acidification of soils, lakes, streams and groundwater. While the former are used to estimate the steady state of a system for a given load by neglecting time-dependent processes and finite pools, dynamic models are used to predict the gradual chemical response of a receptor to a changing deposition by including the various

buffer and adsorption/desorption mechanisms. These simple dynamic models have been shown successfully to reproduce the current soil and water chemistry (Posch *et al.*, 1989; Wright *et al.*, 1990; Kämäri *et al.*, 1995).

Recently, the need to study the effects of increased N input and of forest management practices on terrestrial ecosystems have called for more complex models to describe the whole forest nutrient cycle. The NUCSAM model (Groenenberg *et al.*, 1995) is a multi- layer site-scale model with upward and downward solute transport and describes biogeochemical processes on a daily basis. The SMART 2 model (Kros *et al.*, 1995) is an extension to the original SMART model (DeVries *et al.*, 1989) and includes processes of litter fall, mineralization and root uptake of nutrients, as well as canopy interactions, but still being temporally and spatially aggregated. Since the aim of this study is the investigation of the effects of forest felling, SMART 2 was chosen and was applied here to an experimental catchment in eastern Finland (Kangasvaara), using a temporal resolution of one year.

This paper focuses on the analysis of potential long-term annual element fluxes within and out of the experimental catchment. Using the calibrated SMART 2 model, a special emphasis was given to the evaluation of the soil and runoff chemistry changes resulting from disturbances of the nutrient cycle due to forest felling in part of the catchment. Moreover, the effects of likely deposition scenarios are compared to the effects of final cutting.

Materials and methods

SITE DESCRIPTION

The Kangasvaara catchment is a small boreal forested basin (56 ha), located in Northern Carelia in Eastern Finland (Fig. 1), in an area receiving small amounts of acidifying deposition. The main soil types in Kangasvaara are somewhat thin, weakly developed iron podzols, peaty podzols, and shallow fibric histosols (*Sphagnum* peat). The soils are developed on shallow (often less than 2 m thick on slopes), stony to very stony till materials. Most of the catchment (88%) is covered by a 145 year old unmanaged forest which has developed after a forest fire around 1850. Dominant tree species are Norway spruce (54%), Scots pine (30%), and birch and other deciduous forest (16%). In the winter of 1996/97, an area of 17.4 ha was cut and replanting is planned for 1999. Further details on the catchment can be found in Table 1.

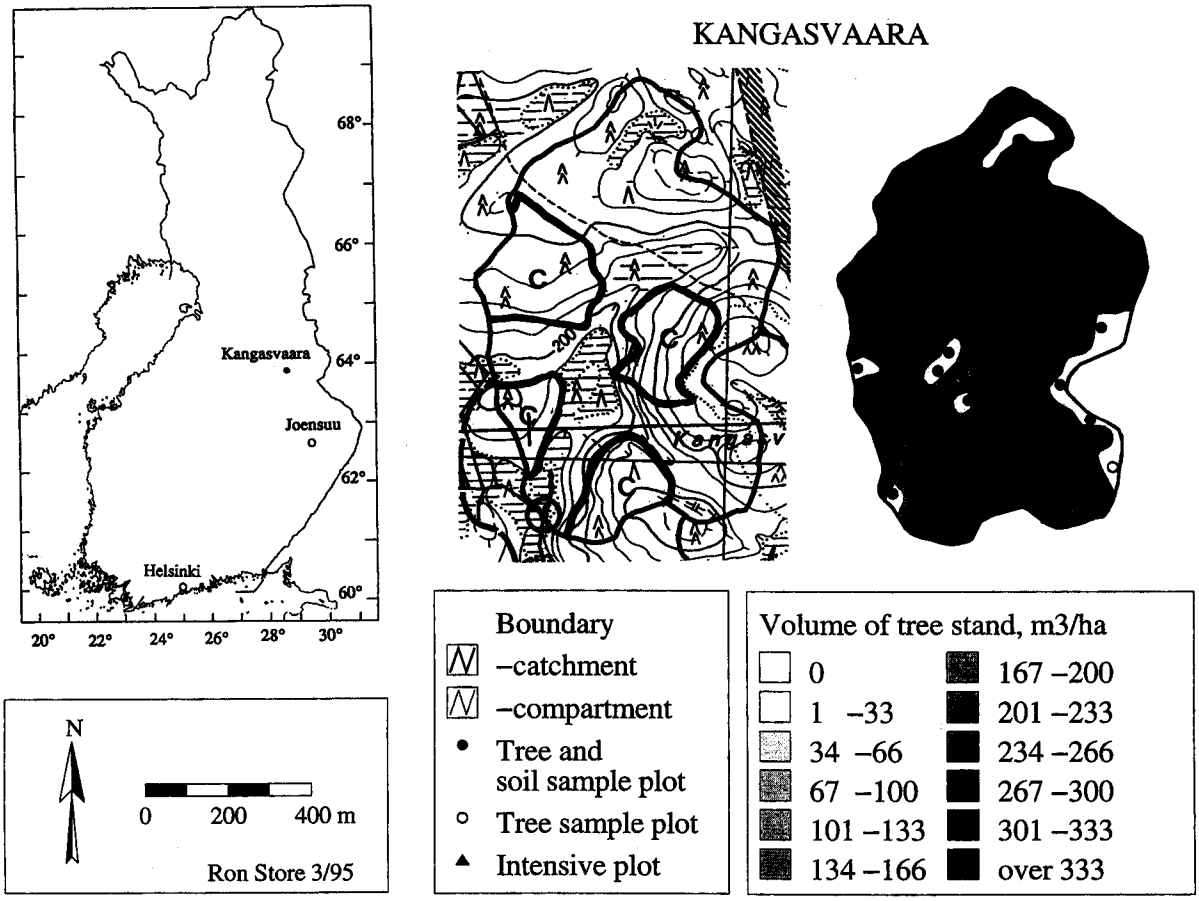

Fig. 1. *The Kangasvaara catchment: location in Finland, topography and landcover (areas cut in fall 1996 indicated by C, weir and runoff sampling site by a large circle), and stand stem volumes and location of permanent sampling plots within the catchment.*

Table 1. Main characteristics of the Kangasvaara catchment (Finér *et al.*, 1997).

Variable	Unit	Value
Latitude	—	63°51′N
Longitude	—	28°58′E
Elevation	m a.s.l.	187
Area	ha	56
Peatlands	%	8
Standing volume	m^3 ha^{-1}	275
biomass	kg m^{-2}	17.2
Soil thickness	m	2.3
Bulk density:		
organic layer	g cm^{-3}	0.18
mineral layer	g cm^{-3}	1.02
Cation exchange capacity (CEC):		
organic layer	meq kg^{-1}	147
mineral layer	meq kg^{-1}	6.13
Organic matter content (topsoil)	kg kg^{-1}	0.11
TOC (runoff, av. 1993–94)	mg C l^{-1}	6.34
C:N ratio (top soil)	—	29
Precipitation (av. 1993–94)	mm a^{-1}	540
Bulk deposition (av. 1993–94):		
SO_4-S deposition	meq m^{-2} a^{-1}	15.97
NO_x-N deposition	meq m^{-2} a^{-1}	7.45
NH_4-N deposition	meq m^{-2} a^{-1}	12.12

The catchment is one of the research areas of the VALU project, which started in 1990 and is carried out by several research organisations with the aim of determining the water and nutrient fluxes at five catchments and the subsequent effects of forest harvesting and soil preparation (Finér *et al.*, 1997). The basic approach is to use paired catchments for which complete water and nutrient budgets can be made. An extensive measuring programme has been established for the catchments and the results of climate/weather, bulk deposition and through fall measurements, soil water fluxes, soil and tree stand characteristics, and the stream water and nutrient discharge covering the pre-treatment calibration period are described by Finer *et al.* (1997).

Standard meteorological data have been collected by an automatic weather station located about 100 m east from the Kangasvaara catchment outlet. The meteorological data includes air and soil temperatures, precipitation, air humidity, solar radiation, wind speed, snow cover and its water content. Tree stand measurements were carried out to characterise the structure and the stem volume of forest compartments. Tree stand variables for compartments were collected from a network of permanent circular measurement plots during 1990–1992 (Finér *et al.*, 1997). Litter fall collection was started in 1992 on three intensively monitored plots in Kangasvaara. Soil sampling was carried out on a selection of the permanent circular tree measurement plots in the catchment. The locations of these different types of monitoring plots in Kangasvaara are shown in Fig. 1.

THE SMART 2 MODEL

The effects of the various scenarios on soil and stream water chemistry were evaluated using SMART 2 (Kros *et al.*, 1995; Mol-Dijkstra *et al.*, 1998), a two-layer soil model which includes a description of the nutrient cycle of a forest. The upper layer in the model includes the ekto-organic soil layers. The lower layer in the model, referred to as the mineral layer, includes the endo-organic layer and the mineral soil. The soil and soil solution chemistry is modeled by SMART (see De Vries *et al.*, 1989; Posch *et al.*, 1993), which is applied to each layer separately and forms an integral part of SMART 2. The growth and maintenance uptake of N and base cations (Ca, Mg and K) by vegetation is driven by a user supplied growth function. The supply of those elements is computed from deposition, weathering (for base cations) and the mineralization of litter and dead roots, which is influenced by water and pH within each layer. Nitrification and denitrification are modelled as simple first order rate processes. The immobilization of N is controlled by the prevailing C:N ratio.

The SMART model is based on the concept of anion mobility by incorporating the charge balance principle

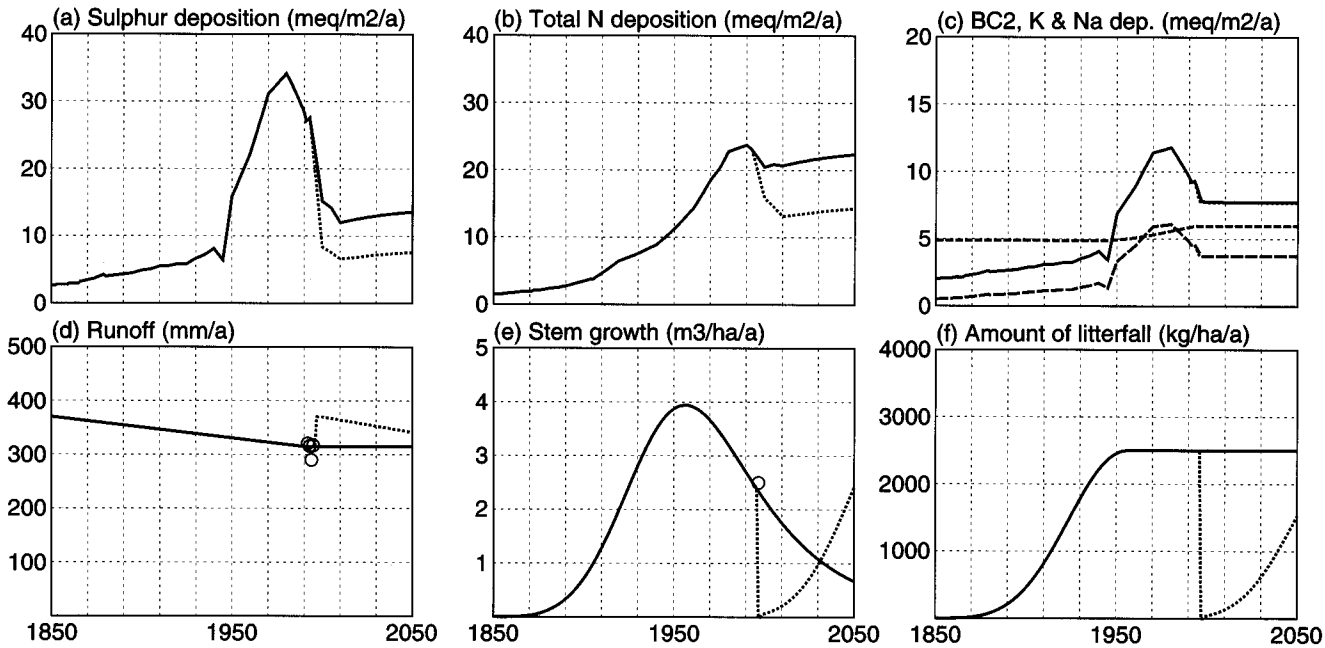

Fig. 2. *Time development (1850–2050) of the variables driving SMART 2: (a) S deposition for the two emission scenarios (CRP solid and MFR dotted line), (b) Total N deposition (CRP and MFR); (c) Deposition of base cations (BC2=Ca+Mg solid line, K long dashes, Na short dashes); their future development is the same in both scenarios; (d) Runoff for both the cut (dotted line) and uncut area (solid line), (e,f) Development of average stem growth and litter fall shown for both for the area of continued growth (solid line) and for the cut and afforested area (dotted line). The one-time contribution of cutting to litter fall (9000 kg ha^{-1}) is not displayed in the figure (f). Circles denote measured total runoff rates and stem growth.*

(Reuss *et al.*, 1986; 1987). The soil solution chemistry is driven by the net element input from the atmosphere, the nutrient cycle and the geochemical interactions in the soil. Solute transport is described by assuming complete mixing of the elements within each layer. The input-output reactions of cations and acidic anions are described by mass balance equations. Equilibrium soil processes are described by equilibrium equations. Sulphate sorption is described by a Langmuir isotherm. The pH value is influenced by all rate-limited and equilibrium processes causing proton production or consumption. In linking SMART to SMART 2, it is assumed that the organic layer is devoid of aluminum hydroxides.

DEPOSITION HISTORY AND SCENARIOS

Site-specific scenarios for deposition, both historical and future scenarios, were derived as described by Johansson *et al.* (1996). In this methodology, later named the DEPUPT model, the deposition of each compound is divided into four different components (wet and dry deposition, and for both of these anthropogenic and sea salt components) using measured bulk and throughfall deposition.

The marine components are calculated using sodium (Na) as a tracer and the marine deposition components are assumed to remain constant over time. The components originating from anthropogenic sources are scaled to present measured values. The dry deposition fraction is taken from the present difference between throughfall and bulk deposition. In the case of N species, the difference may be negative in which case the dry deposition fraction is neglected. The contribution of the forest filtering to dry deposition is modelled as a function of the stem volume. The deposition which cannot be allocated to marine or anthropogenic origin is assigned to canopy exchange.

Starting from present deposition values, both historical and future deposition patterns are constructed. The deposition history for sulphur (S) was extracted from data by Mylona (1996) for 1880–1991 for each EMEP grid cell. Average N histories for the whole of Europe were estimated on the basis of work by Asman and Drukker (1988). The non-marine dry deposition component of base cations was assumed to be partly connected to anthropogenic activities. The historical base cation pattern was assumed to follow the historical S deposition curve. The recent decline in the base cation deposition has been demonstrated both by Finnish measurements, the decline being about 30% between years 1986–1996 at the monitoring station of Valtimo (18 km from Kangasvaara; Finnish Environment Institute, unpublished), and by monitoring data elsewhere in Europe and North-America (Hedin *et al.*, 1994). The same recent trend is reflected in the base cation deposition used as input for model simulations (Fig. 2).

The future deposition scenarios were constructed by making assumptions on the future development of anthropogenic emissions. The future depositions of ammonia (NH_4), base cations and chloride (Cl) were assumed to remain at the present level in the model runs. The future deposition scenarios for S and N were constructed by making assumptions on the future development of anthropogenic emissions and by using a transport model DAIQUIRI (Syri *et al.*, 1998) to calculate the resulting deposition fields. The DAIQUIRI model is used to generate grid-average deposition fields for prescribed country and local emissions. It is based on transfer matrices obtained from the results of two transport models: a mesoscale model for Finland and neighbouring areas (Hongisto, 1992) and a long-range transport model, the EMEP model (Barrett *et al.*, 1995) for the rest of Europe.

Two scenarios for future deposition of S and N are considered in this paper. In the Current Reduction Plan (CRP) scenario, the future deposition of S is derived from 2010 emissions according to the Second Sulphur Protocol (UN/ECE, 1994) and the deposition of N is assumed to stay at the present level. In the Maximum Feasible Reductions (MFR) scenario, the deposition of S is based on maximum technically feasible reductions, and the deposition of nitrate (NO_3) declines by 30% by the year 2010. The historical and future time development of all deposition constituents (S and N for both scenarios) is shown in Fig. 2.

EVAPOTRANSPIRATION AND RUNOFF

Mean annual precipitation for the years 1993/94 has been used for the whole simulation period (Table 1). Evapotranspiration (assumed to include interception) has been estimated with the ASTIM model (Ikonen *et al.*, 1998) for bare soil (170 mm) and fully grown forest (225 mm); intermediate values were obtained by linear interpolation. ASTIM (Areal Surface Transfer Interface Model) is a one-dimensional soil/vegetation/atmosphere transfer model based on the Deardorff model (Deardorff, 1978). The vegetation is described by a one-layer canopy with a characteristic stomatal resistance (big leaf approach). The soil is a two-layer storage of moisture and heat characterised by conductivity, hydraulic potential, thermal conductivity, porosity etc. The model calculates energy fluxes, temperature and soil moisture using synoptic weather observations. Furthermore, it is adjusted and developed for an areal application with defaults for several soil/land-cover classes. It solves the balance equations at the ground and canopy level using energy, moisture and heat equations valid at the idealized land surface. The resulting runoff (Fig. 2) is consistent with measured annual runoff values for 1992–1995.

FOREST GROWTH AND LITTER FALL

The SMART 2 model requires the time development of forest growth and litter fall as driving forces. In the original model formulation (Kros *et al.*, 1995), only a logistic or constant growth could be described. In the latest version of the model, however, an arbitrary growth function can be specified by the user. In this application, a growth curve reflecting observed pine growth in Eastern Finland (Häggman 1994) and calibrated to the present volume and growth rate has been used (Fig. 2). This function is skewed towards a faster growth in the earlier stage of forest development and slower growth for the mature forest. Also, annual litter fall can either be input to the model as a constant value or as a function of time. In this paper, litter fall is assumed proportional to stem growth until maximum growth is reached and this maximum value is retained for subsequent years. Forest growth and litter fall drive the demand for N and base cation uptake using specified maximum nutrient contents in woody biomass and leaves (Table 2).

In addition to the two deposition scenarios, the effects of final cutting, carried out in part (31%) of the Kangasvaara catchment in 1996 (Fig. 1), on the runoff chemistry are investigated in this paper. To simulate this final cutting, the forest growth and litter fall functions were set to zero in 1996 and resumed growth after three years, in 1999, the planned year for reforestation. The temporal development of transpiration and interception were adjusted accordingly (Fig. 2). During final cutting, only stems have been removed; leaves and branches were left in the catchment. Their influence on the nutrient cycle was modelled as a one-time contribution (estimated as 0.9 kg m^{-2}) to the amount of litter in SMART 2 and was then subject to the same decay/mineralization mechanisms as the litter layer. The contribution of stumps and coarse roots as well as of branches was neglected because they contain fewer nutrients and their decay is much slower.

Table 2. Model parameters taken from forests in eastern Finland (Finér, 1989; 1992; Helmisaari, 1992).

Parameter	Unit	Value
Thickness of the rooting zone	m	0.30
Fraction of fine roots in litter layer	—	0.50
Maximum amount of litter fall	kg m^{-2} a^{-1}	0.25
K foliar exudation fraction	—	0.50
N reallocation fraction for leaves	—	0.40
N content in leaves	%	1.60
Ca+Mg contents in leaves	%	0.78
K contents in leaves	%	0.55
N content in stems and branches	%	0.19
Ca+Mg content in stems and branches	%	0.23
K content in stems and branches	%	0.05
Mineralization factor of fresh litter	—	0.35
Mineralization rate constant of old litter	a^{-1}	0.12

MODEL INPUTS AND CALIBRATION

Inputs and parameters for SMART 2 were derived from measurements in the Kangasvaara catchment (Table 1), inferred from other sites in eastern Finland (Table 2), or are the outcome of the model calibration (Table 3). The SMART 2 simulations were started in 1850 (after a forest fire which was assumed to have destroyed all the forest in the catchment) and the time step used was one year, implying that annual averages had to be used and intra-annual variations could not be captured by the model. SMART 2 was calibrated to observed forest growth and soil base saturation measured in 1993, and stream water quality data taken from the years 1993–1996. The annual stream water concentrations were calculated as volume weighted annual averages. The chemical and physical soil properties were calculated as averages for the catchment by weighting over the area and soil layer that each soil sample is assumed to represent. In the soil, complete nitrification and no denitrification is assumed. The former assumption is of minor significance, since the forest at the site is N deficient and SMART 2 assumes preferential NH_4 uptake.

The time development of stem growth and litter fall, deposition of S, N species, and base cations, as well as catchment runoff are shown in Fig. 2. Future depositions (Fig. 2) are depicted for the CRP and MFR scenario, whereas runoff, stem growth and litter fall are shown for both undisturbed growth and for final cutting. The amount of N demanded by forest growth during the first decades after the forest fire in 1850 could not possibly be met by deposition and mineralization. SMART 2 has not been designed to model natural forest succession after a forest fire. The extra N needed to produce the tree biomass described by the growth curve in the early phases of forest development was assumed to be supplied by the mineralization of pioneer N-fixing vegetation after the forest fire, and in the model this missing N was added to the deposited and mineralized N.

The SMART 2 model was calibrated to 1993–1996 observations of soil and water chemistry. This procedure allowed the poorly known parameters used to run the model to be determined. In Table 3, the values of these parameters obtained in the calibration are presented. Given the historical deposition and forest growth patterns and reasonable values for the numerous parameters, SMART 2 was able to reproduce the observed soil and stream water chemistry prior to final cutting.

Results

The calibrated SMART 2 model was used to investigate the impact of forest removal from part of the Kangasvaara catchment on the soil and runoff water chemistry under the CRP scenario. These impacts were also compared to the effects of further reducing the deposition of S and N under the MFR scenario.

The forest fire in 1850 was assumed to destroy all standing biomass and most of the litter layer and to result in a fairly high base saturation both in the organic and mineral top soil. The ensuing forest growth, however, quickly depletes this thin litter layer of base cations and N to the extent that the demand prescribed by the growth curve (Fig. 2) had to be satisfied by assuming mineralization of N from pioneer N-fixing vegetation (see above). The litter layer builds up slowly over about hundred years until an equilibrium with N mineralization rate is reached (Fig. 3). Forest growth peaks in the 1950s, and the N growth uptake follows that pattern. Total N uptake, i.e. the growth and maintenance uptake, peaks in the 1970s and decreases slightly as the forest matures. The base saturation in the mineral soil layer is fairly stable over the whole time horizon. The substantial emission reductions under the MFR scenario show hardly any impact over the next 50–60 years since the deposition values according to the reference (CRP) scenario are already among the lowest in Europe (Fig. 3).

The final forest cutting in part of the catchment greatly alters the internal N cycling within the forest stand. The most pronounced effect is the reduction of total forest N uptake to practically zero in the cut areas (Fig. 4). At the

Table 3. Parameters obtained as a result of the model calibration.

Parameter	Unit	Litter layer	Mineral layer	Water
Ca+Mg weathering rate	meq m^{-3} a^{-1}	10	10	—
Na weathering rate	meq m^{-3} a^{-1}	6	6	—
K weathering rate	meq m^{-3} a^{-1}	2	2	—
Selectivity constant for Al—BC exchange	mol l^{-1}	10	10	—
Selectivity constant for H-BC exchange	l mol^{-1}	$10^{3.5}$	10^5	—
Gibbsite equilibrium constant	l^2 mol^{-2}	10^8	10^8	10^8
Maximum SO_4 adsorption capacity	meq kg^{-1}	0	0	—
pCO_2 (multiple of pCO_2 in air)	—	60	60	2
pK_a	—	4.5	4.5	4.5

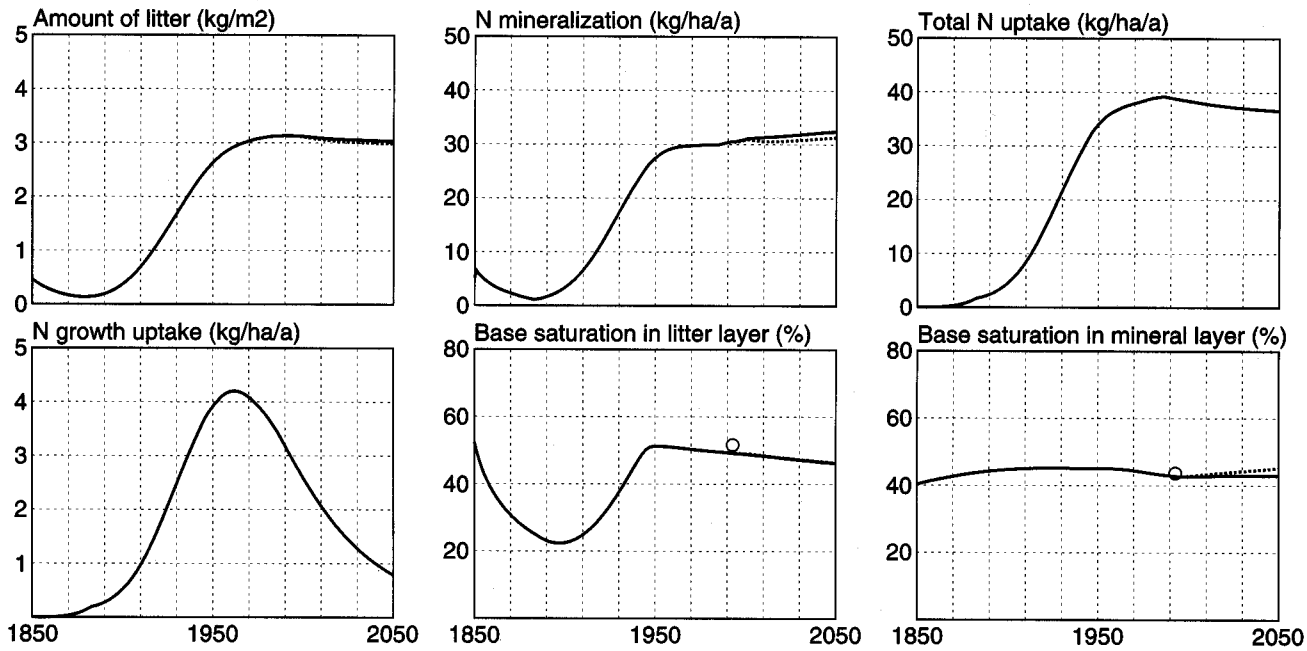

Fig. 3. *Response of the soil in the non-cut area of the Kangasvaara catchment to the two deposition scenarios: CRP (solid lines) and MFR (dotted lines). Measured values are indicated by circles.*

same time as the plant uptake is reduced, cutting adds leaves and branches to the litter layer. This one-time contribution to the nutrient cycle at the time of cutting, estimated at 9 000 kg ha^{-1}, represents about three to four years of litter fall. This leads to a peak in the N mineralization rate to values above 50 kg ha^{-1} a^{-1}. There is very little new litter fall, however, and, therefore, after some years, mineralisation decreases to values that are much smaller than before cutting, until the regrowing forest is developed enough to produce significant amounts of litter to be mineralised.

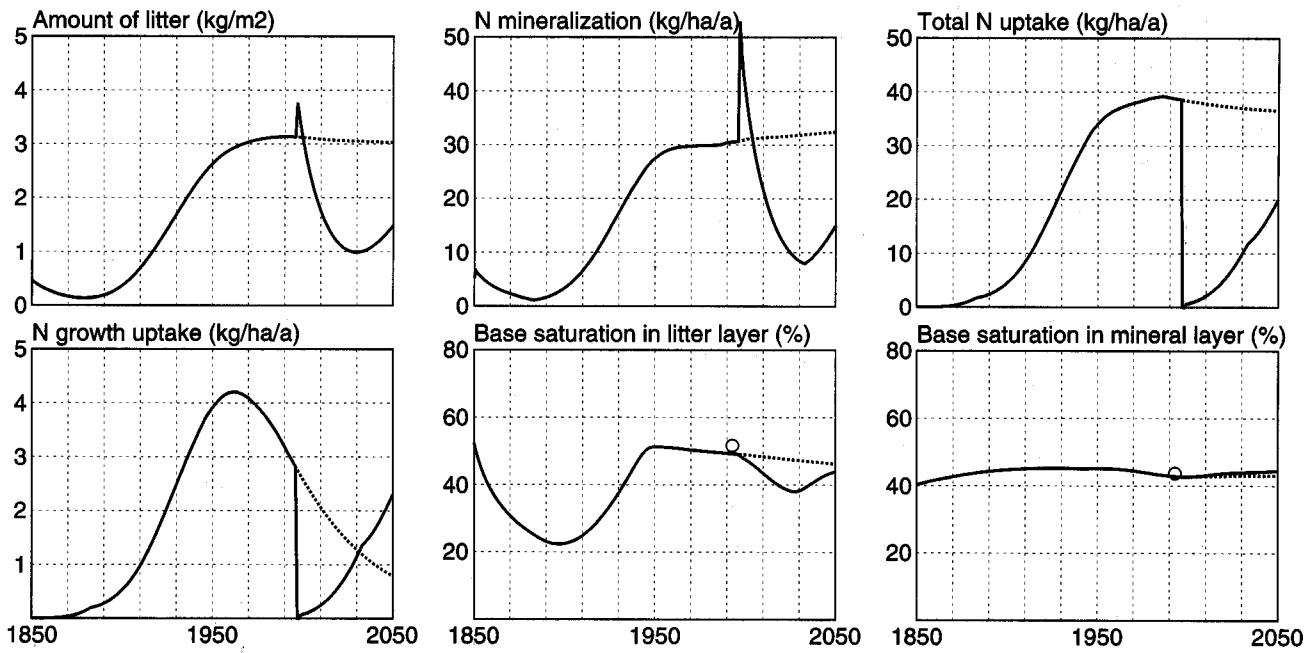

Fig. 4. *Response of the soil in the Kangasvaara catchment to the CRP scenario for the un-cut (dotted lines) and cut (solid lines) areas. Measured values are indicated by circles.*

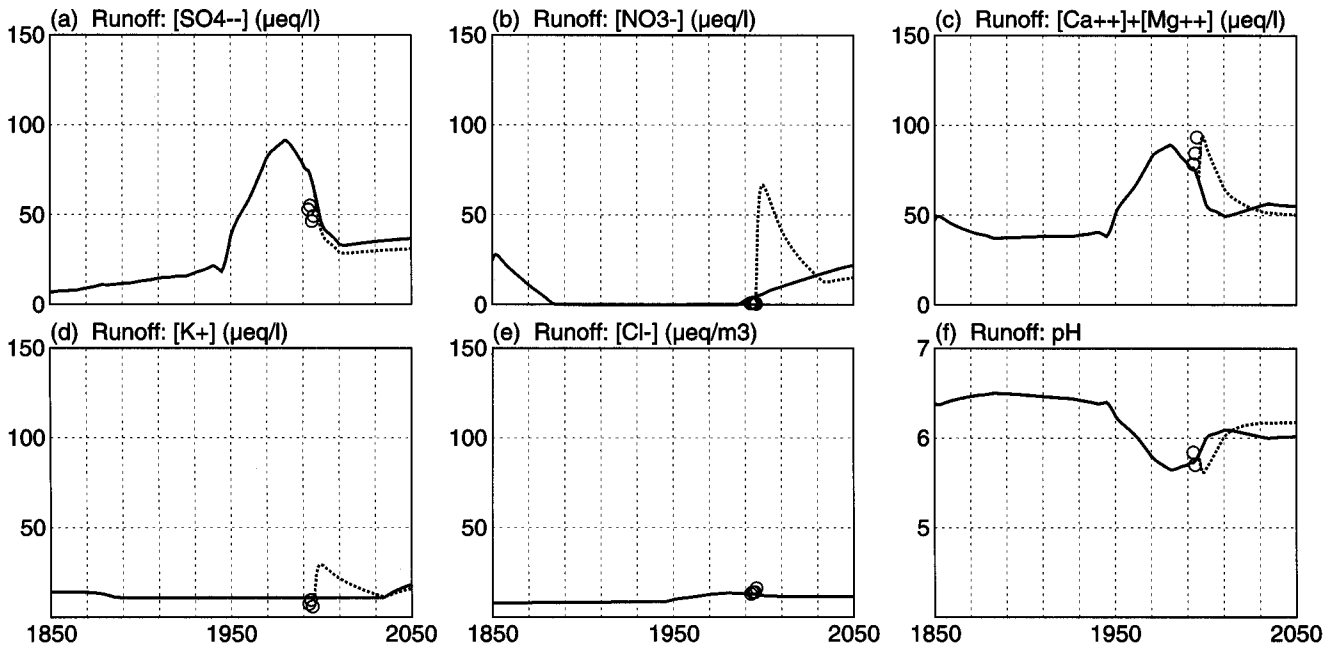

Fig. 5. *Chemistry of the catchment runoff for the CRP scenario with 31% of the area cut in 1996 (dotted line) compared with the hypothetical case of no cutting (solid line): (a) SO_4, (b) NO_3, (c) divalent base cations, (d) P, (e) Cl, and (f) pondus Hydrogenii. Measured values are indicated by circles.*

The forest is replanted after cutting, and the total uptake starts to increase but is still lower at the end of the simulation (2050) than before cutting. The N growth uptake, however, increases over about 50 years to values that are about without cutting, i.e. to values for an ageing forest. After cutting, enough mineralized nutrients are available to maintain rapid growth of the forest. This rapid growth, however, consumes base cations so that the base saturation of the litter layer decreases slightly, while the change of base saturation in the mineral layer is hardly discernible (Fig. 4).

The changes in the runoff water chemistry depend on the changes in the leaching from the areas with final cutting as well as on their distribution and size within the catchment. In the model, the runoff waters from the cut areas are mixed (area-weighted) with the waters from the uncut areas. From the date of cutting onwards, the development of the catchment runoff water was modelled separately for both cases, for the final cutting (31%) in 1996, and for the hypothetical case of no cutting at all (Fig. 5).

Assuming no cutting, the model predicts a decrease in base cation concentrations and a slow increase in NO_3 concentrations for the years to come. The increasing NO_3 concentrations demonstrate a small excess of N supply (deposition + mineralisation) over N demand (uptake + immobilisation). The response of the base cations reflects not only the recent decrease in base cation deposition, and the decrease in base cation uptake due to the ageing of the forest but, even more importantly, the decreased leaching associated with decreased leaching of strong acid anions.

After cutting, the model predicts a pulse of NO_3, increasing from 0 to 60 μeq l^{-1}, potassium from 15 to 30 μeq l^{-1}, and divalent base cations from 75 to 95 μeq l^{-1}. These pulses start to decrease immediately as mineralisation slows down and uptake increases and it takes about 30–40 years to reach the levels of the undisturbed forest. There is also a small but noticeable effect on the SO_4 concentration (due to reduced deposition to the cut areas), and the acidity of the runoff water.

Discussion

No attempts to model the nutrient dynamics and long-term responses of soil and water chemistry to a final cutting within parts of a catchment are known. However, there have been modelling studies which take account of some aspects of afforestation/deforestation. Neal *et al.* (1986) considered the effect of changes in runoff following afforestation on soil and water chemistry. Later, the combined effects of runoff, canopy-enhanced dry deposition and net growth uptake of base cations was taken into account (Cosby *et al.*, 1990; Ferrier *et al.*, 1993). Finally, Wright *et al.* (1994) scaled up predictions about effects of afforestation to a region, taking net uptake of base cations into account as the most important variable. In the present study, the combined effects of runoff yield, deposition and the full nutrient cycle have been considered to allow an assessment of the historical and future development of soil

chemistry and water quality in the catchment. The incorporation of the nutrient cycle into the model enables the predictions of medium-term peaks in nutrient fluxes following a forest felling.

In the calibration of the historical forest development at the Kangasvaara catchment, the main problem was to satisfy the N demand of the growing forest. The forest biomass in the area is high and the overall availability of N is small. This results in a lack of N during peak growth. The original model formulation did not include N fixation, but to make up for the discrepancy between supply by deposition and by mineralisable litter and demand for growth, a term corresponding to this apparent N deficit was introduced into the model.

In SMART 2, N mineralisation is modelled as a function of soil pH and C:N ratio in the litter layer with mineralisation slowing down and ceasing completely at higher C:N ratios. It was, however, decided not to apply the C:N reduction function in this application. Nitrogen has clearly been, and still is, the growth limiting factor for the forests in the region. Consequently, the C:N ratios in the humus layer of Finnish forest soils can be very high, up to 90 (Tamminen and Starr, 1990). Laboratory experiments have indicated that even C:N ratios above 80 do not inhibit N mineralisation (Rankinen, 1992). Furthermore, there is evidence that the C:N ratio is not always sufficient to describe mineralisation, since organic compounds may be in a form that the micro-organisms cannot utilize (Jansson and Persson, 1985). Therefore, to allow mineralised N to enter the forest soils and maintain the forest growth suggested by the standard growth curves, the mineralisation was allowed to continue independent of the C:N ratio, as an exponential function of the amount of litter.

The results from studies of small catchments have revealed that, for some years after the forest felling, there is an enhanced leaching of nutrients from clear-cut areas. However, any buffer zones left between the felling site and the stream have proved efficient in capturing the loading of suspended solids as well as phosphorus and N compounds so that they prevented from entering the surface waters (Ahtiainen and Huttunen, 1999). Therefore, since there is a clear *Sphagnum* peat strip in Kangasvaara surrounding the stream, it is probable that most of the nutrient amounts predicted to be leached from the cut areas will never reach the stream. However, they will most likely increase concentrations in the groundwater. The developments of inorganic N concentrations predicted by SMART 2 for runoff are consistent with groundwater concentrations obtained in clear-cut catchments of experimental areas some 100 km North-West of Kangasvaara (Kubin, 1998). In these areas, NO_3 concentrations in the groundwater continued to rise for 5–7 years after the clear-felling, reached clearly elevated values (40–60 μeq/l), and remained high for 10 years after treatment.

Naturally, the reliability of the calibration and the reconstruction of the forest and soil and water chemistry depend on the selected pattern for the deposition history. The difference between actual and derived history is likely to be largest at sites where the local sources for air pollutant emissions dominate (Forsius *et al.*, 1997). For Kangasvaara, no large emission sources of N or S are near the site, and therefore, the use of a generic European emission/deposition pattern for N should be warranted.

At present, the annual export flux of NO_3 from Kangasvaara is extremely low (<1 kg N km^{-2} a^{-1}) as compared to any other forested area in Fennoscandia (Lepistö *et al.*, 1995) or Europe (Gundersen, 1995). The soils in Kangasvaara are coarse and poor in nutrients, and the atmospheric deposition in the area is small (Finér *et al.*, 1997). In addition, there are small bogs in the catchment, which may well retain N. Therefore, the prediction of the true behaviour and dynamics of the catchment would require a thorough flow routing of the runoff, together with a description of the release/retention processes of peat soils.

Conclusions

Despite the uncertainties and shortcomings in the model structure, SMART 2 was able to reproduce the present-day soil and runoff water chemistry, the historical deposition and forest growth patterns and reasonable values for the parameters. The predictions of the model for the chemical effects of forest cutting seem plausible and they coincide well with the long-term changes observed in the groundwater in a similar clear-cut catchment north of Kangasvaara.

The model demonstrates the consequences of breaking the nutrient cycle and predicts that the final cutting on parts of the catchment will result in increased leaching of inorganic N and base cations from the cut part of the catchment for about 10 years. The resulting concentrations in the stream will depend on the capability of the buffer zones surrounding the stream to capture and utilize these nutrients.

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