Changes in Solute Chemistry of Drainage Waters Following the Clearfelling of a Sitka Spruce Plantation

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SUMMARY

Water was collected weekly from the ditch systems of two plots, one draining standing forest, the other ground felled at 35 years of age. Before felling, the mean concentrations and annual export of ions were similar. In the first year after felling both water yield and the mean concentrations of potassium, nitrate, ammonium, phosphate and iron increased, compared with the standing forest, so that the export of these ions increased greatly. Except for ammonium, these levels were maintained in the second year after felling. Concentrations of those ions predominantly deposited from the atmosphere, sodium, sulphate and chloride, decreased relative to the control plot, although there was no reduction in amounts exported until the second year after felling. Concentrations of calcium and magnesium also decreased relative to the control plot but export increased, before falling in the second year after felling. Aluminium concentrations did not change but export increased in the first year following felling. Acidity (pH) of drainage water did not differ significantly between the plots in any year.

In terms of drainage water quality, these data suggest that the impact of clearfelling on this site type is not great though it could temporarily increase the reported differences between coniferous forest and grassland.

INTRODUCTION

The clearfelling study carried out at the Hubbard Brook experimental catchments, USA (Likens *et al.*, 1970) showed marked changes in drainage water chemistry and solute outputs following felling. These results caused concern about nutrient loss from sites and the impacts of clearfelling on water quality. Since this pioneering study many related investigations have been carried out in a number of countries (e.g. Dyck, Webber and Barton, 1981; Krause, 1982; Nykvist and Rosén, 1985). These have examined, for example, the variation in the impacts of clearfelling with site conditions and the processes controlling element release and export. Despite the large area of

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British forest to be felled before the end of the century, there are no published data from Britain. The site conditions and silvicultural methods used in the recently established forests of upland Britain, contrast with those in countries in which studies have been carried out. The present study is one of a series now in progress, designed to investigate the impact of felling these first rotation upland plantations, in terms of nutrient loss and drainage water quality.

SITE

The study used two adjacent plots of a drainage experiment in Kershope Forest, Cumbria (Pyatt *et al.*, 1985). The site, formerly upland grassland dominated by *Molinia caerulea* (L) Moench, was ploughed and planted with Sitka spruce (*Picea sitchensis* (Bong.) Carr.) in 1948. The drainage experiment comprises three blocks, each containing six plots, with a range of drain spacing and two depths. The drains were dug between 1965 and 1968. The plots used in the present study (Block 1, Plots 5 and 6 in Pyatt *et al.*, 1985) are each approximately two hectares; they have a slope of 3° and an easterly aspect. The soils are Cambic stagnohumic gleys (Avery, 1980) developed in clay-rich till derived from the underlying Carboniferous rocks. The thickness of the surface organic horizon averages 33 cm (control plot) and 31 cm (experimental plot). The till, originally calcareous, has become decalcified to a depth between 75 and 150 cm. The water table fluctuates between 30 and 80 cm depth below ground surface. Drains in both plots are at 20 m spacing but they were dug to 90 cm on the control plot and 60 cm on the experimental plot. The plots are bounded by deep drainage ditches, to prevent lateral flow onto or off the plots and the drainage water from each plot is led away via a main exit drain. Hydrological studies have indicated that very little water is lost by percolation below the levels of these drains.

Nine of the 18 plots of the drainage experiment were clearfelled in 1982 and 1983, yielding 362 m^3ha^{-1} of timber. One of the two plots used in the present study was felled (referred to here as the felled or experimental plot) between April and November 1983 (age 35 years, Forestry Commission General Yield Class 16), the other plot being an unfelled control. At felling, slash was left on site, in common with routine forest practice in the area, and timber was extracted by cable crane to avoid damage to the drains. After felling, the drains were cleared by hand of any material which had fallen in during felling and extraction. This process also removed spruce needles which had accumulated since the previous clearing of the drains. The drains of the unfelled, control plot were also cleared to ensure comparability.

Prior to felling, ground vegetation was absent except for small areas of bryophytes. After felling revegetation was slow, amounting to about 25 per cent of the area, after two years.

METHODS

Drainage water, from the main exit drain of each plot, was sampled at weekly intervals. To ensure that samples were taken from moving water, a 2 m length of 15 cm diameter PVC pipe was installed in the floor of each exit drain so that all water leaving the plot was channelled through it. Discharge was monitored continuously, downstream of each sampling point, with a chart recorder above a V-notch weir. The instantaneous flow was recorded at each sampling. A small number of flood event samples were taken in the four year period.

Precipitation was sampled using a PVC and polyethylene sampler (Stevens, 1981) sited approximately 100 m from the study plots in an area of newly planted forest. The upper rim of the sampler was 500 mm above the ground. Samples were collected weekly. Precipitation volumes were recorded separately using a ground level gauge (Bucknell, Hill and Newson, 1977).

In the laboratory, drainage water and precipitation were treated in the same way. The pH of a subsample was measured using a combination electrode. The remaining sample was filtered through a glass fibre filter (Whatman GF/F rinsed with distilled water). Calcium, magnesium and iron were determined by atomic absorption spectrophotometry and sodium, potassium and aluminium by flame emission spectrometry. The molybdenum blue method with $SnCl_2$ reductant was used for phosphate-P (Allen *et al.*, 1974). Nitrate was reduced with hydrazine and the NO_2 determined using the Griess-Ilosvay method (Rowland, Grimshaw and Rigaba, 1984). The indophenol blue method was used for ammonium-N (Rowland, 1983) and the thiocyanate method for chloride (Allen *et al.*, 1974). Sulphate-S was determined by the barium chloride turbidimetric method.

RESULTS

Data are presented for 1982, the year before felling, 1983, the year of felling, and 1984 and 1985, the first two years after felling. Annual precipitation input and drainage water discharge for the four years is given in Fig. 1. Precipitation in 1982 and 1985 was well above the annual average for the site of 1250 mm (Meteorological Office, 1977); in 1983 and 1984 it was about average but these two years, particularly 1984, had drier than average summers. The two years after felling thus differed markedly in annual precipitation. In the year before felling, drainage discharge from the experimental plot was only 11 per cent more than that for the control plot, but in the first year after felling it was more than double that from the control. This difference also occurred in the second year after felling but was less marked than the first year.

Mean annual pH for precipitation and drainage water are given in Table 1. pH is consistent between years with no marked change after felling.

Mean annual solute concentrations for the drainage waters are given in

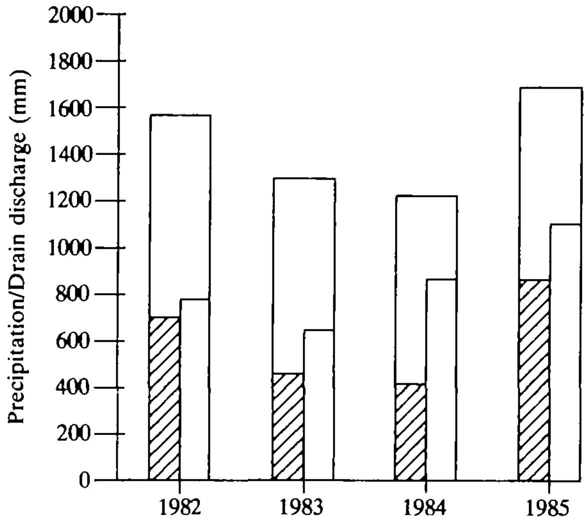

Figure 1. Annual precipitation input and drain discharge. The wide bars represent precipitation and the narrower bars represent control plot discharge (hatched) and experimental plot discharge (open).

TABLE 1. *Annual mean pH, calculated via H ion concentration, for precipitation and drainage water.*

	1982			1983			1984			1985		
	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.
Precipitation	4.0	4.5	5.4	3.8	4.3	5.3	3.9	4.5	5.4	3.7	4.2	5.4
Control plot drainage	3.8	4.1	4.4	3.7	4.0	4.6	3.8	4.0	4.5	3.7	3.9	4.3
Experimental plot drainage	3.7	4.0	4.4	3.6	3.9	4.4	3.7	3.9	4.1	3.5	3.8	4.1

Figure 2. Before felling, although the concentrations of a number of ions are lower for the experimental plot than the control, differences are small. Following felling there are large differences between the solute concentrations for the two plots. In drainage water from the experimental plot, potassium, iron, nitrate, ammonium and phosphate concentrations increased following felling while calcium, magnesium, sodium, sulphate and chloride concentrations decreased, relative to the control plot. The data from the control plot show considerable year to year variations for all solutes, but these are smaller than the changes produced by the felling of the experimental plot.

Figures 3 and 4 show the temporal variation of discharge at sampling, pH and the concentrations of three ions, during the year before and the year after felling. For all five plots in 1982, the two lines follow each other very closely; potassium concentrations tended to be higher in the summer, sulphate levels were highest in October, while nitrate showed no clear seasonal pattern. Throughout 1984, nitrate concentrations were higher in the drainage waters from the felled plot than in those from the control. In summer, concentrations peaked after periods of low flow on both plots; in autumn and winter, concentrations were unrelated to flow. Potassium concentrations were higher in the drainage waters from the felled plot during the winter months of 1984, but lower than those of the control plot during summer months. Sulphate concentrations in drainage water from the felled plot were lower than those from the conrol throughout 1984; the difference between the two plots was most marked in winter. The increase in drain discharge following felling is clear from these diagrams. Throughout 1982, flow rate at the time of sampling was similar for the two plots. In 1984 flows were higher from the felled plot on almost every occasion; the difference between the plots was most marked at high flows. Despite 1984 having a relatively dry summer, the drain from the experimental plot ceased to flow on only two sampling dates. Flow from the control plot ceased for long periods, twelve sampling dates being dry. Prior to felling there is a slight summer peak in pH in both plots. In 1984, although a similar peak is present for the control plot, it is absent from the felled plot. This may reflect the higher discharges from the felled plot; whatever the cause, the effect is not sufficient to produce a difference in the annual mean pH.

Annual solute fluxes in precipitation and drainage water are shown in Fig. 5. Inputs in precipitation were calculated from the weekly data on precipitation volume and solute concentrations. Outputs in drainage water were derived by multiplying total annual discharge by annual discharge-weighted mean concentration. Dann, Lynch and Corbett (1986), working with sulphate data, examined errors associated with different methods of calculating outputs in drainage water, and concluded that this method tended towards underestimation. Variations in solute outputs from the control plot, from year to year, are quite marked; for most ions these variations are strongly related to the annual volume of precipitation. Uprooting of trees by the wind along the edge of the control plot, adjacent to the felled area, probably contributed to higher values for the control plot in 1985. The export of most solutes from the experimental plot increased significantly after felling, compared with the control. In the first year after felling large increases are shown by potassium (× 5), nitrate (× 5), ammonium (× 9) and iron (× 5). Although phosphate also increased several fold, values were still below 0.5 kg $ha^{-1}y^{-1}$. In the same year, outputs of calcium and magnesium increased and sodium, sulphate and chloride remained constant even though the mean concentrations declined after felling compared with the control plot; the increased water output more than balanced the reductions in concentration. For potassium, iron, nitrate and phosphate the elevated rate of export continued in the second year after felling, even when allowance is made for

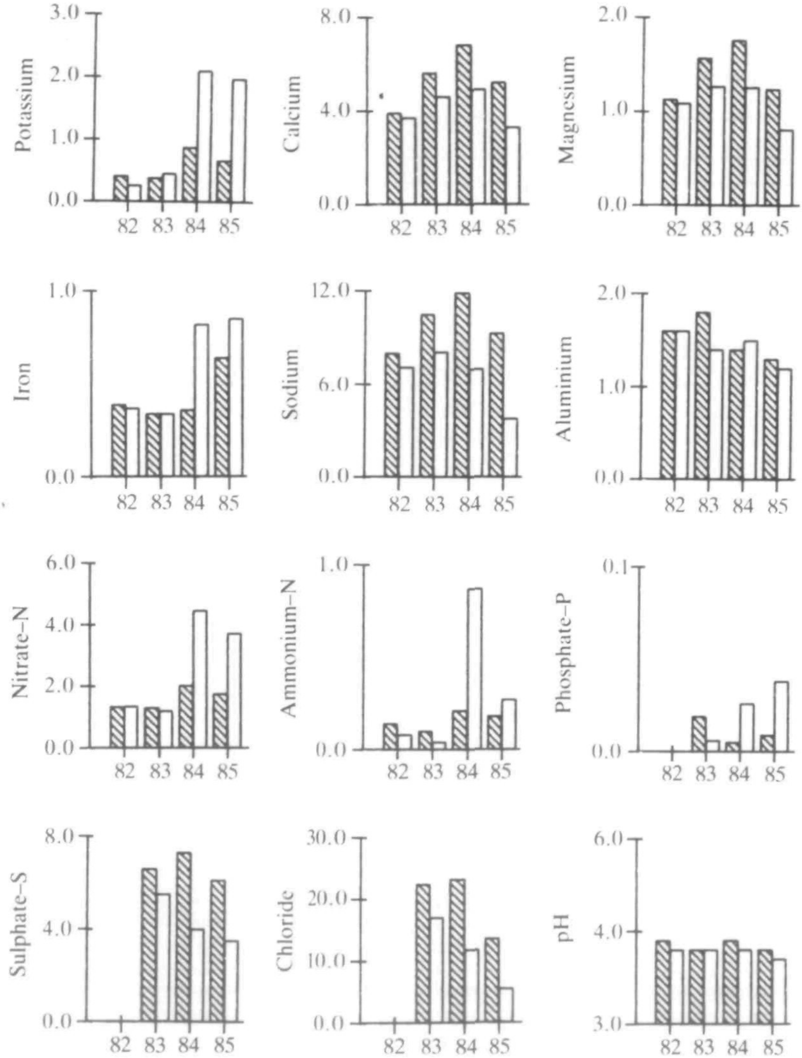

Figure 2. Mean annual discharge-weighted concentration of ions (mg l^{-1}) and pH of drainage water. The hatched bars refer to the control plot and the open bars to the experimental plot. SO_4-S and Cl data are not available for the whole of 1982, and have therefore been omitted.

changes in the rate of export from the control plot. However, less calcium, magnesium, sodium, sulphate and chloride were exported from the experimental plot than from the control plot in the second year. Aluminium and ammonium were exported in similar quantities from both plots. Prior to felling, solute inputs of potassium, ammonium and phosphate exceeded solute exports. After felling solute outputs in drainage water exceeded

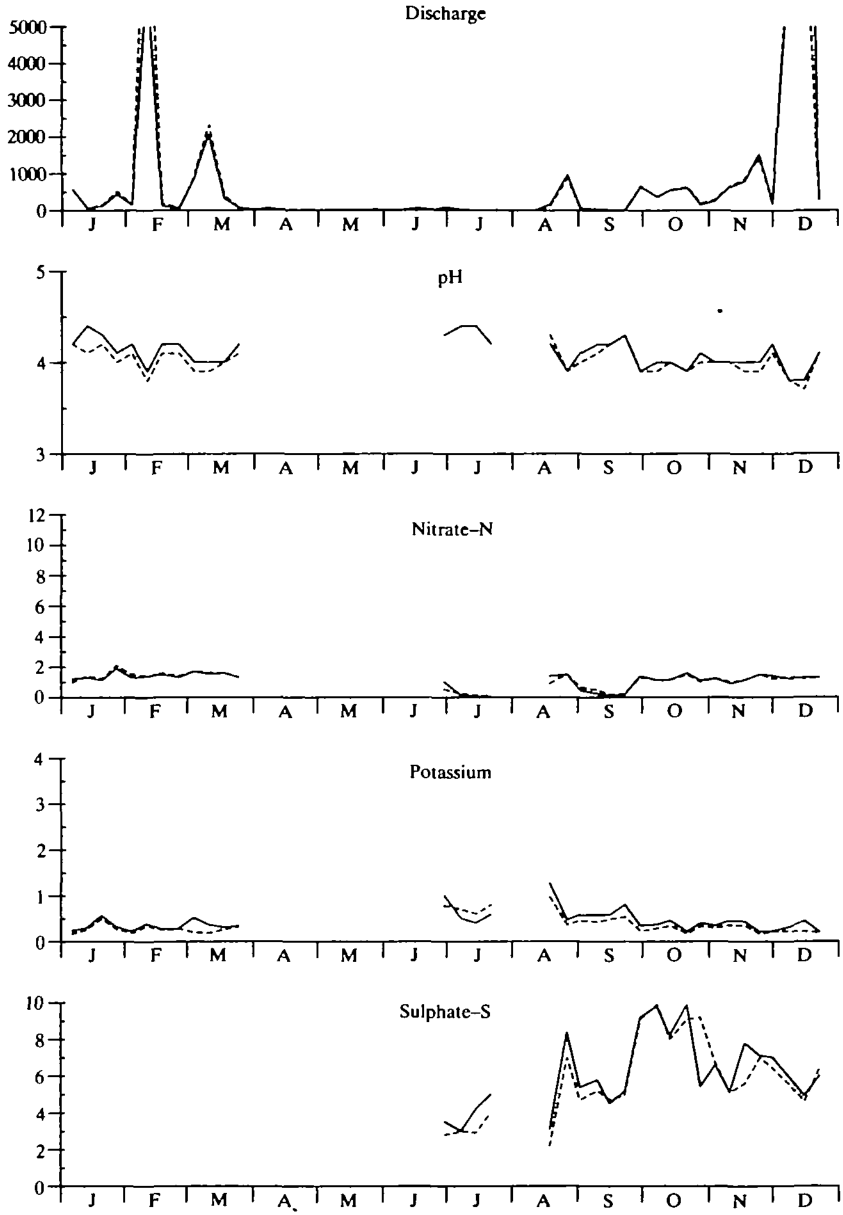

Figure 3. Seasonal patterns of drainage discharge at sampling ($cm^3 s^{-1}$), pH and the concentrations of three ions ($mg\ l^{-1}$), 1982. The control plot is indicated with a continuous line and the experimental plot with a broken line. Sulphate data are not available for the early part of the year.

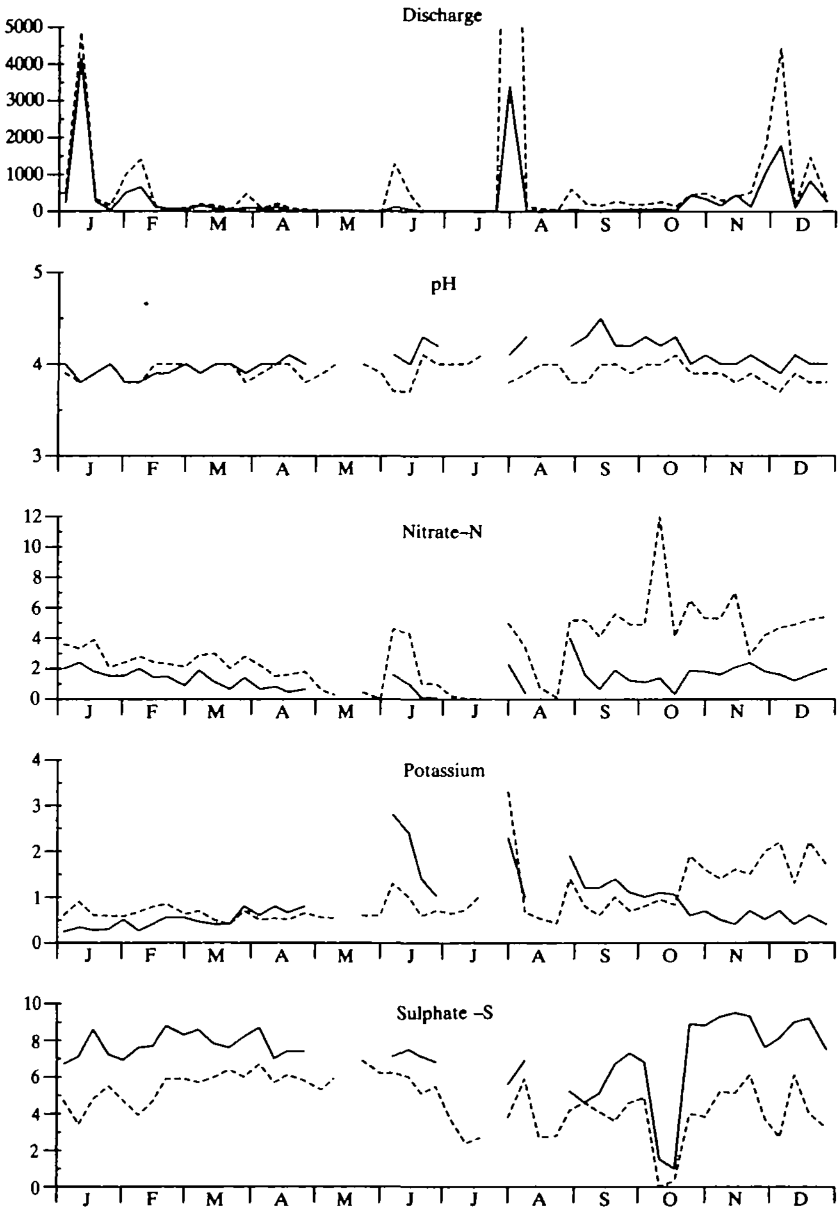

Figure 4. Seasonal patterns of drainage discharge at sampling, pH and the concentration of three ions, 1984. Units and key as Figure 3.

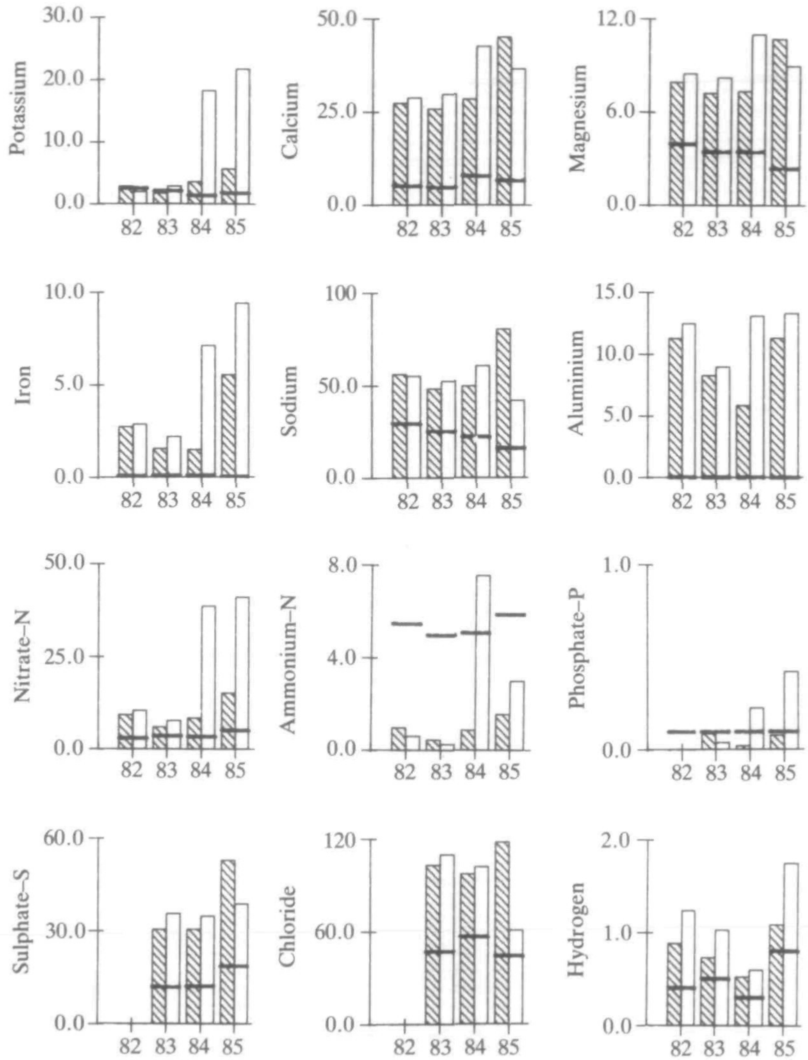

Figure 5. Export of ions dissolved in drainage water (kg ha^{-1} y^{-1}). The hatched bars refer to the control plot and the open bars to the experimental plot. Annual precipitation inputs are indicated by bold horizontal lines. SO_4-S and Cl data are not available for the whole of 1982, and have therefore been omitted.

precipitation inputs for all measured ions, with the exception of ammonium in 1985.

DISCUSSION

The results presented above clearly indicate changes in the rate of release of nutrients, and other ions, into drainage waters following clearfelling. These changes will result from alterations in the rate and pattern of a number of controlling processes, e.g. Vitousek (1983). The removal of the tree canopy reduces the rainfall interception and halts transpiration losses until revegetation, which results in wetter soils (Pyatt *et al.*, 1985) and increased fluxes of water through the site. Canopy removal also reduces filtering of elements from the atmosphere. Needle and branch fall ceases to be a continuous, slow process and is replaced by a single major input of slash. The removal of the tree halts root uptake from the soil and makes the entire root biomass available for decomposition. The climate of the site is modified, resulting in a more variable temperature regime, which will influence the decomposition of the litter layer, as well as of the slash and roots. In addition to changes in the rate of decomposition as a result of changes in the physical environment, Gadgil and Gadgil (1978) have demonstrated that the decomposer organisms are released from suppression at felling; they attribute this suppression to mycorrhizas. These various processes are all interlinked and will affect different ions in different ways.

Concentrations and outputs of the biologically most important ions — potassium, nitrate, ammonium and phosphate — all increased after felling. Potassium is only loosely held in plant tissues and a rapid release of this ion, from the felling debris, into drainage water is not surprising. The phosphate present as nucleic acids, in the tissues of the felling debris could be mineralised relatively quickly. Some of this phosphate may be leached out into drainage waters during wet periods. Cessation of root uptake will also be an important factor, particularly as there was no ground vegetation before felling. Prior to felling, recorded inorganic nitrogen inputs to the site were almost equivalent to outputs in drainage waters. As the bulk precipitation collector almost certainly underestimated dry deposition of nitrogen, total inputs most probably exceeded outputs. Release of ammonium and nitrate from the felling debris is unlikely during the early stages of decomposition (Swift, Heal and Anderson, 1979); in fact, there are indications from current work at the site that the slash acts as a sink for atmospheric inputs of inorganic nitrogen. The increased outputs must be derived from soil sources, becoming available in the absence of root uptake. The formation of nitrate involves the release of hydrogen ions and is thus a potential source of increased drainage water acidity.

Sulphate, sodium and chloride are the ions deposited in greatest quantities from the atmosphere. Following removal of the trees the capture of these ions from the atmosphere as aerosols, gaseous and particulate material, could be expected to decline. Although in the first year after felling concentrations of these ions in drainage water did decline, total output of these ions from the experimental plot actually exceeded the output from the control plot. It was not until the second year after felling that both concentrations and total outputs of these solutes declined on the experimental plot. This lag suggests that it takes some time for accumulations of these ions to be leached from the soil. The removal of root uptake may also be an important factor in the short term; data from a site in north Wales indicate considerable annual cycling of all three ions (Stevens pers. comm.).

The increased outputs of calcium and magnesium from the experimental plot in the first year after felling probably reflect the combined effect of biological and physico-chemical processes. Increased decomposition and decreased root uptake could both increase the available, mobile pool. Ion exchange in the soil, driven by the increased nitrate flux, could displace calcium, magnesium and aluminium into solution. The glacial till is exposed in parts of the ditch system and may also be important, providing a pool of readily released calcium. Aluminium is most probably mobilised by ion exchange or dissolution from soil sources. The decreased export of these three ions in the second year after felling may be a consequence of the decreased export of the sulphate and chloride, when accumulations of these anions in the soil became depleted.

It has been demonstrated, at other upland sites with acid, organic soils, that iron in drainage waters is linked to organic matter (Grieve, 1984). The increased throughput of water following felling could have increased the mobilisation of dissolved organic matter and iron.

In terms of water quality, this study represents a worst possible case for this type of site; water is collected directly from drains before any effects have been ameliorated by riverine processes. These processes include reaction with the channel floor and uptake by organisms. In routine forestry it is unlikely that an entire water supply catchment would be clearfelled over a short period, and thus elevated concentrations would be diluted by water from standing forest or grassland. Although the concentration of nitrate increased several fold following felling, the concentration was in excess of the limit recommended by the World Health Authority on only one occasion. Phosphate was detected in drainage water more frequently following felling, but the quantities exported from the site were not high, suggesting that clearfelling is unlikely to lead to algal blooms in lakes or reservoirs. Phosphate concentrations were generally lower than those reported by Harriman (1978), for streams draining standing forest which had been fertilised. Harriman and Morrison (1982) have demonstrated that Sitka spruce forest can increase the acidity of drainage water. It is significant therefore that at Kershope, in the first year after felling, there was no marked change in drainage water pH, in view of the increased export of nitrate occurring while export of sulphate remained high. At sites less well buffered by calcium further acidification of drainage water could occur as a consequence of clearfelling. These data suggest that, although the impact of clearfelling on drainage water chemistry is not great, it could temporarily increase the reported differences between coniferous forest and grassland.

A longer run of data is needed to evaluate fully the nutrient losses in drainage waters after clearfelling, and to calculate total losses from the site. It is clear, however, that in the first year after felling the output of the major plant nutrients in drainage waters is greater than the input in rainfall. Results from other sites have shown that, for some ions, such a net export can continue for several years, e.g. Likens *et al.* (1978). The soils at Kershope are not regarded as particularly nutrient deficient and no fertilizer was applied during the first rotation. The losses at this site may not, therefore, have any significant impact on tree growth in the second rotation. This is in line with management experience, on similar soils, where second rotation crops have not required fertilizer to date.

On this site at Kershope Forest some significant changes consequent upon clearfelling have been identified, but the fact that these are unlikely to have significant implications for water quality or site fertility may be in part a feature of the site. At sites where there were nutritional problems for the first rotation, fertility and even water quality could be further impaired by clearfelling. Thus, it is important that we understand the processes controlling the changes in solute outputs so that we can better predict the likely impact on soil and water at other locations. Continuing work at Kershope and other sites is focussing on these processes.

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