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Effect of harvest intensity and ground flora establishment on inorganic-N leaching from a Sitka spruce plantation in north Wales, UK

P.A. STEVENS[1] & M. HORNUNG[2]
[1]*Institute of Terrestrial Ecology, Bangor Research Station, Penrhos Road, Bangor, Gwynedd, LL57 2LQ, UK;* [2]*Institute of Terrestrial Ecology, Merlewood Research Station, Grange-over-Sands, Cumbria LA11 6JU, UK*

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Abstract. Inorganic-N concentrations in soil solution of whole tree harvest (WTH) and conventional fell (CF) plots were monitored for two years before felling and four years after felling. Concentrations in the mineral soil after felling were higher than in standing forest for up to 14 months in both felling treatments. In the WTH plots inorganic-N concentrations then dropped steadily until four years after felling they approached zero. In contrast, inorganic-N concentrations of the CF plots remained comparatively large. Inorganic-N was dominated by nitrate throughout the period of the study, and especially in the mineral horizons.

Felling debris was not a source of inorganic-N, unless indirectly through release and mineralisation of soluble organic-N. Vegetation cover, biomass and N content were substantially greater in the WTH plots two to three years after felling, compared with the CF. Vegetation cover and brash cover (slash cover in N. America) were negatively correlated. There was also a negative correlation between inorganic-N concentration in soil water samplers and the vegetation cover within the collection area of, or a 1 m square surrounding, these samplers.

Two factors are probably responsible for the reduction in inorganic-N concentrations after felling in the WTH — the rapid re-establishment of vegetation and the lack of a N source in felling debris. In the CF plots, brash prevents re-establishment of vegetation over wide areas for at least four years. However, brash is not directly a source of inorganic-N at this stage.

Introduction

Forest clearfelling often leads to increased concentrations of nitrate in soil water and streams (Likens et al. 1970; Tamm et al. 1974; Adamson et al. 1987; Vitousek & Melillo 1979; Stevens & Hornung 1988). The release of nitrate is the result of a combination of factors, including:

- disruption of the forest nutrient cycle; removal of vegetation as the nitrogen sink and subsequent leaching of the available N.
- release of N from decomposing felling debris.
- increased rates of nitrification (possibly through removal of inhibition of nitrification by the trees) in the forest floor and soil organic matter, aided by higher soil temperatures after felling.

In some N. American forests, a number of processes have been identified as delaying or preventing nitrate mobilization (Vitousek et al. 1982). Chief among these are slow rates of net mineralization and a lag in nitrification after felling. Typically, however, enhanced nitrate concentrations are observed for a period of between 3 and 5 years after felling, with an eventual reduction to pre-felling or background levels. This eventual reduction is explained as the result of nutrient uptake by regrowing vegetation, exhaustion of readily decomposable substrate and inhibition of nitrification by regrowing vegetation (Bormann & Likens 1979). Successional species may make a significant contribution to nutrient conservation after felling (Boring et al. 1979), but felling debris from coniferous species is not readily decomposable and may be a sink for inorganic-N (Rosén & Lundmark-Thelin 1987).

In Beddgelert forest, north Wales, an experiment to compare the effect of conventional felling (CF) and whole tree harvest (WTH) on soil water chemistry, stream water chemistry, and long term site nutrient status was established in 1982. In the CF plots, felling debris (known as 'brash' in the UK, and 'slash' in N. America) remained on site in common with standard British forestry practice. In the WTH plots, all above ground tree material (except stumps) was removed. This paper describes the effect of the two felling treatments on soil solution inorganic-N concentrations and how these may be influenced by the presence of brash and re-establishing vegetation.

Site

The site is located in a former glaciated cwm (cirque or corrie) forming part of Beddgelert forest, a commercial conifer plantation, situated in the Snowdonia National Park, north Wales. The geology of the site is dominated by Ordovician slates, with small areas of intrusive dolerite dykes. Glacial and colluvial deposits occur widely, together with extensive post-glacial stabilized scree. Soils are dominantly ferric stagnopodzols (Avery 1980), a representative profile comprising 2 cm of Sitka spruce forest floor (L horizon), 4 cm of peat (O horizon), 6 cm of dark greyish brown, humus-rich Ah horizon, 9 cm of grey, clay-rich leached Eag, 27 cm of bright yellowish-brown Bs, and a gradual transition into pale yellowish- or grey-brown stony C horizon. Some chemical and physical characteristics of the soil profile are given in Stevens & Hornung 1988. The climate is mild and wet. Mean annual rainfall for the years 1982 to 1987 inclusive was 2810 mm. The tree crop is first rotation Sitka spruce (*Picea sitchensis* (Bong.) Carr.) planted between 1931 and 1936 which, after thinning, consisted in 1982 of approximately 690 stems per hectare. There was essentially no ground flora in the standing forest.

Methods

Four experimental blocks, each 0.6 ha in area, were set out in comparatively uniform stands at altitudes ranging from 320 m to 350 m and on slopes ranging from 12° to 30°. Half of each of the four blocks was felled conventionally and timber extracted by cable-crane, leaving brash randomly spread on the plot (CF plots). The other half of each block was felled and all above-ground material (except stumps) removed, also by cable-crane (WTH plots). Felling dates of the four blocks 1 to 4 were September 1984, June 1984, August 1983 and July 1983 respectively.

Soil water sampling

Soil water samples were obtained from the L, O, Eag, Bs and C horizons from January 1982 to September 1987 from all four blocks. Sampling was every two weeks until January 1986 in blocks 3 and 4, and every two weeks until January 1987 in block 1; sampling was then every four weeks until September 1987. Sampling of block 4 was every two weeks throughout. Initially, these samples were from standing forest, with felling taking place 18, 19, 29 and 32 months after the start of the study in blocks 4, 3, 2 and 1 respectively. In each block, four water samplers were installed in each horizon, of which two were in the plot proposed for whole tree harvest, and two in the plot proposed for conventional felling. In each block, water from the two collectors in each felling treatment was bulked prior to analysis.

Soil water collectors in the L and O horizons consisted of tensionless, plastic tray lysimeters, each 250 cm^2 in area, and installed by sliding beneath the appropriate horizon from a small pit downslope. Water collection was in darkened 6 litre polythene bottles, but without chemical preservative. Soil water collectors in the Eag, Bs and C horizons were porous ceramic cup suction samplers, similar to those of Wagner (1962).

Throughfall and bulk precipitation

Canopy throughfall (before felling), brash throughfall (CF plots after felling) and bulk precipitation (WTH plots after felling) were collected to provide information on the chemical composition of water entering the soil and to examine any release of inorganic-N from the felling debris.

Canopy throughfall was collected every two weeks from twelve 15 cm diameter funnels and bulked on site. The funnels were randomly located in a 20 m by 20 m plot situated between blocks 1 and 2. Bulk precipitation was sampled every two weeks in two 15 cm diameter gauges located in open space near the site. Brash throughfall was sampled every two weeks from June 1984 onwards in five 16 cm by 21 cm plastic seed trays with outlet spouts located at random beneath fresh brash such that falling needles accumulated in the trays. Samples from the five trays were bulked prior to analysis, but breakage resulted in a reduction to three trays after June 1985.

Vegetation and brash cover, vegetation biomass and nitrogen content

These were determined in the four WTH plots and four CF plots in September–October 1986. Two 10 m squares were selected at random from each plot.

Twelve 30 cm by 30 cm quadrats were set out at a regular spacing along diagonals of each square. In each quadrat, vegetation species and cover, and brash cover were recorded. The whole of the above ground biomass in each quadrat was harvested by clipping, separated into individual species or species groupings, dried at 80 °C for 48 hours, and weighed. Material of each species or species grouping from each of the 8 plots was then bulked, by plot, subsampled and ground for chemical analysis. Although the total area sampled totalled only a little over 1 m^2, the spread of the individual quadrats ensured that the complete range of vegetation and brash cover percentage was included in the sampling procedure.

Vegetation cover percentage (excluding bryophytes) within the collection areas of the L and O lysimeters, and within a square metre centred on the Eag, Bs and C suction samplers, was recorded in April 1988.

Chemical analysis

Soil water, canopy and brash throughfall and bulk precipitation samples were filtered through Whatman GF/F glass fibre filters within 24 hours of collection and then stored at 5–6 °C, for up to 6 weeks, before analysis for NO_3-N and NH_4-N by autoanalyser using standard methods (Allen et al. 1974). Certain highly coloured L and O horizon samples required a modification to the standard nitrate method to improve nitrate recovery (Rowland et al. 1984). Storage of these samples did not result in significant changes in the nitrate and ammonium concentrations (Stevens & Hornung 1988). Total nitrogen in vegetation samples was determined by Kjeldahl digestion (Allen et al. 1974).

Data manipulation

Because the felling of two blocks took place in the summer of 1983 and two blocks in the summer of 1984, concentration data have been rearranged according to the length of time before or after felling, rather than according to actual collection date. The four blocks are therefore treated as four replicates with the felling date as time zero. However, because only $1\frac{1}{2}$ years data are available before felling for blocks 3 and 4 only 2 replicates are available for the period $1\frac{1}{2}$ to $2\frac{1}{2}$ years before felling. A similar situation arises for the period 3 to 4 years after felling.

Results

Soil solution

Inorganic-N concentrations were very similar in comparable horizons of the two treatments for several months after felling – for around 6 months in the L, O and Eag horizons, and around 14 months in the Bs and C horizons. After these periods, concentrations dropped consistently in all 5 horizons of the WTH plots for the remainder of the study period while those in the CF plots remained relatively high (Fig. 1, Table 1).

In the CF plots, L horizon concentrations were similar both before and after felling. In the O and Eag horizons, concentrations peaked a year after felling and then dropped to a level below that before felling. In the Bs and C horizons of the CF, concentrations peaked a year after felling but then remained at higher levels than before felling.

The five horizons of the WTH plots all showed a similar pattern after felling. Maximum concentrations occurred a year after felling, followed by a steady reduction over the period from 14 to 48 months from felling. Inorganic-N concentrations in the WTH plots were extremely low or undetectable four years after felling.

A seasonal pattern in concentration is apparent in Fig. 1 for all five horizons in the CF plots. Highest concentrations were generally in the summer months from June to September. In contrast, the WTH plots show a less pronounced seasonal pattern.

Inorganic-N in all five horizons of both treatments was predominantly nitrate, but especially in the Eag, Bs and C horizons where ammonium was normally close to, or below the detection limit of $0.1\,mg\,l^{-1}$. There was no significant difference between the proportion of nitrate in the total inorganic-N, either between treatments or between years before and after felling.

Brash throughfall

Very little inorganic-N was leached from felling debris; concentrations in brash throughfall were normally well below $1\,mg\,l^{-1}$ and undetectable during the two winters following felling (Fig. 2). Throughout the post-felling period, brash throughfall concentrations (inorganic-N volume-weighted mean $0.21\,mg\,l^{-1}$ of which $0.07\,mg\,l^{-1}$ was nitrate-N) were lower than bulk precipitation concentrations (inorganic-N volume-weighted mean $0.39\,mg\,l^{-1}$ of which $0.19\,mg\,l^{-1}$ was nitrate-N). Summer peaks in concentration were also evident in both brash throughfall and bulk precipitation. Concentrations of inorganic-N in brash throughfall and bulk precipitation were also lower than in canopy throughfall before felling (inorganic-N volume-weighted mean canopy throughfall concentration was $0.94\,mg\,l^{-1}$ of which $0.55\,mg\,l^{-1}$ was nitrate-N).

Vegetation biomass, N content and cover

Previous work on felled sites has shown that biomass of regenerating vegetation is normally greater in WTH compared with conventionally-felled sites, although the number of sites where both felling treatments were available is very limited (Mann et al. 1988). At Beddgelert, biomass, N content and vegetation cover were all larger in the WTH plots than in the CF plots (Table 2). However, there were substantial differences between blocks which bear no relationship with

Table 1. Annual mean inorganic-N concentrations ($mg\,N\,l^{-1}$), $\pm$ standard error, for two years before felling and four years after felling in five soil horizons in WTH and CF treatments at Beddgelert Forest. Figures in brackets are the percentage of the inorganic-N which is nitrate-N.

Treatment	Horizon	Before felling (years)			After felling (years)		
		2–1	1–0	0–1	1–2	2–3	3–4
WTH	L	2.46 ± 0.35 (57)	3.49 ± 0.36 (62)	1.53 ± 0.17 (67)	0.81 ± 0.11 (77)	0.51 ± 0.07 (70)	0.25 ± 0.08 (92)
	O	2.88 ± 0.36 (66)	3.35 ± 0.33 (76)	2.59 ± 0.37 (73)	1.13 ± 0.12 (81)	0.53 ± 0.07 (81)	0.26 ± 0.05 (88)
	E	1.82 ± 0.21 (91)	2.23 ± 0.18 (100)	3.98 ± 0.63 (97)	2.05 ± 0.28 (94)	0.61 ± 0.07 (90)	0.16 ± 0.05 (94)
	B	1.03 ± 0.10 (93)	1.35 ± 0.11 (88)	2.47 ± 0.18 (100)	2.36 ± 0.30 (81)	0.83 ± 0.07 (93)	0.44 ± 0.09 (80)
	C	1.24 ± 0.11 (87)	1.43 ± 0.09 (99)	2.64 ± 0.21 (98)	2.51 ± 0.26 (97)	1.21 ± 0.08 (94)	0.48 ± 0.07 (100)
CF	L	2.43 ± 0.29 N.S. (53)	3.35 ± 0.42 N.S. (59)	2.82 ± 0.39 ** (71)	2.06 ± 0.31 ** (65)	1.88 ± 0.26 *** (52)	2.27 ± 0.42 *** (58)
	O	2.74 ± 0.28 N.S. (66)	3.68 ± 0.41 N.S. (70)	3.27 ± 0.48 N.S, (72)	2.18 ± 0.27 * (80)	1.67 ± 0.27 ** (76)	1.60 ± 0.35 *** (88)
	E	1.96 ± 0.15 N.S. (95)	2.79 ± 0.21 N.S. (98)	4.09 ± 0.36 N.S. (97)	2.48 ± 0.18 N.S. (95)	2.07 ± 0.16 *** (93)	0.50 ± 0.09 *** (96)
	B	1.41 ± 0.11 N.S. (91)	1.82 ± 0.15 ** (100)	2.83 ± 0.19 N.S. (100)	3.26 ± 0.27 *** (91)	2.29 ± 0.15 *** (91)	2.06 ± 0.36 *** (100)
	C	0.68 ± 0.04 *** (90)	0.77 ± 0.05 *** (99)	2.71 ± 0.16 N.S. (97)	3.51 ± 0.32 N.S. (97)	2.42 ± 0.16 *** (96)	2.02 ± 0.20 *** (99)

*, ** and *** after a CF concentration indicate a significant difference at $P = 5\%$, 1% and 0.1%, respectively between CF and WTH treatments for that year.
N.S. = not significantly different

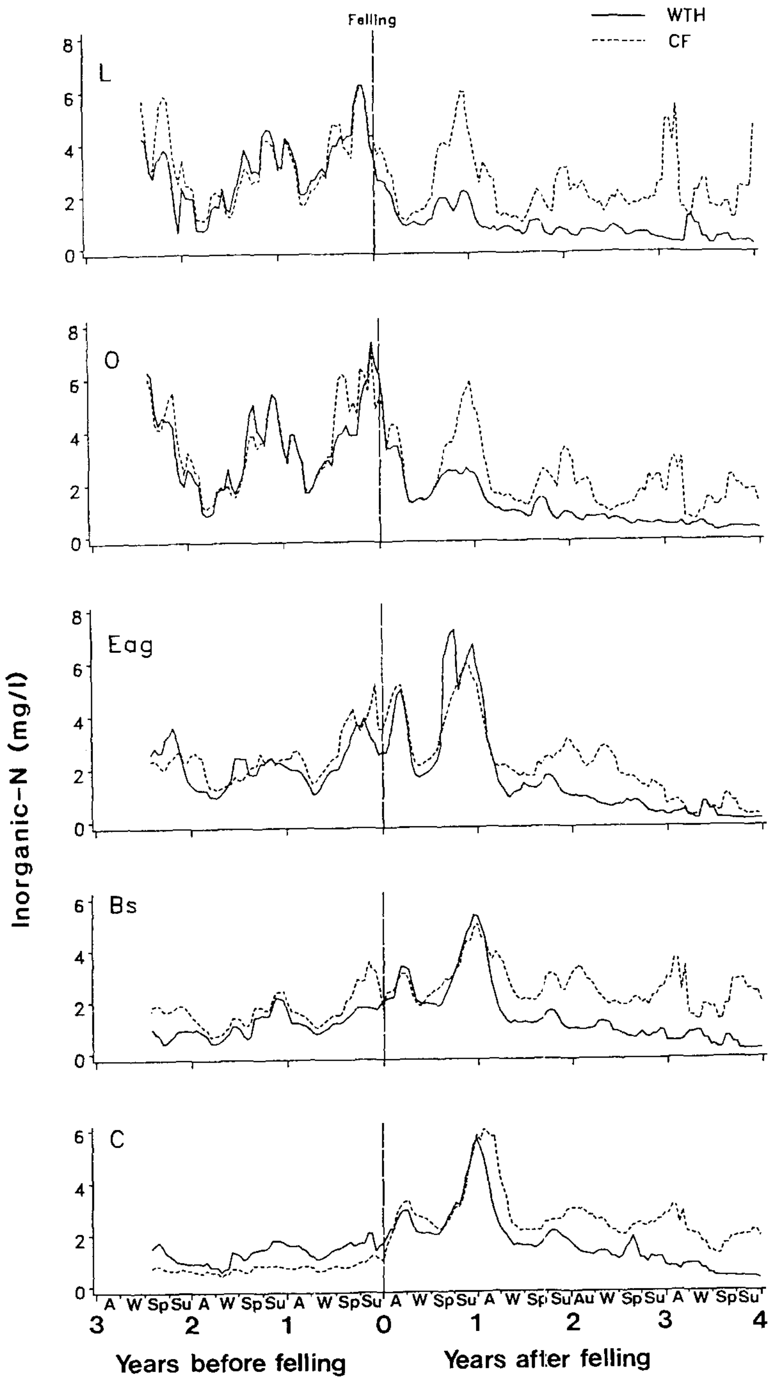

Fig. 1. Dissolved inorganic-N concentrations (mg N l^{-1}) in L, O, Eag, Bs and C horizon solution samples from whole tree harvest (WTH) and conventional fell (CF) plots at Beddgelert. Points plotted are running means of 4 fortnightly values.

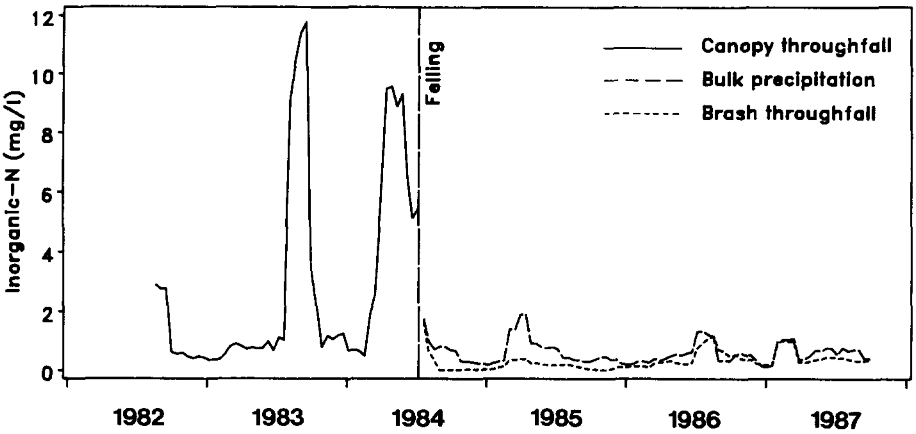

Fig. 2. Dissolved inorganic-N concentration (mg N l^{-1}) in canopy throughfall (before felling), bulk precipitation and brash throughfall (after felling) at Beddgelert Forest. Points plotted are running means of 4 fortnightly values.

length of time since felling took place. For instance, biomass and the total nitrogen per hectare in block 2 was more than double that in block 3, the latter having been felled a year earlier. Block 2 was dominated by a robust stand of *Agrostis* spp., whereas block 3 was dominated by the naturally less bulky *Deschampsia flexuosa*. Similarly, the high biomass figures for block 4 are explained by the presence of substantial clumps of *Juncus effusus*.

Vegetation cover in the CF plots is very significantly negatively correlated with brash cover (r^2 = 0.965, significant at P = 0.001). Brash clearly prevents vegetation re-establishment. The relationship between vegetation cover (in April 1988) and inorganic-N concentrations (means for 1987) is less clear (Fig. 3). In the Eag and C horizons there appears to be a negative correlation between cover

Table 2. Above ground biomass, nitrogen content, vegetation cover and time since felling of felled plots in Beddgelert Forest.

Plot	Above ground biomass (kg ha^{-1})	N in above ground biomass (kg hg^{-1})	Vegetation cover (%)	Months since felling
1 WTH	1198	20.5	46	24
1 CF	575	7.6	16	24
2 WTH	4974	69.1	85	26
2 CF	2857	44.8	56	26
3 WTH	2514	27.8	70	36
3 CF	1374	20.0	59	36
4 WTH	3848	47.2	74	38
4 CF	3132	40.4	46	38

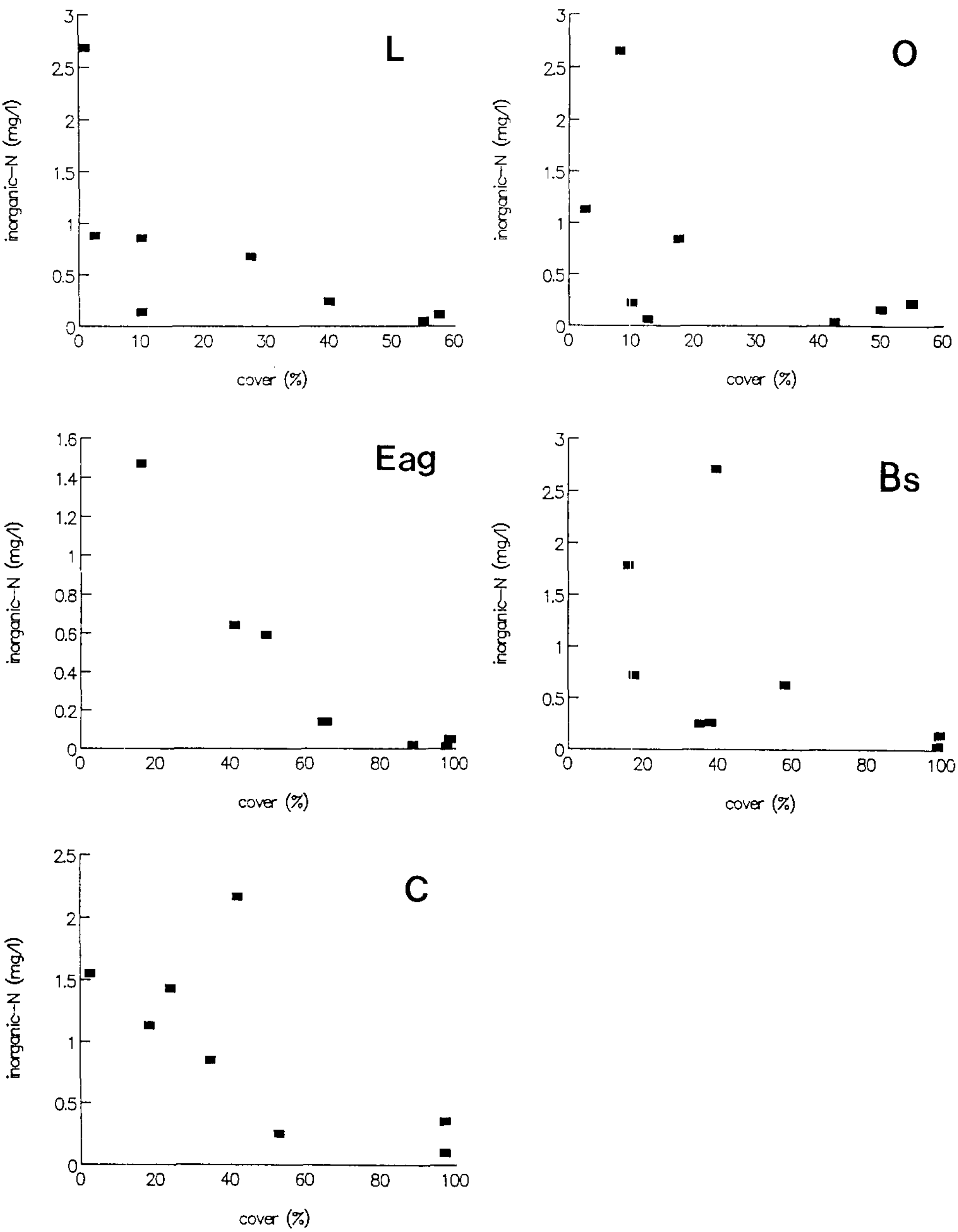

Fig. 3. Relationship between mean dissolved inorganic-N concentrations (mg N l^{-1}) for 1987 in five soil horizons at Beddgelert and vegetation cover. Vegetation cover was measured in April 1988 within the collection areas of the L and O horizon lysimeters, and in 1 m^2 quadrats centred on the Eag, Bs and C horizon suction samplers.

percentage and inorganic-N concentration. However, this correlation is significant ($r^2 = 0.839$, $P = 0.01$) only in the Eag horizon. In the L, O and Bs horizons, a considerable range of concentrations occurs at low cover values and the main conclusion to be drawn from Fig. 3 is that a high vegetation cover percentage is associated with very low inorganic-N concentrations.

Discussion

Re-establishment of vegetation after felling has been found to be at least partly responsible for preventing nitrate leaching after felling (Vitousek et al. 1982), or limiting the duration of the nitrate pulse in streams (Bormann & Likens 1979; Patric 1980). Similarly the reduction in concentration of inorganic-N in the soil waters of the Beddgelert WTH plots may also be explained through uptake by the substantially greater cover and biomass of vegetation established after two years compared with the CF plots. The surface organic horizons in the WTH plots would have been rapidly exploited by the root systems of the newly-established plants and inorganic-N concentrations depleted during the 12 months following felling. However, active nitrification and conversion from soluble organic-N to nitrate within the mineral horizons of these soils (Stevens & Wannop 1987) would ensure that nitrate concentrations remained high beyond the reach of roots. As the plant root systems developed, deeper horizons would have been progressively tapped for nutrients, and mineral horizon nitrate concentrations would decline.

In the CF plots, vegetation did not re-establish rapidly where brash was present, presumably through poor light conditions, lack of soil disturbance, limited germination of buried seed (Hill & Stevens 1981), and absence of a suitable seedbed. The comparative lack of vegetation on the CF plots could be responsible for the continuing high inorganic-N concentrations in soil solution 3–4 years after felling. Alternatively, or additionally, the brash on the CF plots might provide a source of N not available on the WTH plots, but if so, it is clear from Fig. 2 that it is not in the inorganic form. Indeed, brash would appear to be a sink for inorganic-N in bulk precipitation, confirming the results of Rosén and Lundmark-Thelin (1987). This phenomenon has been explained as the high nitrogen demand during decomposition of material with a large C/N ratio (Staaf & Berg 1982).

Brash may, however, be the source of dissolved organic-N. Organic-N has been shown to be the major form of dissolved nitrogen leached from felling debris (Rosén & Lundmark-Thelin 1987) and dissolved organic-N is known to be an important component of the dissolved nitrogen in the near-surface soil of felled plots of Beddgelert forest (Stevens & Wannop 1987). Nitrification is very active in the soils of Beddgelert forest (Stevens et al. 1989), and dissolved organic-N from brash would be readily transformed to nitrate.

An alternative explanation for greater inorganic-N concentrations in the CF plots is that the presence of brash may modify the microclimate and result in changes in the rates of mineralization and nitrate production.

Water quality implications

The freely drained soils and the high rainfall at the site will result in substantial nitrate leaching, estimated at around 70 kg N ha^{-1} yr^{-1} through the C horizon in the second year after felling (Stevens & Hornung 1988). Nitrate leaching from the WTH plots will initially occur at a similar level to that through the CF plots, but will rapidly decline and after four years will be less than the standing crop C horizon nitrate leaching losses, between 9 and 16 kg N ha^{-1} yr^{-1} (Stevens et al. 1989). Whole tree harvest would therefore appear to be the preferable option if conventional felling operations result in sustained high streamwater nitrate concentrations.

Conventional clearfelling in Beddgelert forest has not resulted in very large increases in streamwater nitrate concentrations (Stevens et al. 1988) mainly because catchments have been only partially felled. At Kershope forest in Cumbria, northern England, however, nitrate concentrations in ditches draining conventionally-felled plots were much higher and exceeded the European Economic Community drinking water limit of 11.3 mg N l^{-1} on one occasion (Adamson et al. 1987); such high concentrations would have been rapidly diluted downstream by water from unfelled or moorland areas with lower nitrate concentrations, but enhanced nitrate concentrations were recorded for at least 3 years after felling (J. K. Adamson, pers. comm.). Although maximum concentrations of nitrate in soil waters were similar at Beddgelert in both WTH and CF treatments, the duration of the nitrate pulse was very much shorter in the WTH than in the CF. If these soil nitrate pulses are reflected in the streamwaters, then WTH would be preferable as the pulse would end within 18 months of felling (assuming rapid revegetation). This would allow clearfelling within catchments to occur progressively, without the cumulative effects on streamwater nitrate concentration which might occur with conventional felling and a nitrate pulse lasting at least 3 years.

Silvicultural implications

Removal of N from the site in harvested material has been estimated at 428 and 128 kg N ha^{-1} yr^{-1} for the WTH and CF treatments respectively (Stevens et al. 1988). However, there are unlikely to be long term problems with the N nutrition of the successive tree crops at this site – total nitrogen in the soil to the base of the rooting zone is 9400 kg N ha^{-1} (Stevens et al. 1988) and mineralization rates are comparatively rapid (Stevens et al. 1989). Bulk precipitation inputs and streamwater outputs of inorganic-N are 10 and 14 kg N ha^{-1} yr^{-1} respectively (Stevens et al. 1989) for small catchments in Beddgelert forest, indicating that, at least in mature plantations, there is no shortage of available N. However, in the short term the very low inorganic-N concentrations in the WTH plots 3 to 4 years after felling could be a source of concern as the newly planted trees will be competing with well-established and increasing ground vegetation for a very limited supply of available N. In contrast, the greater availability of inorganic-N in the CF plots, and the eventual release of N (and possibly P) from the brash indicates that conventional felling should favour second rotation crop nutrition. The main problem with the CF treatment is that establishment of the second rotation trees is hampered by the physical presence of the brash.

Conclusions

Inorganic-N concentrations in soil waters of whole tree harvested plots were significantly lower than in CF plots from one year after felling to 4 years after felling. Inorganic-N was dominated by nitrate and substantial leaching would have taken place following felling in both treatments.

Concentrations of inorganic-N were very low after vegetation had become re-established at moderate to high cover values, which is the case after only two years in the WTH plots.

Brash is not directly a source of dissolved inorganic-N to the CF plots in the 3 years after felling – in fact it appears to be a sink for inorganic-N in bulk precipitation which passes through. Dissolved organic-N leached from the brash, and not determined in this study, is a possible source of inorganic-N in the CF plots if readily mineralized. However, the magnitude of the individual effects of vegetation in reducing the inorganic-N concentrations of the WTH plots, and brash in increasing the inorganic-N concentrations of the CF plots, cannot be determined from this experiment.

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