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Environmental effects of forestry at Big Bush Forest, South Island, New Zealand: I Changes in water chemistry

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Abstract

This study considers short-term (immediate post-harvesting) and long-term (forest establishment) changes in water chemistry (base cations, total N, and total P) in streamflow from three experimental catchments in Big Bush Forest, central Nelson. One (DC2) has been left in beech/podocarp forest as the control (4.77 ha). In 1980 catchment DC1 (8.57 ha) was skidder-logged and DC4 (20.19 ha) was hauler-logged. In DC1, concentrations of the dominant cation (Na^+) rose from a pre-treatment mean of 2.83 mg L^{-1} to a maximum of 5 mg L^{-1}, then declined to 3.82 mg L^{-1} four years after harvesting. For K^+, the pre-treatment mean concentration was 0.75 mg L^{-1}, rising to a maximum of 5.4 mg L^{-1}, but one year later had fallen to a mean of 0.90 mg L^{-1}. Fluctuations in concentrations of Ca^{2+} and Mg^{2+} were smaller. Similar patterns of change were recorded at DC4. Total N concentrations at DC4 increased 10-12 times compared with the control, but seldom exceeded 1 mg L^{-1}, and were close to pre-treatment levels four years after harvesting. The response of total P was similar but more subdued. Cation yields over the period 1980-1986 for DC1 and DC4 were double that of the control (22.4 kg ha^{-1} yr^{-1}). Total N yields (0.18-0.44 kg ha^{-1} yr^{-1} at the control) were much lower than those for cations. At DC4 they increased by up to an order of magnitude after harvesting, and were still 3-5 times higher than the control four years later. Total P (0.08-0.14 kg ha^{-1} yr^{-1} at the control) increased 2-3 times after harvesting. Rainfall chemistry data from other sites suggest an approximate balance between cation and nutrient inputs and outputs for undisturbed beech/podocarp forest. Recent short-term monitoring suggests that cation and nutrient yields in streamflow from pine plantations at mid-rotation will be comparable to those from mature beech/podocarp forest. Yields of total N in the first few years after harvesting were comparable to or less than those recorded for pasture.

Introduction

In the 1970s plans to convert native beech forest to commercial pine plantations in the headwaters of major rivers of the South Island of New Zealand raised concerns that water yields and the chemistry of local streams might be irreparably altered. In response to these concerns the former New Zealand Forest Service established two experimental catchment studies, one in the Maimai area near Reefton and the other in Big Bush Forest, near Nelson, to evaluate the effects of converting beech (*Nothofagus* spp.) forest to exotic pine (*Pinus radiata*) plantation on water yield, stream water chemistry, and sediment production. Most of the research at these two sites has focussed on the pre-treatment and immediate post-harvesting hydrological effects, e.g. at Maimai, Pearce *et al.* (1976), Neary *et al.* (1978), Pearce *et al.* (1980), Mosley and Rowe (1981), and for Big Bush, Pearce *et al.* (1982a,b) and Jackson (1985). Attention has now turned to the long-term hydrological effects of replacing native forests with exotic plantations at Maimai and Big Bush (e.g. Rowe and Fahey, 1991; Rowe and Pearce, 1994; Rowe *et al.*, 1994; Fahey and Jackson, 1997), but nothing has yet been published on the short-term and long-term changes in water chemistry after conversion of native forest to pine plantation at Big Bush. Graynoth (1979) discussed the effects on water chemistry of harvesting both beech and pine forests at a site with similar rainfall and lithology about 10 km from the Big Bush catchments.

The need for information on water quality changes arising from forest harvesting and re-establishment has increased with the introduction of the Resource Management Act in 1991. This Act is designed to promote the sustainable management of the country's natural and physical resources. Under it regional authorities are responsible for assessing actual and potential effects of land-use change. Better understanding of the fluxes at the catchment scale will assist land and water managers in developing strategies to minimise the effects of land use on water quality.

This paper examines the extent to which removal of the original forest cover, land preparation before planting, and establishment of a commercial tree crop has influenced stream water chemistry in both the short and long term. The results are compared with those of other studies in New Zealand, including those measuring fluxes from pastures.

Field area

The three study catchments are located 5 km north-west of the Hope Saddle in Big Bush Forest, a region of extensive mixed evergreen native forest remnants and plantation species (mostly *P. radiata* with some

Pseudostuga menziesii) near the headwaters of Donald Creek, a tributary of the Tadmor River (Fig.1). The area has four experimental catchments, ranging in area from 4.8 to 20.2 ha, with a mean elevation of approximately 550 m asl. They are typical of catchments in the dissected hill country of the Nelson-Motueka region underlain by moderately weathered, tightly compacted, early Pleistocene Moutere Gravel Formation (Bowen, 1964; Johnston, 1979). The dominant native canopy species are hard beech (*Nothofagus truncata*) and red beech (*N. fusca*). Kamahi (*Weinmannia racemosa*), miro (*Prumnopitys ferruginea*), and rimu (*Dacrydium cupressinum*) are subdominant. The understorey consists of *Nothofagus spp.* saplings, up to a few metres tall, and broadleaved shrubs, up to 2 m tall (mainly *Cyathodes spp.* and *Coprosma spp.*), with a soil-surface cover of beech litter and seedlings on upper slopes and dense fern (*Blechnum discolor*) on lower slopes. Campbell and Mew (1986) identified three soil series across the catchment: yellow-brown earths (62% of profiles), podzolised yellow-brown earths (32%) and podzols (5%). These soils are now classed as brown soils and podzols, (A. Hewitt pers. comm.) and can also be classified as Dystrochrepts or Humults. Their distribution is complex, with yellow-brown earths the most widespread, while podzol and podzolised soils are more common on ridges and spurs. Soil pH, total P and base saturation are low, and C/N ratios are high, reflecting the influence of the forest vegetation (Campbell and Mew, 1986).

The nearest climatological station (now closed) was at Golden Downs, 13 km to the northeast. The mean annual temperature for the period 1930-1980 at this station is 10.5°C (January mean 15.7°C, and July mean 4.6°C) (New Zealand Meteorological Service, 1983). The mean annual rainfall (1929-80) is 1307 mm and is fairly evenly distributed through the year. The mean annual rainfall at Kaka, 5 km northwest of the catchments, is 1701 mm (New Zealand Meteorological Service, 1987). Two recording rain gauges in the catchments show the average annual rainfall to be about 1550 mm (1977-1994).

Experimental methods

Measurements of rainfall and streamflow began in November 1975, but water chemistry monitoring did not begin until 1979. The three years from 1977 to 1979 were used to characterise the hydrological regime of the undisturbed catchments (Pearce *et al.*, 1982a). The beech forest was harvested and pines planted in 1980-81. The effects of the treatments on water chemistry were studied in detail from 1980 until 1986, and a few additional samples taken in 1988 and 1993 were used to assess the longer-term recovery.

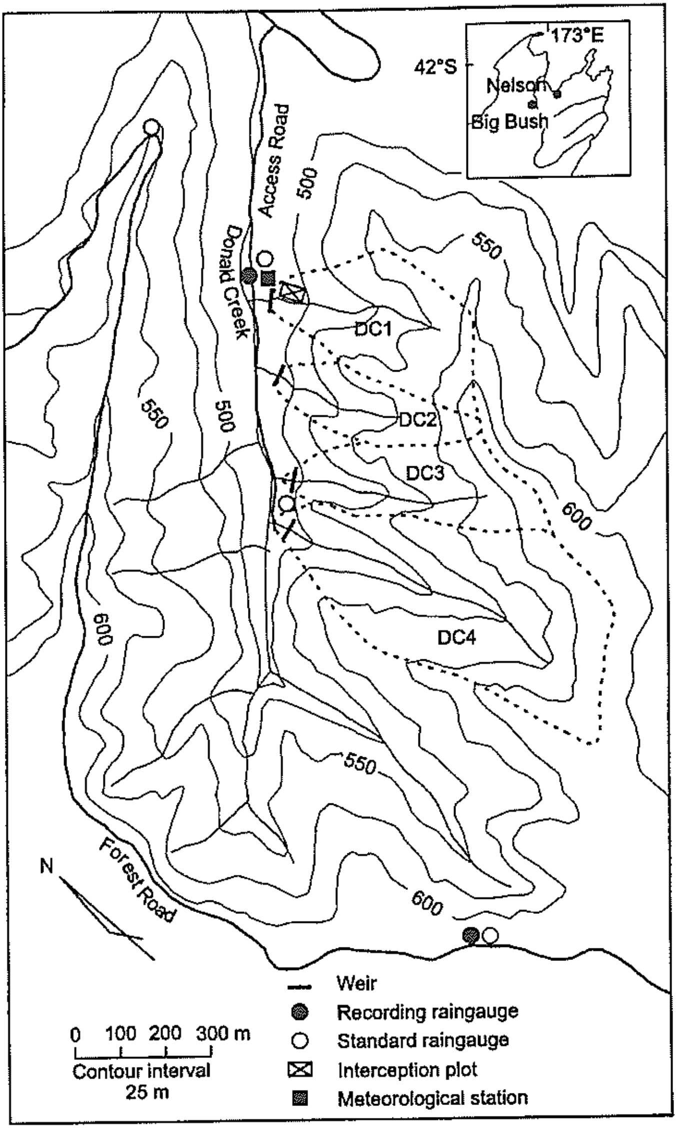


Figure 1 - Map of Big Bush showing location of experimental catchments and associated instrumentation.

Catchment treatments

Catchment DC1 (8.57 ha) was skidder-logged over 83% of its area between April and December 1980 using contour skid-tracks at 40-m intervals (Table 1). A 10-m wide riparian strip was left on either side of the stream channel. The catchment was partially burnt in May 1981, and after root-raking, was planted in *P. radiata* at 1250 stems ha^{-1} in September 1981. Catchment DC2 (4.74 ha) was left in native beech as the control. Catchment DC3 (7.84 ha) was logged selectively by skidder over 85% of its area between December 1980 and March 1981 and subsequently managed for sustained beech growth. It is not considered further in this study. Catchment DC4 (20.19 ha) was clearfelled over 94% of its area and the logs extracted by skyline hauler between May 1980 and June 1981. It was not burnt, but a 5-m wide stream protection zone suffered some damage during log extraction. The catchment was planted in *P. radiata* in September 1981.

Initially there was little vegetation cover over the disturbed soil in DC1 or the mostly undisturbed forest floor in DC4. Two years after logging there had been scattered invasion by exotic annual weeds, bracken (*Pteridium aquilinum*) and water fern (*Histiopteris incisa*), and some sparse regeneration or regrowth of species present in the original forest. Five years after planting, DC4 had an almost complete cover of emergent pines over a dense understorey of ferns and broadleaf shrub species from the original beech forest (*Nothofagus*, *Cyathodes*, *Coprosma*, *Grisilinia*, and *Rubus*). Bracken was a major component of the early cover on burnt sites in DC1, while on the area that was not burnt the vegetation cover was similar to that in DC4. The pines in catchments DC1 and DC4 were thinned to 250 stems ha^{-1} in the 1986-1987 summer. A survey of sample plots in December 1993 showed that the pines were similar in DC1 and DC4, with mean tree height of 18-20 m, trunk diameter (DBH) 0.32 m, stocking of 200-250 stems ha^{-1}, and basal area 17 m^2 ha^{-1}. Understorey and ground

Table 1 - Forest management practices in catchments DC1, DC2, and DC4, Big Bush hydrological study.

Catchment	Area (ha)	Riparian reserve (%)	Management	Harvested	Burned	Planted
DC1	8.57	17	skidder-logged	Apr-Dec 1980	May 1981	Sep 1981
DC2	4.77	-	undisturbed	–	–	–
DC4	20.19	6	hauler-logged	May 1980 - Jun 1981	–	Sep 1981

cover clearly differed between catchments with bare soil or slash from thinning on 18% and 2%, fern (mainly bracken) on 50% and 22%, and shrub cover on 32% and 75% in DC1 and DC4 respectively. Nitrogen-fixing plants, including gorse, broom, lotus, and lucerne, were rare and confined to the bulldozed tracks on catchment perimeters.

Hydrological measurements

Runoff was monitored with 90° V-notch weirs and Belfort float-type recorders. Water levels are recorded to ±2 mm, and annual runoff is known to ±5%. Quickflow was separated from delayed flow during and between storms using the procedure of Hewlett and Hibbert (1967). Rainfall was measured with two Lambrecht syphoning gauges, one on the upper-most perimeter of the catchment (Upper Donald) and the other near the DC1 weir (Lower Donald), and with a network of standard manual gauges (Fig.1). Annual flows for DC1, DC2, and DC4 during the main water-sampling period are shown in Figure 2.

Water sampling

Samples for water chemistry were collected in polythene bottles at the weir outlets during routine servicing trips which were normally at weekly

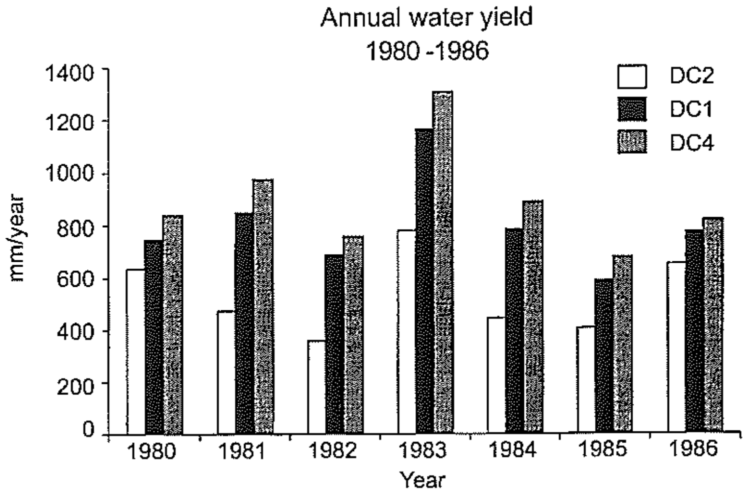


Figure 2 - Annual water yields for catchments DC1 (skidder logged), DC2 (control), and DC4 (hauler logged) at Big Bush for the period 1980-1986.

intervals over the period 1980-1986. Most of the samples were taken during low-to-moderate flows. Data are also available from automatic samplers installed at catchments DC1 in April 1980, DC2 in May 1981, and DC4 in May 1980. These samplers were also used to monitor the water chemistry of 8-10 storms in the period June 1980 to December 1983 for the three treated catchments, thereby ensuring that a range of flow regimes was covered. Data from these storms are representative of the immediate post-clearfelling period when annual water yields were 40-60% above those of the control. Only three storms were monitored during the same period at the control catchment. Samples that could not be returned to the laboratory immediately were frozen. Once back in the laboratory the samples were stored at 4° C, and normally analysed within 2 weeks.

The longer-term effects of the treatments on water quality are indicated by samples taken under low-flow conditions in April 1988 (Stenzel and Herrmann, 1990) and during the recession after a moderate flood in December 1993.

Chemical analyses

Concentrations of base cations (Na^+, K^+, Mg^{2+} and Ca^{2+}) were measured by atomic absorption spectrophotometry. Soluble orthophosphate (PO_4^{3-} - P) and nitrate nitrogen (NO_3^- - N) were determined colorimetrically on a Pye-Unicam AC6 automatic chemistry unit using the manufacturer's recommended procedures, modified to detect low concentrations. Concentrations for NH_4^+ - N were measured using a method described by Searle (1975) which was adapted for use on the AC6 system and modified for low concentrations. Total phosphorus and total nitrogen samples were pre-treated using persulphate digestion procedures. Detection limits were <0.01 mg L^{-1} , and the results were rounded to 0.01 mg L^{-1}. Electrical conductivity and pH were usually measured in the field.

Statistical analyses

Data for base cation concentrations were assessed for normality of distribution with the Shapiro-Wilk test. In most cases the data were skewed, thus precluding use of parametric tests of equality. The non-parametric (distribution-free) Wilcoxon rank sum procedure was used to test for statistically significant differences in central tendency of independent samples.

Chemical yield calculations

Monthly streamflow volumes were multiplied by the mean of the accompanying weekly cation concentrations for the month, and the product divided by the catchment area to give cation yields (expressed in kg ha^{-1}). This procedure for calculating cation yields has been used by Feller and Kimmins (1984) in British Columbia, by Swank and Crossley (1987) at Coweeta in North Carolina, and by Rowe and Fahey (1991) at Maimai. The concentration levels of total N and total P were normally low but exhibited occasional sharp rises and falls. Thus it was decided to calculate the yearly outputs of total N and total P as the product of the mean annual concentration and the annual flow.

Total cation yields for selected storms in the immediate post-harvesting to early post-planting period were computed from the product of flow during a given time interval (30 minutes to 2 hours) and the mean of the cation concentration of samples collected at the beginning and end of the interval. The data from the intervals were summed over the duration of the storm. The linear relationship between total storm flow (quickflow plus delayed flow during the storm) and cation output for the selected storms was used to calculate cation yields for the remaining storms during the period 1980-1986. Cation data were also collected for recession periods comprising delayed flow after storms. These were used to estimate total cation yield for delayed flow between storms in the period 1980-1986 by computing the average concentration for all cations for these delayed flows, and multiplying this value by the total between-storm delayed flow. The storm flow and between-storm delayed flow yields were summed and the results compared with those derived from the weekly sampling schedule. There were insufficient data for calculation of chemical yields after 1986.

Table 2 - Mean pH and electrical conductivity for the control catchment (DC2) and for the treated catchments during the periods 1984-86 and mid 1985-86, respectively. The sample standard deviations are given in parentheses.

Catchment	No. of obs.	pH	No. of obs.	Conductivity µS cm^{-1}
DC2	88	5.8 (±0.6)	44	22.0 (±3.8)
DC1	40	5.8 (±0.6)	46	24.2 (±4.7)
DC4	71	5.7 (±0.5)	46	23.5 (±4.9)

Results

Electrical conductivity and pH

Routine measurements of electrical conductivity and pH did not begin until January 1984, and June 1985 respectively. They were taken at 1-to-2 week intervals, and are representative of the late post-harvesting period. The mean values for the three catchments were not significantly different (Table 2). Thus while the immediate effects of harvesting on pH and conductivity cannot be assessed, there was no apparent lasting effect in either case.

Cation concentrations

(a) Control catchment

The dominant cation was Na^+, followed in descending order by Ca^{2+}, K^+, and Mg^{2+} (Table 3). However, the time trends in concentration for the weekly samples suggest a more complex picture than that depicted in Table 3. At the time DC1 was treated, for example, Na^+ concentrations in DC2 oscillated distinctly around the mean value, and both K^+ and Ca^{2+} showed similar peaks in concentration (Fig. 3). The proximity to maritime sources of Na^+ may help explain the short- and long-term trends in the concentration of this ion, whereas the observed K^+ peaks may be related to transfer and deposition of wind-borne material from DC1 to DC2 during the attempt to burn accumulated slash in the DC1 catchment. Unusually high Ca^{2+} concentrations were observed in summer at DC2 for 1981, 1982, 1983, and 1985. These all correspond with periods of zero flow, and are believed to result from mild dissolution of the concrete weirs in standing water. Comparisons of the data for Na^+, K^+, Ca^{2+}, and Mg^{2+} in the three periods listed in Table 3 showed that the means for 8 out of 12 pairs of samples were not significantly different ($p \geq 0.02$).

(b) Treated catchments

Differences between pre-treatment, treatment, and post-treatment concentrations for each base cation were statistically significant according to the Wilcoxon rank-sum test ($p \geq 0.001$), except for two cases at DC4 (pre-treatment Na^+ versus treatment Na^+, and pre-treatment Ca^{2+} versus treatment Ca^{2+}: $p \geq 0.20$). At DC1 (maximum disturbance), Na^+ concentrations were only slightly affected by clearfelling and land preparation. Following a pre-treatment mean of 2.83 (± 0.63) mg L^{-1} (Table 3), Na^+ peaked at 4.88 mg L^{-1} in mid-February 1981, but then fell quickly. In the post-treatment period (beginning October, 1981)

Table 3 - Mean cation concentrations and the sample standard deviations (in mg L^{-1}) for the control catchment (DC2), and for the treated catchments over the pre-treatment (Jan.-Jul. 1980), treatment (Aug. 1980-Sept. 1981), and post-treatment periods (Oct. 1981-Dec. 1986).

Catchment		No. of obs.	Na^+	K^+	Mg^{2+}	Ca^{2+}
DC2	Pre-	39	2.85 (±0.37)	0.57 (±0.10)	0.35 (±0.05)	1.03 (±0.26)
	Treat-	65	2.73 (±0.65)	0.63 (±0.28)	0.30 (±0.06)	1.01 (±0.36)
	Post-	157	3.17 (±0.36)	0.57 (±0.18)	0.36 (±0.04)	1.18 (±0.28)
	Total	261	3.04 (±0.49)	0.60 (±0.27)	0.35 (±0.06)	1.14 (±0.31)
DC1	Pre-	31	2.83 (±0.63)	0.75 (±0.24)	0.40 (±0.09)	1.15 ±(0.35)
	Treat-	60	3.22 (±0.63)	1.30 (±0.78)	0.51 (±0.11)	1.51 (±0.43)
	Post-	194	3.82 (±0.58)	0.90 (±0.24)	0.56 (±0.09)	1.71 (±0.37)
DC4	Pre-	25	2.84 (±0.43)	0.57 (±0.09)	0.38 (±0.07)	1.25 (±0.04)
	Treat-	56	3.09 (±0.68)	0.94 (±0.50)	0.43 (±0.10)	1.47 (±0.47)
	Post-	198	3.68 (±0.58)	0.74 (±0.27)	0.46 (±0.08)	1.52 (±0.37)

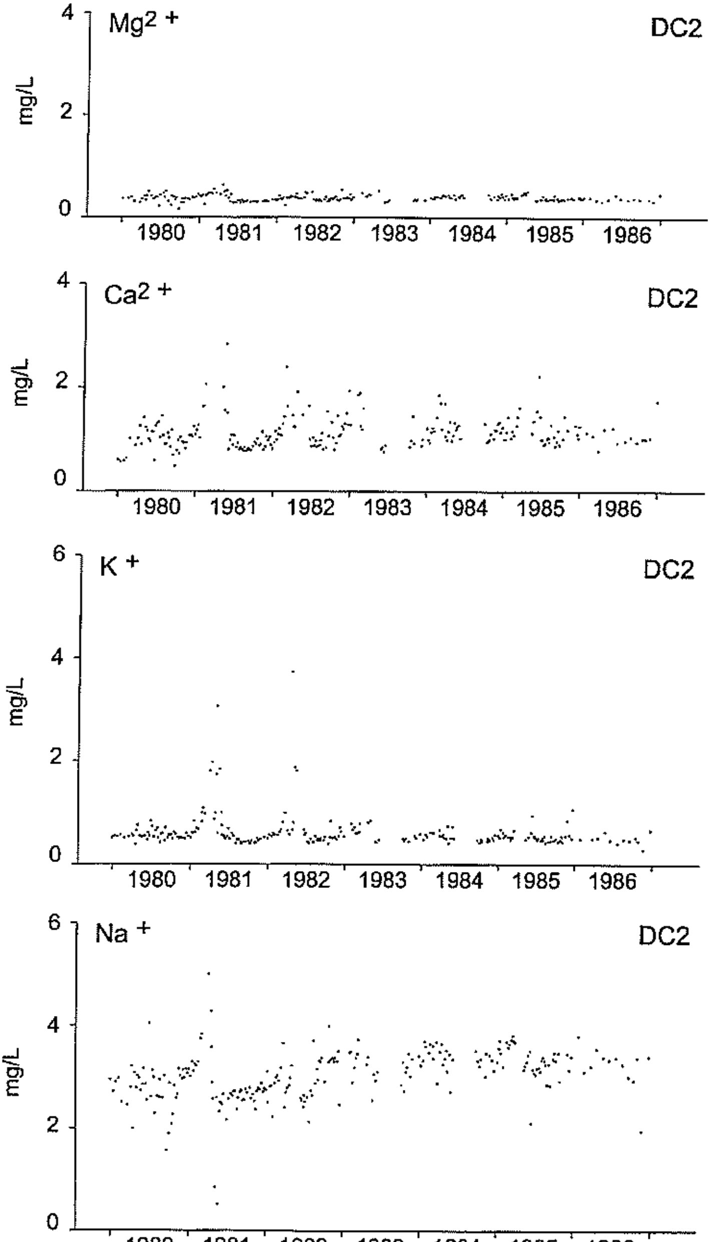


Figure 3 - Time plots of cation concentrations for Na^+, K^+, Mg^{2+}, and Ca^{2+} recorded at the control catchment (DC2)

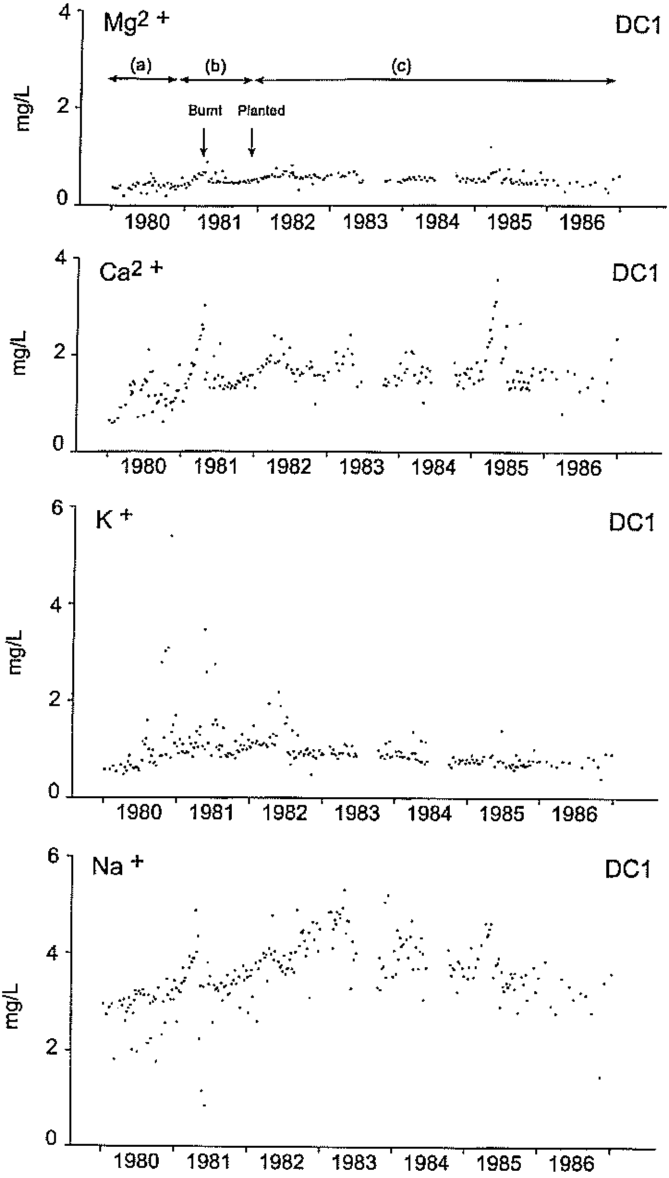


Figure 4 - Time plots of cation concentrations for Na^+, K^+, Mg^{2+}, and Ca^{2+} recorded at the skidder-harvested catchment (DC1) from 1980 to 1986, representing (a) the pre-treatment period (Jan.-July 1980), (b) the treatment period (Aug. 1980 - Sept. 1981), and (c) the post-treatment period (Oct. 1981 - Dec. 1986).

concentrations rose gradually until late 1983, peaking at 5.22 mg L^{-1} in November, then declined even more gradually through to the end of the record (Fig. 4). The mean for this period was 3.82 (±0.58) mg L^{-1} (Table 3). High concentrations tended to correspond with periods of low flow. The pre-treatment mean for K^+ was 0.75 (± 0.24) mg L^{-1}. During the treatment period (August 1980 to September 1981) K^+ levels fluctuated markedly, peaking towards the end of clearfelling in October 1980 at 5.40 mg L^{-1}. Concentrations also rose sharply after the catchment was burnt. None of the high readings corresponded with exceptionally high or low flows. A year after planting, these fluctuations had subsided and for the post-treatment period the mean concentration was 0.90 (± 0.24) mg L^{-1} (Table 3, and Fig. 4). Calcium showed a similar but more subdued response to catchment treatment (Fig. 4), increasing from a mean of 1.15 (± 0.35) mg L^{-1} in the pre-treatment period to 1.51 mg L^{-1} (maximum of 3.04) soon after logging. The post-treatment mean was 1.71 (±0.37) mg L^{-1} (Table 3). By contrast, Mg^{2+} concentrations were much more uniform (Fig. 4 and Table 3), with no detectable variation over time, suggesting that the concentration of this cation remained unaffected by catchment disturbance. The means and time trends for DC4 were similar to those described above for DC1 (Table 3 and Fig. 5). Once again the high Na^+ concentrations corresponded with times of low flow, but the K^+ levels were highest towards the end of harvesting, representing an apparent response to treatment rather than flow.

(c) Storm Responses

K^+ concentrations varied positively with flow, whereas Ca^{2+} and Mg^{2+} concentrations were largely unaffected (Fig. 6). Concentrations of Na^+ were normally inversely related to flow. The increase in K^+ during storms may be due to leaching during infiltration through the litter layer where K^+ accumulates during dry periods. On the other hand, Na^+ is derived primarily from external marine sources, and is diluted in storm runoff.

Nitrogen and phosphorus concentrations

(a) Control catchment

Nutrient concentrations in the control catchment, averaged over the period of record, were all <0.10 mg L^{-1} (Table 4). Time trends are shown in Figure 7a.

(b) Treated catchments

Only total N and NO_3^- - N levels were noticeably influenced by catchment

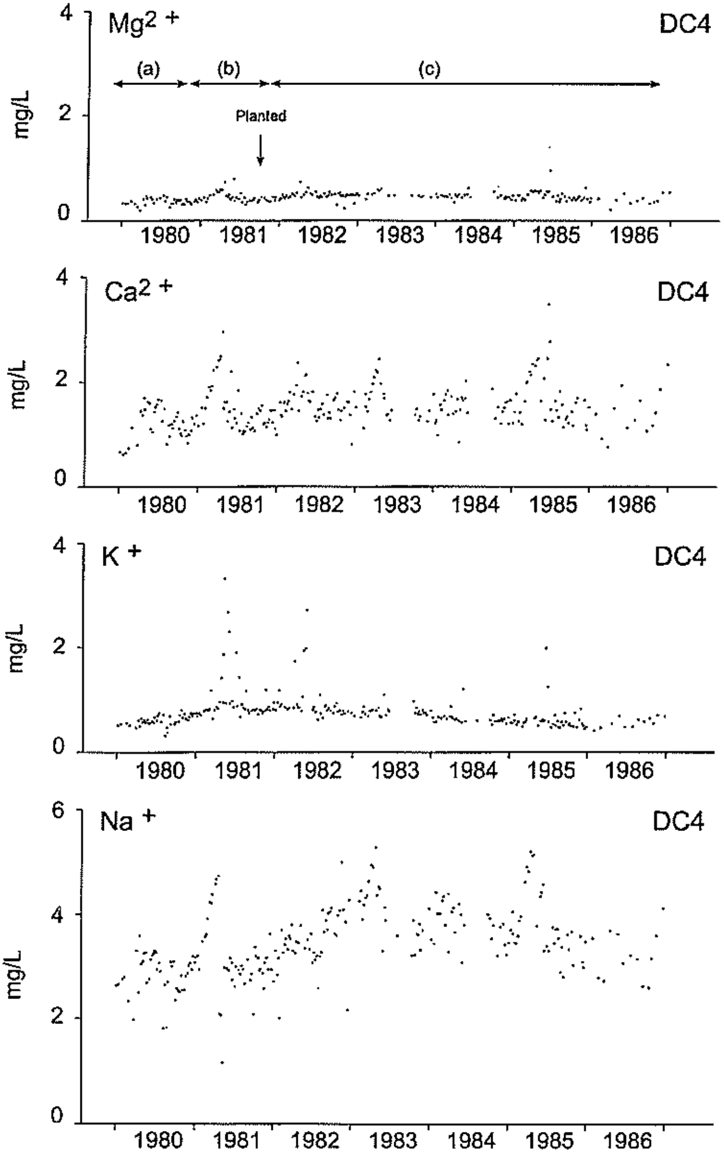


Figure 5 - Time plots of cation concentrations for Na$^+$, K$^+$, Mg^{2+}, and Ca $^{2+}$ recorded at the hauler-harvested catchment (DC4) from 1980 to 1986, representing (a) the pre-treatment period (Jan.-April 1980), (b) the treatment period (May 1980 - Sept. 1981), and (c) the post-treatment period (Oct. 1981 - Dec. 1986).

Table 4 - Mean nutrient concentrations (in mg L^{-1}) for the control catchment (DC2) and the treated catchments (1980-86).

Catchment	No. of obs.	Total N	NO_3^--N	NH_4^+-N	Total P	PO_4^{3-}-P
DC2	256	0.07 (±0.06)	0.01 (± 0.02)	0.04 (±0.09)	0.03 (±0.02)	0.03 (±0.03)
DC1	277	0.28 (±0.19)	0.15 (±0.17)	0.04 (±0.07)	0.05 (±0.03)	0.04 (±0.03)
DC4	273	0.34 (±0.25)	0.21 (±0.22)	0.03 (±0.07)	0.04 (±0.03)	0.04 (±0.03)

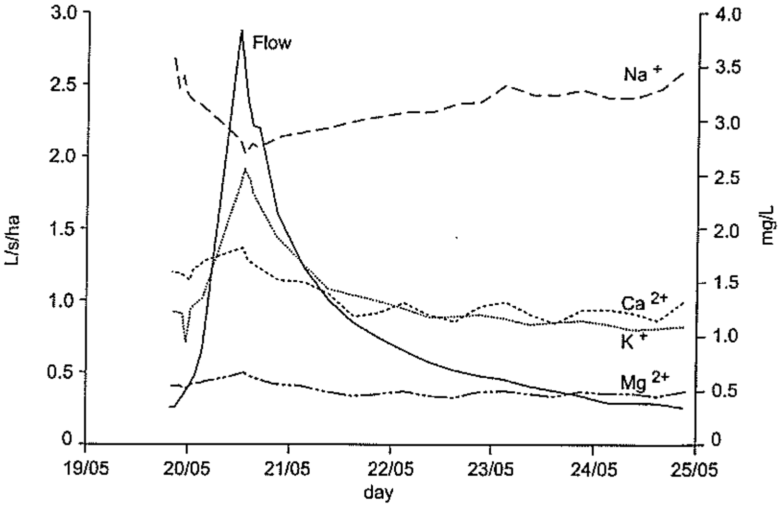


Figure 6 - Time plots of specific discharge and cation concentrations for Na^+, K^+, Mg^{2+}, and Ca^{2+} recorded at the skidder-harvested catchment (DC1) during an early post-harvesting storm on 19 May 1981.

treatments, with DC4 showing the largest response (Table 4). However, although spot readings of total N at DC4 increased after treatment by 10-to-12 times compared with DC2, they seldom exceeded 1 mg L^{-1} (Fig. 7b). A general decline in concentration is evident from October 1983 through to the end of 1986 (Fig. 7b). A similar but more muted response is evident in the total phosphorus record (Fig. 7b).

Cation yields

(a) Control catchment

Yearly cation yields ranged from 17.1 kg ha^{-1} in 1982 to 28.8 kg ha^{-1} in 1980, with a mean of 22.4 kg ha^{-1} yr^{-1} over the 7-year period (Table 5).

Table 5 - Cation yields in kg ha^{-1} yr^{-1} for all catchments (1980-86)

	Control	Treated	
Species	DC2	DC1	DC4
Na^+	13.9	27.9	31.3
K^+	2.4	7.1	7.0
Mg^{2+}	1.5	4.0	4.1
Ca^{2+}	4.6	11.9	13.2
Total	22.4	50.9	55.6

This compares favourably with the total of 36.2 kg ha^{-1} calculated by Neary *et al.* (1978) for DC1 before harvesting.

(b) Treated catchments

Cation yields for DC1 and DC4 over the same period were 50.9 and 55.6 kg ha^{-1} yr^{-1} respectively, which is more than double the output of the control (Table 5).

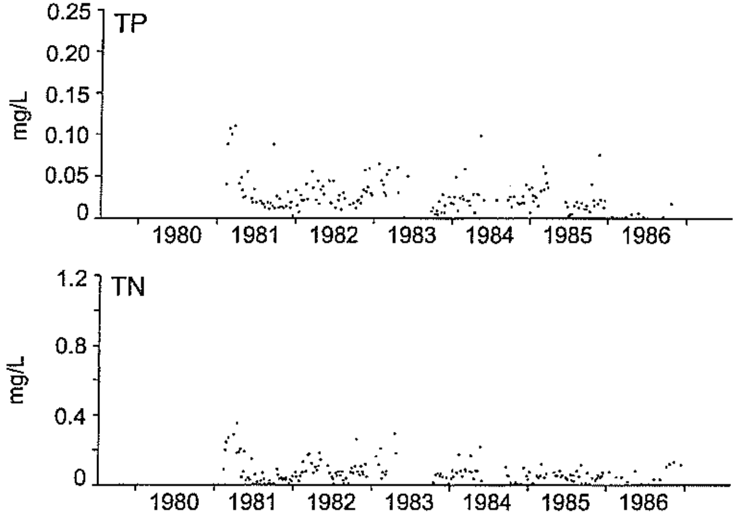
The difference in monthly total cation yield between the treated catchments and the control indicates not only the response of catchments to disturbance but also the time taken to return to pre-treatment levels (Fig. 8). The two treated catchments showed a similar response: a progressive increase in cation yield over the first 2-3 years, followed by a gradual decline. None of the catchments had returned to pre-treatment levels by late-1986.

(c) Storm responses

The storm recorded on 8/7/83 generated the largest flow (91.5 mm) of the 12 storms monitored for cation and sediment yields at DC1. It removed an estimated 44 kg of cations (5.1 kg ha^{-1}), the second biggest contribution of any storm during the period of record for DC1. A previous storm on 14/4/83 produced 89.7 mm of runoff and removed 54.6 kg, or 6.3 kg ha^{-1}. Based on the 18-year series (1977-1994) of annual maximum quickflow events for the control catchment (DC2), storms with a total runoff of 90 mm have a return period of about 12 years. Events of this size were more frequent at DC1 and DC4 in the post-harvest period (1981-1985).

For DC4, no cation data were available for the storm of 14/4/83, but for the storm on 8/7/83 cation yields were 10 kg ha^{-1}, almost double that of

a) DC2



b) DC4

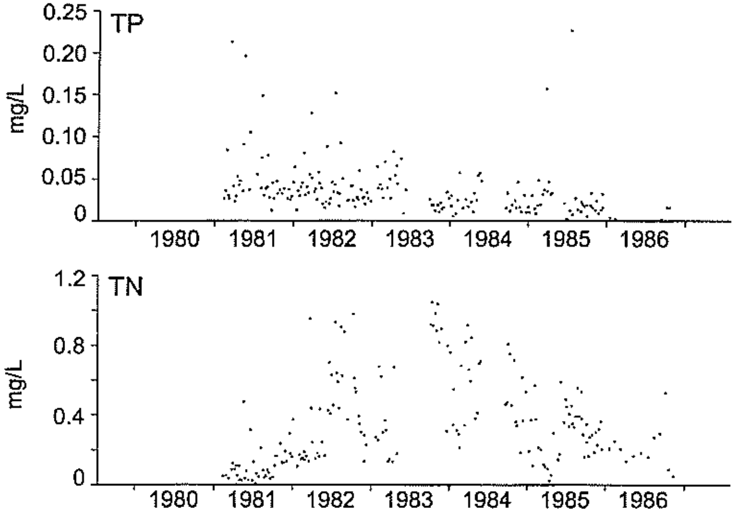


Figure 7 - Time plots of total N and total P concentrations at (a) the control catchment (DC2), and (b) a treated catchment (DC4) for the period 1980-1986.

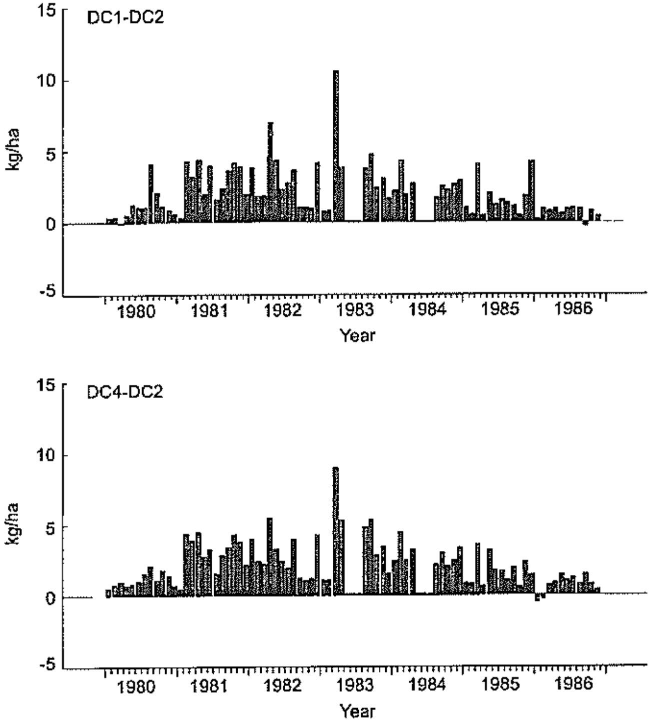


Figure 8 - Plots of the difference in monthly cation yields between (a) DC1 and control catchment DC2, and (b) DC4 and control catchment DC2.

Table 6 - Regression data for the relationship between flow and cation yield for storms monitored with automatic water samplers, and used to estimate annual losses for storms during the period 1980-86.

	DC2 (control)	DC1 (skidder-logged)	DC4 (hauler-logged)
No. of storms	3	12	10
Mean cat. yield	3.6 (±0.35)	21.95 (±14.92)	96.68 (±49.75)
r^2	0.972	0.917	0.907
Slope	0.21	0.52	2.06
Intercept	-1.66	0.23	26.9
St. error of the Y est.	0.83	4.29	16.2

DC1. This is 18% of the annual cation yield for DC4 (Table 5). For DC2 (the control catchment), data are available for only three storms, none of which corresponds with the high-magnitude events described previously for the treated catchments. The largest sampled event produced a total storm flow of 22 mm and an estimated cation yield of 0.5 kg ha^{-1}.

Annual yields associated with storms were estimated for the period 1980-1986 from the relationship between storm flow and cation yield (Table 6). Catchment DC4 had the highest annual cation yields in storm flow (33.3 kg ha^{-1}). The cation yields in baseflow (delayed flow between storms) were also calculated and the catchments showed a similar ranking (DC4 > DC1 > DC2). Apart from the control, average annual yields in baseflow were lower than those in storm flow by 20-30%.

Total nitrate and phosphorus

(a) Control catchment

Annual yields of total N in streamflow from the control catchment were low, and ranged from 0.18 kg ha^{-1} in 1985 to 0.44 kg ha^{-1} in 1983 over the 6-year record (Table 7). Total P yields were also very low (maximum 0.14 kg ha^{-1} in 1981 and 1983). These figures are comparable to those quoted by Neary *et al.* (1978) for DC1 before clearfelling (0.21 and 0.59 kg ha^{-1} for total P and total N respectively).

(b) Treated catchments

Catchment DC4 showed the biggest annual increase in total N yield after disturbance (Table 7). Yields reached 5.80 kg ha^{-1} in 1983, which was 33% higher than that for DC1. This can be explained, at least in part, by the high runoff from DC4 in 1983 (1350 mm or 13% more than from DC1). Over the period of record, average total N yields from DC1 and DC4 were an order of magnitude higher than those from DC2. By 1986, annual total N yields had fallen at DC1 and DC4 but were still 3-5 times higher than that for the control. Total P yields doubled or trebled after disturbance, with DC1 and DC4 showing a similar response. However, the maximum yield was only 0.54 kg ha^{-1} at DC4 in 1981.

Discussion

The water chemistry data for the control catchment, DC2, and the two harvested catchments, DC1 and DC4, can be compared with data collected by Graynoth (1979) for four larger catchments in Golden Downs Forest, approximately 10 km north of Donald Creek. One catchment in native

Table 7 - Annual yields of total N and total P in kg ha^{-1} for all catchments (1981-86)

	Total N			Total P		
Year	DC2	DC1	DC4	DC2	DC1	DC4
1981	0.32	1.27	1.28	0.14	0.47	0.54
1982	0.32	3.15	3.76	0.11	0.33	0.38
1983	0.44	3.93	5.80	0.14	0.40	0.34
1984	0.19	1.86	3.73	0.08	0.23	0.18
1985	0.18	1.12	2.34	0.08	0.18	0.24
1986	0.31	1.07	2.13	0.10	0.06	0.04
Mean	0.29	2.07	3.17	0.11	0.28	0.29

forest was selected as a control and the data compared with clearfelled and partially clearfelled catchments nearby for a 4-month period (Table 8). The concentration levels for the control and harvested catchments at Golden Downs are similar to those listed for Big Bush (Tables 3 and 4), suggesting that the data for Donald Creek are representative of small undisturbed and harvested catchments draining Moutere Gravel terrain.

It is impossible to determine what proportion of the increase in cation concentrations and yields observed at DC1 and DC4 can be attributed to the increase in flow after forest removal, and what proportion can be attributed to soil disturbance. Low flows were higher overall during the post-treatment period at both harvested catchments. Since Na^+ concentration is inversely related to flow, it is assumed that the general increase in Na^+ concentration after harvesting is in response to treatment, and not to increased flow. On the other hand, K^+ concentration is directly related to flow, making it difficult to establish whether the increased concentration and yield levels after harvesting and burning at DC1 and harvesting at DC4 are a response to an increase in flow, to the treatment, or to a combination of these two.

The increases in total N and P yields (Table 7) from the harvested catchments at Big Bush are consistent with those expected for a disturbed ecosystem. They are attributed to disturbance and not to increased flow because they are clearly much greater than the variations in annual yields of N and P from control catchment DC2, although the difference in annual runoff from DC2 in a wet year (e.g., 1983) as compared with a dry year (e.g., 1982; see Fig. 2) is similar to the increased water runoff after forest cutting. Nitrogen-fixing plants are not a significant component of the

Table 8 - Water chemistry data from forested, clearfelled, and partially clearfelled catchments in Golden Downs Forest (from Graynoth, 1979).

Catchment	Area (ha)	Treatment	Na^+	K^+	Mg^{2+}	Ca^{2+}	NO_3^-	TP
					mg L^{-1}			
Long Gully	232	Control	3.3	0.73	0.55	1.4	0.05	0.02
L. Gilbert Ck.	185	Clearfell	3.7	0.68	0.68	1.6	0.36	0.04
Rough'ns Ck.	2051	Clearfell	3.6	0.84	0.67	1.7	0.12	0.03
U. Gilbert Ck.	47	Clearfell with buffer	3.6	0.88	0.59	1.4	0.60	0.02

Table 9 - Annual cation and nutrient inputs (kg ha^{-1}) from rainfall at the Maimai experimental catchments, and Puketurua.

Source	Na^+	K^+	Mg^{2+}	Ca^{2+}	TP	PO_4^{3-}	TN	NO_3^--N	NH_4^+-N
Maimai (1980-84)†	32.7	13.6	4.2	4.3	0.53	0.53	*	3.2	1.9
Maimai (Neary *et al.* 1978)	28.9	5.7	3.9	2.1	0.26	0.16	2.81	0.65	0.73
Taita (Miller, 1961)	59	6.6	11.2	7.3	0.22	*	2.8	*	*
Taita (Claridge,1975a)	45	4.0	4.5	4.1	*	*	*	*	*
Puketurua (McColl, 1978)	17.0	4.0	0.7	2.5	0.40	0.05	*	0.25	1.0

† based on unpublished Landcare Research data

vegetation in either the undisturbed beech forest or the disturbed environment in the catchments at Big Bush. In the nitrification process microbial activity converts organic N to NH_4^+, some of which is oxidised to NO_3^- with the subsequent release of H^+ ions. The highly mobile NO_3^- ions are readily leached, whereas NH_4^+ is more likely to be immobilised by microbial action and assimilated by plants and animals. In undisturbed forests the nitrification process does not reach its full potential because much of the NH_4^+ produced is utilised by plants rather than being converted to NO_3^- (Likens *et al.*, 1977). Nutrients are retained, and any losses are normally replaced by inputs from rainfall. Thus streams draining native forests should have low concentrations of NH_4^+ and NO_3^-. After clearfelling, nutrient up-take by plants virtually ceases and the nitrification accelerates (Vitousek and Melillo, 1979). Previously unavailable N in slash and litter is converted by decomposition to NH_4^+ and micro-organisms oxidise NH_4^+ to NO_3^-. Some of the excess H^+ ions released in the process can be exchanged for basic cations. These in turn can be removed from the soil to appear in streamflow. In addition, the forest floor is exposed to greater amounts of light, heat, and moisture after clearfelling, increasing the rates of decomposition and mineralisation of organic materials. The release of these materials is a source of increased concentration of ions in streams. Fire can accelerate the nitrification process in forest soils. As clearfelled and burnt areas become revegetated, up-take of nutrients by live or growing plants will rise, reducing the concentrations of cations, NO_3^- and NH_4^+.

The response of cation and nutrient concentrations in streamflow to disturbance at Big Bush is similar to that observed in humus and soils at Larry's Creek near Reefton. Phillips and Goh (1985) monitored N-mineralisation in humus and soil beneath undisturbed beech forest and adjacent clearfelled and burnt plots at Larry's Creek, and observed nitrification to be enhanced after disturbance. Burning caused NH_4^+ levels to increase for up to 4 months. Large increases in NO_3^- in the soil solution were also attributable to nitrification. Goh and Phillips (1991) found that clearfelling of beech at Larry's Creek and subsequent slash burning increased K^+ and Ca^{2+}, and to a lesser extent Mg^{2+} in humus and the upper soil profile, whereas Na^+ concentrations were largely unaffected.

No measurements were made of inputs of nutrients and base cations from rainfall at Big Bush. However, data are available from rainfall samples collected at intervals of 1-2 weeks for the period 1980-1984 at the Maimai experimental catchments 100 km to the south-west (Table 9). Annual rainfall totals are higher at Maimai (2300 mm), but otherwise environmental conditions are similar to those at Big Bush. Input data are calculated as the product of the mean concentration and the rainfall total. Neary *et al.* (1978) also analysed the chemistry of rainfall at Maimai and except for NO_3^-, there is reasonable agreement between the two sets of data (Table 9). The Maimai data are also in the same order of magnitude as rainfall inputs listed by Miller (1961) and Claridge (1975a) for Taita near Wellington (Table 9). The proximity of Taita to oceanic salt sources, coupled with the windier environment, may explain the generally higher base cation concentrations at this site. Annual inputs from the Puketurua experimental catchment north of Whangarei are also given for comparison (McColl, 1978); they resemble the inputs listed for Maimai and Taita.

A comparison of the rainfall chemistry data in Table 9 with cation and nutrient outputs for DC2 (Tables 5 and 6) shows that more Na^+, K^+, Mg^{2+}, total N and total P are entering the system in rainfall than are being removed in streamflow. This may in part be explained by the higher rainfall at

Maimai and the shorter distance of other sites from the sea compared with Big Bush. In general, however, the data suggest that undisturbed beech forest at Big Bush shows an approximate balance between cation and nutrient inputs and outputs. Harvesting by either tractor or hauler causes a 2-fold increase in the export of base cations and a 10-fold increase in the export of total N in streamflow.

Table 10 - Base cation and nutrient yields (kg ha^{-1} yr^{-1}) in streamflow from native forest catchments, catchments recently harvested, and catchments in pasture.

Location	Na^+	K^+	Mg^{2+}	Ca^{2+}	TP	PO_5^{3-}	TN	NO_3^--N	NH_4^+-N
Native forest									
Ballance (Bargh, 1977)	*	*	*	*	0.24	*	1.96	*	*
Taita (McColl *et al.*, 1977)	*	*	*	*	0.20	*	*	0.01	*
Taita (Claridge, 1975b)	30.4	2.8	2.7	2.8	*	*	*	*	*
Maimai - M6 (Neary *et al.*, 1978)	35.1	7.3	4.2	13.9	0.35	0.21	0.58	0.44	0.23
Purukohukohu (Cooper & Thomsen, 1988)	*	*	*	*	0.12	*	3.67	2.84	0.56
Big Bush - DC2 (this study)	13.9	2.4	1.5	4.6	0.11	*	0.29	*	*
Harvested									
Maimai - M7 (O'Loughlin *et al.*, 1980)	67.4	75.4	21.8	59.2	0.57	*	*	2.25	*
Big Bush - DC1 (this study)	27.9	7.1	4.0	11.9	0.37	*	2.07	*	*
Pasture									
Taita (McColl *et al.*, 1977)	*	*	*	*	0.29	*	*	1.36	*
Puketurua - Pukewaenga† (McColl, 1978)	13.1	6.0	8.7	21.6	0.44	0.19	*	0.26	0.27
Tuakaka (Bargh, 1978)	*	*	*	*	6.50	*	5.20	*	*
Purukohukohu (Cooper & Thomsen, 1988)	*	*	*	*	1.67	*	11.95	1.19	0.48

† post-fertilizer floods

Annual yields of total N and total P in streamflow from DC2 are comparable to those recorded for native forest catchments elsewhere in New Zealand. Bargh (1977), for example, estimated that total N and P yields over one year from a 10 ha catchment under broadleaf evergreen species in the northern Tararua Ranges to be 1.96 and 0.24 kg ha^{-1} respectively (Table 10). At Taita, McColl *et al.* (1977) measured total P yields at 0.2 kg ha^{-1} yr^{-1} for native forest. NO_3^- - N losses were estimated at 0.01 kg ha^{-1} yr^{-1}. The undisturbed native forest at Purukohukohu has unusually high N outputs (Cooper and Thomsen, 1988).

After one of the Maimai experimental catchments (M7) was clearfelled and harvested by hauler, cation and nutrient concentrations increased dramatically (O'Loughlin *et al.*, 1980). When converted to annual outputs, NO_3^- -N yields went up about 20 times and K^+ 25-fold . Streams draining pastoral catchments can also carry substantial quantities of nutrients. Bargh (1978) calculated total P and total N yields from a 180 ha catchment in pasture in the northern Tararua Ranges at 6.5 kg ha^{-1} and 5.2 kg ha^{-1} respectively. Annual total N in runoff from the two harvested catchments at Big Bush in the 2-3 years immediately after harvesting were comparable to those calculated by Bargh (1978) for pasture, but total P yields were substantially lower. At Taita, total P and NO_3^- yields from a catchment in pasture were 0.29 and 1.36 kg ha^{-1} yr^{-1} (McColl *et al.*, 1977) which is comparable to those recorded at DC1. Cooper and Thomsen (1988) found that a pasture catchment at Purukohukohu in the central North Island exported 15 times more P and 3-10 times more N than neighbouring catchments in native forest and pines. The yields for both total P and N were 5 times those observed at Big Bush after harvesting (Table 10).

Close and Davies-Colley (1990) assessed the water chemistry of baseflow in rivers at 96 sites throughout New Zealand. They found that median concentrations were similar to world averages for fresh water concentrations for Na^+, but were lower for K^+, Ca^{2+}, and Mg^{2+}. Concentrations of NO_3^- and NH_4^+ were also much lower than world figures. Mean concentrations for base cations and nutrients calculated from data listed in Appendices A and B of Close and Davies-Colley (1990) were higher overall than at Big Bush, despite the degree of catchment disturbance. However, the mean concentrations for NO_3^- and total P were much the same as those observed by Close and Davies-Colley (1990). These results suggest that nutrient inputs to rivers during forest harvesting on terrain underlain by Moutere Gravels are not excessive when viewed in the light of concentrations at the regional and national level.

A few measurements of base cation and nutrient concentrations have been made at Big Bush since routine monitoring ceased in 1986. Stenzel

Table 11 - Base cation and nutrient concentrations (in mg L^{-1}) measured by Stenzel and Herrmann (1990) at Big Bush for DC1 and DC2, and by Landcare Research staff at DC1, DC2, and DC4 in 1993 to assess the water chemistry at mid-rotation.

Catchment	No. of Obs.	Na^+	K^+	Mg^{2+}	Ca^{2+}	NO_3^--N	PO_4^{3-}-P
Stenzel & Herrmann (1990)							
DC1	1	3.2	0.6	0.4	1.6	<0.01	0.02
DC2	1	3.4	0.9	0.5	1.8	<0.01	0.02
Landcare Research staff							
DC1	3	2.9	0.7	0.5	1.5	<0.1	<0.1
DC2	3	3.5	0.6	0.4	1.0	<0.1	<0.1
DC4	3	3.0	0.5	0.5	1.5	<0.1	<0.1

and Herrmann (1990) analysed samples from DC1 and DC2 as part of their comparison of the effects of acid deposition on the chemistry of small streams in New Zealand and Germany. In December 1993, samples were collected at all four Big Bush catchments to assess the water chemistry of the control and treated catchments mid-way through the forest rotation. The cation concentrations for the two data sets are similar (Table 11), and when they are compared with those representing the period 1980-1986 (Table 3), cation concentrations in flow from DC1 and DC4 are virtually the same as the mean values calculated for samples collected at DC2. Since runoff from pines at mid-rotation is much the same as that from beech forest (Fahey and Jackson, 1997), the water chemistry data suggest that, well before mid-rotation, catchments planted in pines will be yielding similar quantities of base cations and nutrients in streamflow to their counterparts in beech.

No data were collected on the nutrient capital of the forest floor and the soil profile at Big Bush. However, some information for N and K is available from other sources. Campbell and Mew (1986), for example, list soil chemistry data that can be used to estimate N pools at Big Bush. Assuming bulk densities of 0.2 and 1.0-1.4 kg m^3 for the litter layer and mineral soil respectively, the N capital for the forest floor and the upper metre of soil is estimated at 8000 kg ha^{-1}. Total N yields in streamflow represent a very small percentage of this pool. Although no estimates are available for K^+ content in Big Bush soils, Mew *et al.* (1975) quote figures of 108 and 270 kg ha^{-1} for the humus layer and mineral soil respectively, although not all of this will be available for plant growth. The amount of K^+ removed in streamflow from DC1 and DC4 (Table 5) is about 3% of this total, and compares favourably with the figure of 5% quoted by Neary *et al.* (1978) for catchment M7 at Maimai before harvesting.

Conclusions

Apart from Ca^{2+}, cation concentrations monitored at Big Bush in the control catchment were similar to those measured in streamflow from undisturbed beech-podocarp forest at the Maimai experimental catchments (Neary *et al.*, 1978). The higher Ca^{2+} levels at Big Bush may reflect minor lithological differences between the two sites. None of the treated catchments showed any dramatic increase in cation concentrations after disturbance. For the control catchment, nutrient concentrations were low. Only total N and NO_3^- - N responded markedly to disturbance but returned to pre-treatment levels after about 5 years.

An approximate balance may exist in cation and nutrient fluxes for undisturbed beech-podocarp forest at Big Bush. Harvesting by skidder or hauler causes cation and total P yields in streamflow to double and total N yields to increase 10-fold. Annual yields of total N approached those observed for pasture catchments elsewhere in New Zealand for the first few years after harvesting, but fell away in comparison as plantings became established. Total P yields after harvesting at Big Bush were much lower than those monitored in runoff from pasture catchments. Recently collected water chemistry data suggest that cation and nutrient fluxes from pine plantations at mid-rotation on Moutere Gravel are comparable to those from beech forest.

The results from this study demonstrate that additional nutrient loads to streams after clearfelling and burning are small or negligible and are unlikely to reduce water quality downstream. They also show that the increase in cation yields after clearfelling and skidder logging are unlikely to greatly exceed that associated with clearfelling and hauler logging. The same is true for nutrient yields after clearfelling using the two techniques.

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References

Bargh, B.J. 1977: Output of water, suspended sediment and phosphorus and nitrogen forms from a small forested catchment. *New Zealand Journal of Forestry Science 7:* 162-171.

Bargh, B.J. 1978: Output of water, suspended sediment, and phosphorus and nitrogen forms from a small agricultural catchment. *New Zealand Journal of Agricultural Research 21:* 29-38.

Bowen, W.F. 1964: Sheet 15 - Buller. Geological Map of New Zealand, 1:250 000, Wellington, New Zealand Department of Scientific and Industrial Research.

Campbell, I.B.; Mew, G. 1986: Soils under beech forest in an experimental catchment area near Nelson, New Zealand. *Journal of the Royal Society of New Zealand 16:* 193-223.

Claridge, G.G.C. 1975a: Element accessions in rainwater, Catchment 4, Taita Experimental Station, 1969-1974. N.Z. Soil Bureau Scientific Report 24. 56p.

Claridge, G.G.C. 1975b: Transit time: a factor affecting element balances in small catchments. *New Zealand Journal of Science 18:* 297-304

Close, M.E.; Davies-Colley, R.J. 1990: Baseflow water chemistry in New Zealand rivers 1. Characterisation. *New Zealand Journal of Marine and Freshwater Research 24:* 319-341.

Cooper, A.B.; Thomsen, C.E. 1988: Nitrogen and phosphorous in streamwater from adjacent pasture, pine, and native forest catchments. *New Zealand Journal of Marine and Freshwater Research 22:* 279-291.

Fahey, B.D.; Jackson, R.J. 1997: Hydrological impacts of converting native forests and grasslands to pine plantations, South Island, New Zealand. *Agricultural and Forest Meteorology 84:* 69-82.

Feller, M.C.; Kimmins, J.P. 1984: Effects of clearcutting and slash burning on stream water chemistry, and watershed nutrient budgets in southwestern British Columbia. *Water Resources Research 20:* 29-40.

Goh, K.M; Phillips, M.J. 1991: Effects of clearfell logging and burning of a *Nothofagus* forest on soil nutrient dynamics in South Island, New Zealand - changes in forest floor organic matter and nutrient status. *New Zealand Journal of Botany 29:* 367-384.

Graynoth, E. 1979: Effects of logging on stream environments and faunas in Nelson, New Zealand. *New Zealand Journal of Marine and Freshwater Research 13:* 79-109.

Hewlett, J.D.; Hibbert, A.R. 1967: Factors affecting the response of small watersheds to precipitation in humid areas. *In:* Sopper, W.E. and Lull, H.W. *(eds.), International Symposium on Forest Hydrology,* Proceedings of a National Science Foundation Advanced Science Seminar. Pergamon Press, New York: 275-290.

Jackson, R.J. 1985: Effects on soil water of conversion of beech/podocarp forest to pine plantation. In: Campbell, I.B. (ed.) Proceedings of the Soil Dynamics and Land Use Seminar, New Zealand Society of Soil Science, Wellington, pp. 230-242.

Johnston, M.R. 1979: Geology of the Nelson urban area (1:25 000), New Zealand Geological Survey urban series map 1. Map (1 sheet) and notes (52p.), Wellington, New Zealand Department of Scientific and Industrial Research.

Likens, G.E.; Bormann, F.H.; Johnson, N.M.; Fisher, D.W.; Pierce, R.S. 1977: *Biogeochemistry of a Forested Ecosystem.* Springer-Verlag, New York, 146p.

McColl, R.H.S. 1978: Chemical runoff from pasture: the influence of fertiliser and riparian zones. *New Zealand Journal of Marine and Freshwater Research 12:* 371-380.

McColl, R.H.S.; White, E.; Gibson, A.R. 1977: Phosphorus and nitrate runoff in hill pasture and forest catchments, Taita, New Zealand. *New Zealand Journal of Marine and Freshwater Research 11:* 729-744.

Mew, G.; Webb, T.H.; Ross, C.W.; Adams, J.A. 1975: Soils of the Inangahua depression, South Island, New Zealand. *New Zealand Soil Survey Soil Bureau Report, No. 17.*

Miller, R.B. 1961: The chemical composition of rainwater at Taita, New Zealand, 1956-1958. *New Zealand Journal of Science 4:* 844-853.

Mosley, M.P.; Rowe, L.K. 1981: Low flow water chemistry in forested and pasture catchments, Mawheraiti River, Westland. *New Zealand Journal of Marine and Freshwater Research 15:* 307-320.

Neary, D.G.; Pearce, A.J.; O'Loughlin, C.L.; Rowe, L.K. 1978: Management impacts on nutrient fluxes in beech-podocarp-hardwood forests. *New Zealand Journal of Ecology 1:* 19-26.

New Zealand Meteorological Service 1983: Summary of climatological observations to 1980. *New Zealand Meteorological Service Misc. Publ. 177.* 172p.

New Zealand Meteorological Service 1987: Rainfall observations for 1986. *New Zealand Meteorological Service Misc. Publ. 110.* 60p.

O'Loughlin, C.L.; Rowe, L.K.; Pearce, A.J. 1980: Sediment yield and water quality responses to clearfelling of evergreen mixed forests in western New Zealand. Proceedings of the Helsinki Symposium, June 1980: *International Association of Hydrological Sciences Publ. No 130:* 285-292.

Pearce, A.J.; O'Loughlin, C.L.; Rowe, L.J. 1976: Hydrologic regime of small undisturbed beech forest catchments, north Westland. *New Zealand Department of Scientific and Industrial Research, Information Series No.126:* 150-158.

Pearce, A.J.; Rowe, L.K.; O'Loughlin, C.L. 1980: Effects of clearfelling and slash-burning on water yield and storm hydrographs in evergreen mixed forests, western New Zealand. *International Association of Hydrological Sciences, Publication No. 130:* 119-127.

Pearce, A.J.; Rowe, L.K.; O'Loughlin, C.L. 1982a: Hydrologic regime of undisturbed mixed evergreen forests, south Nelson, New Zealand. *Journal of Hydrology (New Zealand) 21:* 98-116.

Pearce, A.J.; Rowe, L.K.; O'Loughlin, C.L. 1982b: Water yield changes after harvesting of mixed evergreen forest, Big Bush State Forest, New Zealand. Paper presented to Soil and Plant Water Symposium, Flock House, Bulls, 20-27 September, 1982.

Phillips, M.J.; Goh, K.M. 1985: Extractable soil nitrogen following clear-cutting and burning in a beech forest. *Soil Science Society of America, Proceedings 49:* 1563-1568.

Rowe, L.K.; Fahey, B.D. 1991: Hydrology and water chemistry changes after harvesting small, indigenous forest catchments, Westland, New Zealand. *In:* Sediment and Stream Water Quality in a Changing Environment: Trends and Explanation. *IAHS Publ. 203:* 259-266.

Rowe, L.K.; Pearce, A.J. 1994: Hydrology and related changes after harvesting native forest catchments and establishing *Pinus radiata* plantations. Part 2. The native forest water balance and the changes in streamflow after harvesting. *Hydrological Processes 8:* 281-297.

Rowe, L.K.; Pearce, A.J.; O'Loughlin, C.L. 1994: Hydrology and related changes after harvesting native forest catchments and establishing *Pinus radiata* plantations. Part 1. Introduction to the study. *Hydrological Processes 8:* 263-279.

Searle, P.L. 1975: Automatic colorimetric determination of ammonium ions in soil extracts with "Technicon Auto-Analyser II" equipment. *New Zealand Journal of Agricultural Research 18:* 183-187.

Stenzel, A.; Herrmann, R. 1990: Comparing the effects of acid deposition on the chemistry of small streams in the South Island of New Zealand with those in the Fichtelgebirge, F.R.G. *Catena 17:* 69-83.

Swank, W.T.; Crossley, D.A. 1987: *Forest Hydrology and Ecology at Coweeta.* Springer-Verlag, New York, 469p.

Vitousek, P.M.; Melillo, J.M. 1979: Nitrate losses from disturbed forests: patterns and mechanisms. *Forest Science 25:* 605-619.