

SOIL-WATER NUTRIENT CONCENTRATIONS AFTER CLEARFELLING AND BURNING OF *PINUS RADIATA*

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ABSTRACT

Tension plate lysimeters were used in Kaingaroa State Forest to determine the impact of harvesting of *Pinus radiata* D. Don (radiata pine), followed by slash-burning, on nutrient losses by leaching. Soil water was monitored just beneath the mineral soil surface, and at 20-, 45-, and 100-cm soil depths. Both operations increased the leaching of nutrients to lower soil depths; however, the effect was small and short-lived. Nitrogen in the nitrate form exhibited the greatest response as elevated concentrations in soil water persisted to 3 years after logging. The maximum monthly mean nitrate level recorded at a soil depth of 100 cm was 1.3 mg NO₃-N/l in the logged area and 2.1 mg/l in the burned area, compared to 0.12 mg/l in the control. Logging and slash-burning in radiata pine forests on the central volcanic plateau have only a small effect on nutrient leaching losses and do not appear to threaten soil fertility.

INTRODUCTION

Soils in exotic forests in New Zealand are required to supply sufficient nutrients for the growth of radiata pine on rotations of 25 to 30 years. The long-term effect of this intensive management on site productivity is not known but nutrient depletion resulting from harvesting will be most serious on nutrient-poor sites. Current harvesting methods remove stemwood and bark, leaving behind those components which have the highest concentrations of most nutrients. However, in view of the amount of biomass removed, nutrient export in logs itself represents an appreciable loss. Will (1968) reported that harvesting stemwood and bark from a stand of radiata pine growing on a good site would remove approximately 128, 18, 157, and 105 kg/ha of nitrogen, phosphorus, potassium, and calcium respectively. If whole-tree harvesting is employed, losses of these nutrients would increase by 75, 56, 43, and 23%. Where broadcast burning of logging slash is practised, nutrient capital may be further depleted as nitrogen, sulphur, and phosphorus are volatilised and lost from the site (Wells *et al.* 1979). In an extreme example, Grier (1975) reported 907 kg N/ha volatilised during an intense wildfire in old-growth forest in eastern Washington.

A more gradual and subtle loss occurs as nutrients are leached from decomposing organic matter and ash layers and lost from the soil system in drainage water. Although leaching occurs to a small extent under undisturbed forests, nutrient loss may be accelerated by clearfelling and by burning. The most dramatic documented example of

accelerated leaching after forest disturbance occurred in the Hubbard Brook Experimental Forest in New Hampshire (Likens *et al.* 1970). After clearfelling and herbicide treatment to prevent regrowth, the concentration of nitrate in streamwater increased by an average of 49 times, and major cation levels rose 6 to 22 times above control levels during the 2 years following treatment. Nitrogen output in the form of the nitrate ($\text{NO}_3\text{-N}$) ion increased from 2.0 kg N/ha to 125.5 kg N/ha and concentrations peaked at 19 mg $\text{NO}_3\text{-N/l}$; calcium concentrations climbed above 11 mg/l during this time.

The Hubbard Brook study was not intended to represent a normal clearfelling operation as logs were not removed from the site and revegetation was prevented by use of herbicides. Thus, the results from this study reveal the level of nutrient loss in streamwater which can be expected under extreme circumstances. Subsequent studies in commercially clearfelled stands in the Gale River watersheds in New Hampshire showed considerably lower nitrate and calcium levels in streamwater than measured in the devegetation study (Pierce *et al.* 1972). The maximum concentrations recorded during the 2 years after cutting were only 6.4 mg $\text{NO}_3\text{-N/l}$ and 6.6 mg Ca/l.

Studies conducted elsewhere in the United States revealed a nutrient-loss pattern similar to those reported from New Hampshire; however, absolute increases were generally much lower (Vitousek & Melillo 1979). Nitrate losses, which are considered to be a good indicator of nutrient losses in general (Likens *et al.* 1969), have ranged from no change after clearfelling of *Eucalyptus globulus* (Labill.) in California (McColl 1978), to 90-fold increases in average streamwater nitrate concentrations (0.02 to 1.8 mg $\text{NO}_3\text{-N/l}$) after clearfelling and slash-burning of cedar-hemlock-grand fir forest (*Thuja plicata* D. Don, *Tsuga heterophylla* (Raf.) Sarg., *Abies grandis* (Dougl.) Lindl.) in Idaho (Snyder *et al.* 1975).

Burning after harvesting further promotes leaching as plant uptake is completely eliminated and nitrate and bicarbonate (HCO_3) increase in soil solution. Metallic cations are converted to oxides during burning and are very susceptible to leaching in association with the nitrate and bicarbonate anions (Tiedemann *et al.* 1979). Although studies such as that by Neary *et al.* (1978) indicate an increase in nutrient output after burning over undisturbed conditions, they do not indicate what nutrient loss would have occurred if the logged area was left unburned. Kimmins & Feller (1976) made such a comparison and showed virtually no increase in streamwater losses of potassium, calcium, and nitrogen due to burning alone.

Sampling streamwater draining from uniformly treated (e.g., totally clearfelled) watersheds represents the most direct approach for assessing changes in nutrient leaching losses. However, in areas where an entire watershed is not treated or in circumstances where there is no surface water present for sampling, lysimeters may provide the only means of estimating leaching losses. In an early study Cole & Gessel (1965) used tension-plate lysimeters and showed that leaching losses were small after clearfelling of a Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) forest in Washington. McColl (1978) used porous ceramic cup lysimeters to investigate the effects of clearfelling a *Eucalyptus* stand on soil-water chemistry and found lower concentrations of potassium, calcium, magnesium, nitrate, and bicarbonate in the clearfelled area than in the undisturbed stand. Kimmins & Feller (1976) combined streamwater sampling with lysimeter samplings of soil water to investigate the effect of clearfelling

and broadcast slash-burning on nutrient output. Their results showed that soil-water leachate concentrations did not accurately reflect streamwater nutrient concentrations, partly because of the high variability in soil-water movement and chemistry. However, both methods did show an increase in nitrate and potassium loss and very little change in calcium loss.

Information on nutrient leaching loss after clearfelling in New Zealand forests is meagre. Neary *et al.* (1978) reported on the nutrient loss in streamwater after clearfelling and slash-burning of a *Nothofagus*-podocarp hardwood forest located on the West Coast of the South Island. The most spectacular result from this study was the large increase in cation loss after burning. This was mainly attributable to the effect of burning the massive accumulation of slash in the stream channel and the fact that heavy rain followed burning by a few days. The authors calculated that the amount of potassium lost (39 kg/ha) during the first 113 days after logging and burning represented 5% of the readily available potassium present in the system, but less than 0.1% of the total potassium capital. Although this study showed the impact of treatment on nutrient loss from the site, it did not show where the increased loss originated and whether the loss was partly due to leaching of nutrients through the soil profile or completely due to burning the slash which had accumulated near the stream channel. The use of lysimeters would have helped in the identification of the processes involved.

Biomass removal may eventually impair the productivity of a site, especially if the nutrient status of the site is inherently low and harvesting is frequent and intensive (Weetman & Webber 1972). However, in a recent review paper, McColl & Grigal (1979) contended that temporarily accelerated nutrient leaching losses induced by intensive forest harvesting are unlikely to have a measurable effect on site quality under well-managed harvest and post-harvest conditions.

In order to investigate nutrient leaching losses after harvesting of radiata pine according to current practice in New Zealand, a study was established in Kaingaroa Forest. Because of the depth of the pumice and the nature of the underlying bedrock it is impossible to accurately quantify runoff using gauged catchments in this region. For this reason and because entire catchments were not treated, lysimeters were used to monitor nutrient movement. Initially it was hoped to quantify nutrient movement but because of the very large variation in water volumes collected this approach was abandoned and only concentrations have been reported.

THE STUDY AREA

Kaingaroa State Forest occupies over 140 000 ha of the Kaingaroa Plateau at an elevation between 500 and 700 m. The surface soils of the plateau are yellow-brown pumice soils derived primarily from rhyolitic pumice ash deposits overlying ignimbrite rock. In some locations buried topsoils are present indicating that vegetation became established and soils formed during periods between volcanic eruptions. Prior to the initial planting of radiata pine and other conifer species, monoao (*Dracophyllum subulatum* Hook f.) and tussock (*Poa caespitosa* Forst.) dominated the vegetation of the plateau (Vucetich *et al.* 1960).

The study was conducted in Cpt 1099 along the northern boundary of Kaingaroa Forest, 30 km south-east of Rotorua. The predominant soil in the experimental area is Pekepeke sand which occurs widely in the northern part of the forest and occupies a total area of 9500 ha (Vucetich *et al.* 1960). Pekepeke sand is a coarse-textured, free-draining soil characterised by a friable sandy topsoil over loose gravel. A buried Taupo silty-sand fossil soil at a depth of 50 cm is a valuable source of moisture and plant nutrients (Pullar 1980). A chemical description of Pekepeke sand from Cpt 1099 (B. D. Webber, unpubl. data) is given in the Appendix.

Rainfall at Kaingaroa Forest headquarters, 8 km to the south of the study area, averages 1491 mm annually (N.Z. Meteorological Service 1979). Precipitation is fairly evenly distributed throughout the year with slightly higher rainfall during the winter.

Radiata pine was planted in Cpt 1099 in 1947 and the compartment was blanked the following year. The stand was low- and high-pruned, poison-thinned in 1957, and commercially thinned in 1962 to a stocking of 321 stems/ha. Prior to clearfelling in 1976 the average stem diameter (d.b.h.) was 45 cm, the average height was 40 m, and the merchantable volume was approximately 600 m³/ha.

METHODS

Site and Treatments

During August-September 1976, most of Cpt 1099 was harvested using rubber-tyred skidders to extract the logs; an area of several hectares in the eastern portion of the compartment was left undisturbed and functioned as a control during the study. The logged-over area was broadcast burned in February 1977 (referred to as the "burned" area) except for a small section of a few hectares which remained unburned (designated the "logged" area). The logged area and the burned area were planted with 2/0 radiata pine seedlings at 2 × 4 m spacing in June 1977. To control the prolific weed growth the logged area was sprayed with amitrole-atrazine in November 1977.

Monitoring System

Three pits were dug in each treatment area for the purpose of installing lysimeters. Alundum tension lysimeters, similar to those described by Cole (1958), were installed at four soil depths in two of the pits in each area. These depths were (1) just beneath the forest floor and mineral soil interface, (2) 20 cm, (3) 45 cm, and (4) 100 cm beneath the mineral soil surface. Using a hanging water column, a tension of 10 kPa (100 cm of water) was applied to each plate to simulate natural soil tension. Owing to possible adsorption of phosphate by the tension plates a single set of tension-free lysimeters was also installed in each remaining pit at the same depths as the tension lysimeters. These lysimeters consisted of dustpan-shaped stainless-steel trays (400 × 270 mm) with flexible tubing attached to a drain hole. The samples obtained from the tension-free lysimeters were analysed for phosphate-phosphorus only. Both types of lysimeters were installed by carefully excavating a horizontal slit of the same width as the lysimeter in the wall of the soil pit and inserting the lysimeter an arm's length into the slit. The lysimeters were sampled weekly beginning in February 1977, volumes

were recorded, and sub-samples were returned to the laboratory for chemical analyses. From February 1978 to the termination of the study in July 1979, the weekly samples were bulked by volume on a monthly basis before analysis.

Laboratory Analysis

Percolate pH and conductivity were determined (at 20°C) as soon as possible, usually within a few hours of collection, and the remaining sample was then preserved by adding 1 ml of mercuric chloride solution (4000 mg HgCl₂/l) per 100 ml of sample. Samples which could not be analysed immediately were frozen.

Soluble orthophosphate, ammonium, and nitrate were determined by automated colorimetric methods: phosphate was determined as the phospho-molybdate complex using ascorbic acid as the reductant, ammonium nitrogen was determined using the nitroprusside catalysed indophenol reaction, and nitrate nitrogen was determined as nitrite after reduction by hydrazine sulphate using the sulphanilamide method. Calcium, magnesium, and potassium were determined by atomic absorption spectrophotometry.

RESULTS AND DISCUSSION

The results of the chemical analyses of the soil leachate are presented as concentrations rather than quantities as the use of lysimeters generally precludes accurate measurement of soil-water flux. Monthly mean concentrations have not been tabulated but are referred to throughout the text and graphed for nitrate and calcium. The values shown in Tables 1–7 represent annual means calculated by averaging monthly mean values. The monthly means were calculated as the unweighted average of weekly concentrations up to February 1978, after which time weekly samples were bulked according to volume for each month. The design of this study precluded any meaningful statistical analysis being performed on the data as lysimeters were installed only in duplicate. Even at the same depths and under the same treatment, variations in nutrient concentrations, and especially in volume, were at times very high.

Rainfall during the first year of the study was fairly normal; however, there was an extended drought in early 1978 and rainfall for the year was only 1270 mm.

pH and Conductivity

The pH of the soil leachate in the undisturbed forest tended to increase as the water moved from the surface soil horizon to deeper layers (Table 1). Greater acidity in the surface leachate can be attributed to a number of factors, particularly the acid nature of radiata pine litter.

The only effect of logging was an increase in the pH of the surface leachate (Table 1). Burning resulted in an additional increase in the pH of the surface leachate and a tendency towards greater alkalinity at lower depths. This finding is in agreement with research reported in the literature (Grier & Cole 1971; Kimmins & Feller 1976; Raison 1979; Synder *et al.* 1975).

The conductivity of the soil water in the undisturbed stand varied only slightly with depth during the first year of monitoring (Table 2). However, in apparent response to an extended drought at the beginning of 1978, conductivity levels in the second

TABLE 1—Annual average pH of soil water at various depths in the soil profile under undisturbed, logged, and logged and burned conditions (standard deviations in parentheses)

Year	Soil depth	Control	Logged	Burned
1977	Surface	5.44 (0.18)	5.91 (0.32)	6.20 (0.32)
	20 cm	6.12 (0.13)	5.92 (0.23)	6.30 (0.28)
	45 cm	6.20 (0.18)	5.81 (0.37)	6.16 (0.22)
	100 cm	5.99 (0.35)	6.00 (0.48)	6.03 (0.22)
1978	Surface	5.36 (0.12)	5.78 (0.20)	6.04 (0.18)
	20 cm	6.22 (0.35)	6.22 (0.18)	6.43 (0.22)
	45 cm	6.07 (0.67)	6.15 (0.26)	6.43 (0.09)
	100 cm	6.17 (0.32)	6.06 (0.23)	6.27 (0.15)

TABLE 2—Annual average conductivity ($\mu\text{S}/\text{cm}$) of soil water at various depths in the soil profile under undisturbed, logged, and logged and burned conditions (standard deviations in parentheses)

Year	Soil depth	Control	Logged	Burned
1977	Surface	44 (15)	49 (17)	76 (64)
	20 cm	45 (15)	50 (22)	61 (28)
	45 cm	40 (7)	70 (46)	64 (26)
	100 cm	37 (5)	53 (20)	41 (5)
1978	Surface	63 (23)	34 (12)	17 (6)
	20 cm	50 (18)	18 (2)	21 (6)
	45 cm	41 (7)	40 (18)	24 (6)
	100 cm	32 (8)	40 (4)	31 (5)

year of monitoring were not as consistent. Similar behaviour was noted for both conductivity and cation concentrations in streamwater at a nearby catchment study (W. J. Dyck, unpubl. data).

As a result of logging, conductivity was slightly elevated at all depths during 1977 but was depressed below control levels in 1978 (Table 2). The low 1978 levels could have been partially as a result of dilution as more water would have been passing through the logged-area soil profile than through the control as a consequence of removing the vegetation. However, this is difficult to ascertain as quantitative measurements were not possible.

After burning, conductivity showed a large increase in the first collection in the top three soil depths, followed by a peak in April and May, and then a relatively rapid decline. The effect was most pronounced in the surface leachate with practically negligible response at 100 cm. Second-year conductivity levels in the burned area were consistently lower than in the control. Cole *et al.* (1975) reported a similar initial response in total ion concentration to burning, at the Thompson Research Centre. However, in their study, 2 years after burning total ion concentration in the surface leachate in the burned areas was still above levels of the unburnt (logged) control. It appears that in the present study leaching of available ions contained in the ash was more rapid than at the Thompson Research site, and that after the initial flux of ions concentrations declined below control levels, possibly due to a combination of

dilution and decreased ion availability. McColl & Grigal (1977) attributed a decline in soil-water nutrient concentrations during the 3 years after a wild fire partly to dilution by a volume increase in soil water.

Ammonium Nitrogen

Under standing forest, very little ammonium was present in the soil water at all depths monitored (Table 3). Accelerated decomposition and curtailment of nutrient uptake by trees after logging resulted in slightly elevated concentrations at all depths during the first year of monitoring. However, levels in the mineral soil subsided very quickly and ammonium concentrations remained elevated only in the surface leachate during the second year of study. During the third year of monitoring, concentrations at all depths were similar to control levels.

TABLE 3—Annual average ammonium nitrogen concentrations (mg/l) in soil water at various depths in the soil profile under undisturbed, logged, and logged and burned conditions (standard deviations in parentheses)

Year	Soil depth	Control	Logged	Burned
1977	Surface	0.039 (0.024)	0.043 (0.026)	0.380 (0.459)
	20 cm	0.019 (0.004)	0.072 (0.052)	0.038 (0.020)
	45 cm	0.033 (0.038)	0.039 (0.070)	0.028 (0.010)
	100 cm	0.008 (0.004)	0.020 (0.031)	0.008 (0.004)
1978	Surface	0.057 (0.024)	0.148 (0.159)	0.024 (0.004)
	20 cm	0.018 (0.006)	0.022 (0.007)	0.017 (0.005)
	45 cm	0.021 (0.004)	0.013 (0.004)	0.022 (0.015)
	100 cm	0.015 (0.009)	0.013 (0.006)	0.011 (0.007)
1979	Surface	0.064 (0.052)	0.068 (0.018)	0.028 (0.003)
	20 cm	0.008 (0.003)	0.017 (0.007)	0.017 (0.010)
	45 cm	0.015 (0.005)	0.010 (0.000)	0.010 (0.001)
	100 cm	0.011 (0.004)	0.012 (0.004)	0.010 (0.001)

Slash-burning produced a large and immediate peak in ammonium concentration in the surface leachate; the average concentration for the month after the burn was 1.18 mg NH₄-N/l *v.* 0.16 mg/l for the logged area. Concentrations in the mineral-soil water under the burned area were generally lower than under the logged-only area, possibly owing to greater activity of nitrifying bacteria and conversion of ammonium to nitrate after burning. Very little ammonium leached beyond 100 cm.

Nitrate Nitrogen

Leaching of nitrate in the unfelled plot was very low during the study period and concentrations were generally less than 0.1 mg NO₃-N/l (Table 4). The mean nitrate value for the surface leachate in 1979 (0.246 mg/l) is an exception; however, it should be noted that this value represents the average of only four monthly means and has a large error value associated with it.

Logging produced a substantial increase in nitrate concentrations in the mineral-soil leachate but only a slight rise in surface-leachate concentrations. During the first year of monitoring, maximum monthly mean concentrations observed at 20-

45-, and 100-cm depths were approximately 2.8 (April), 5.1 (May), and 1.3 (July) mg $\text{NO}_3\text{-N/l}$ respectively (Figs 1 and 2). Thus there was a time lag in peak concentration with depth. Also, the effect of logging on soil-water nitrate concentration disappeared most rapidly in the surface and 20-cm leachates but persisted through to the close of the study in the 100-cm leachate (Fig. 2). This appears to indicate that the nitrate ions were temporarily detained in the soil matrix and released gradually with time. This can possibly be attributed to anion exchange in the fossil topsoil located between 68 and 80 cm in the soil profile.

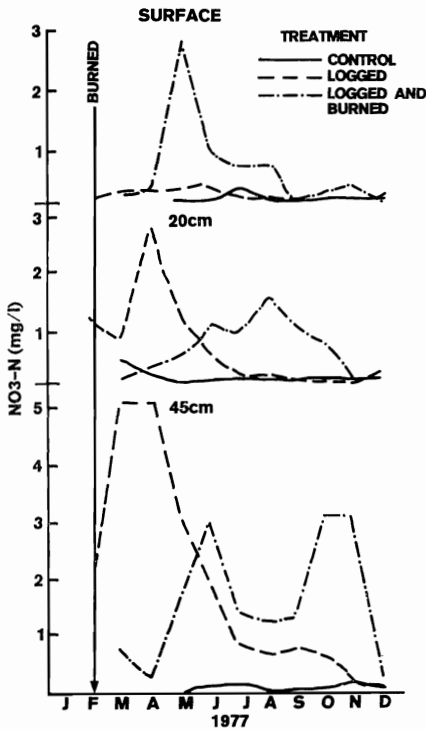


FIG. 1—First-year response of nitrate in soil water to logging and burning at surface, 20-, and 45-cm depths in the soil profile.

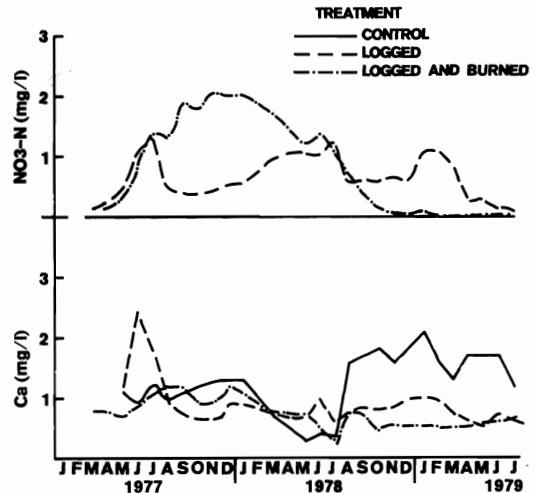


FIG. 2—Response of nitrate and calcium in soil water to logging and burning at 100-cm depth in soil profile.

The apparent lack of response of nitrate in the surface leachate after logging can best be explained by the fact that lysimeter installation was delayed until after burning. Thus the immediate post-logging period was not sampled and the peak nitrate concentrations in the surface and possibly the 20-cm plates were probably missed. This is supported by data from a recent lysimeter study also in Kaingaroa Forest in which nitrate in soil water at 70 cm began to increase 11 weeks after clearfelling of a radiata pine stand (W. J. Dyck, unpubl. data).

Concentrations of nitrate in the burned area responded similarly to those in the logged area, although surface-leachate concentrations were considerably higher during the first year (Table 4). Kimmins & Feller (1976) also noted a greater increase in nitrate levels in soil leachate and streamwater from their burned watershed than from their logged-only site. Although concentrations were higher from the burned watershed, the authors contended that total nitrate loss was not necessarily greater; burning simply appeared to have advanced the date of the increased stream nitrogen loss. Maximum monthly mean concentrations recorded in the burned area of the present study all occurred during the first year and were approximately 2.8 (May), 1.5 (August), 3.1 (November), and 2.1 (November) mg NO₃-N/l for the four depths in descending order (Figs 1 and 2). As in the logged area, the treatment effect diminished rapidly in the upper two sampling zones but continued into the end of the second year at the 100-cm depth (Fig. 2).

TABLE 4—Annual average nitrate nitrogen concentrations (mg/l) in soil water at various depths in the soil profile under undisturbed, logged, and logged and burned conditions (standard deviations in parentheses)

Year	Soil depth	Control	Logged	Burned
1977	Surface	0.067 (0.084)	0.115 (0.098)	0.652 (0.871)
	20 cm	0.082 (0.028)	0.635 (0.824)	0.609 (0.490)
	45 cm	0.096 (0.053)	1.855 (1.805)	1.601 (1.083)
	100 cm	0.066 (0.031)	0.599 (0.380)	1.188 (0.790)
1978	Surface	0.018 (0.003)	0.020 (0.015)	0.024 (0.005)
	20 cm	0.032 (0.023)	0.029 (0.010)	0.020 (0.008)
	45 cm	0.040 (0.036)	0.071 (0.105)	0.083 (0.142)
	100 cm	0.021 (0.015)	0.795 (0.258)	0.871 (0.713)
1979	Surface	0.246 (0.251)	0.210 (0.220)	0.259 (0.260)
	20 cm	0.060 (0.113)	0.122 (0.103)	0.208 (0.222)
	45 cm	0.010 (0.000)	0.018 (0.018)	0.013 (0.006)
	100 cm	0.010 (0.000)	0.542 (0.450)	0.024 (0.018)

Calcium, Magnesium, and Potassium

Calcium levels in the soil leachates were extremely variable. An initial response to logging was evident in the monthly means and the 1977 annual mean at the 45-cm depth (Table 5), and also in the monthly means at 100 cm (Figs 2 and 3). The effect diminished rapidly. During the second and third years of the study, average values in the logged area were generally lower than control leachate levels. The lower calcium levels encountered after the initial effects of logging had passed can be partly explained as a result of dilution due to more precipitation being available for leaching on the cleared area. In contrast to what occurred in the logged-only area, the effect of burning on calcium levels was not evident at the 100-cm depth (Fig. 2). Burning did produce an initial response in calcium concentrations at the surface, 20-, and 45-cm depths (Fig. 3 and Table 5) and concentrations remained elevated longer in the burned area than they did in the logged-only area. Again, the effect of treatment disappeared by the end of the first year.

TABLE 5—Annual average calcium concentrations (mg/l) in soil water at various depths in the soil profile under undisturbed, logged, and logged and burned conditions (standard deviations in parentheses)

Year	Soil depth	Control	Logged	Burned
1977	Surface	2.11 (0.48)	1.12 (0.56)	2.49 (1.44)
	20 cm	2.13 (0.76)	1.13 (0.33)	2.61 (1.26)
	45 cm	1.19 (0.27)	2.17 (1.38)	2.37 (1.24)
	100 cm	1.14 (0.16)	1.16 (0.63)	0.97 (0.20)
1978	Surface	3.52 (1.63)	0.83 (0.49)	1.24 (0.82)
	20 cm	2.06 (0.60)	0.96 (0.28)	1.21 (0.26)
	45 cm	1.17 (0.54)	0.68 (0.22)	0.80 (0.30)
	100 cm	1.02 (0.61)	0.80 (0.12)	0.64 (0.24)
1979	Surface	2.98 (0.90)	2.43 (0.13)	1.63 (0.28)
	20 cm	2.03 (0.82)	1.11 (0.45)	1.66 (0.23)
	45 cm	2.16 (0.70)	0.49 (0.38)	0.81 (0.25)
	100 cm	1.61 (0.30)	0.73 (0.17)	0.55 (0.05)

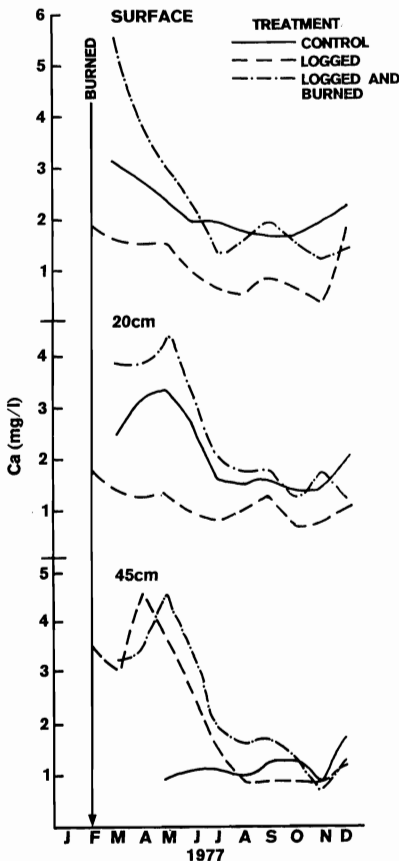


FIG. 3—First-year response of calcium in soil water to logging and burning at surface, 20-, and 45-cm depths in the soil profile.

Behaviour of magnesium (Table 6) closely paralleled that of calcium although the impact of burning on magnesium concentrations was evident at the 100-cm depth. The effect of logging showed up clearly at 45 and 100 cm in the first year of monitoring and maximum monthly mean values recorded at these depths were 4.1 (April) and 5.0 (June) mg Mg/l respectively. As for calcium, burning resulted in increased first-year concentrations of magnesium in the surface, 20-, and 45-cm leachates, and also at 100 cm. In both the logged and the burned areas an increase in concentration in the second year was evident only at 100 cm. Third-year concentrations were below control levels for both treatments at all depths. Again, the low concentrations were partly due to dilution from increased drainage water.

TABLE 6—Annual average magnesium concentrations (mg/l) in soil water at various depths in the soil profile under undisturbed, logged, and logged and burned conditions (standard deviations in parentheses)

Year	Soil depth	Control	Logged	Burned
1977	Surface	1.07 (0.19)	0.46 (0.26)	1.38 (1.00)
	20 cm	1.15 (0.48)	0.84 (0.38)	1.61 (0.93)
	45 cm	1.11 (0.35)	1.94 (1.41)	1.89 (1.28)
	100 cm	0.67 (0.10)	1.74 (1.42)	1.30 (0.44)
1978	Surface	1.77 (1.33)	0.42 (0.23)	0.59 (0.35)
	20 cm	1.06 (0.36)	0.64 (0.19)	0.63 (0.07)
	45 cm	0.91 (0.25)	0.51 (0.11)	0.48 (0.23)
	100 cm	0.55 (0.33)	0.74 (0.12)	0.77 (0.29)
1979	Surface	1.60 (0.56)	1.32 (0.28)	0.89 (0.28)
	20 cm	0.87 (0.20)	0.67 (0.10)	0.80 (0.18)
	45 cm	2.14 (0.89)	0.41 (0.19)	0.50 (0.22)
	100 cm	0.98 (0.15)	0.52 (0.06)	0.62 (0.07)

Potassium concentrations in the surface soil leachate showed a marked response to treatment as maximum monthly mean concentrations reached 25 mg K/l in the logged area (February), and 22 mg K/l in the burned area (March) during the first year of the study. The corresponding maximum control value was 6 mg K/l. Levels of potassium in the surface leachate in the logged area remained above control levels for the duration of the study (Table 7). The response of potassium concentrations to both logging and burning diminished markedly with depth. However, potassium levels at the 20-cm depth remained above control levels for the first year after burning. Only in the logged area was a response to treatment evident at the 45-cm depth. Neither treatment effected a response in potassium levels at the 100-cm depth. Potassium is easily leached from vegetation and ash, thus accounting for the high concentrations of the element in surface leachate. It is much less mobile in the soil matrix as it is readily held by certain clays and it is held more tightly as the soil pH increases (Tisdale & Nelson 1975 p. 255). This possibly explains why in the burned area, where soil pH increased the most, potassium concentrations rose only in the surface and 20-cm depths.

It is probable that post-logging peak concentrations of calcium, magnesium, and potassium in the surface and 20-cm leachate were not detected because of the delay in installing the lysimeters. The post-burning peaks in the surface leachate were also possibly missed as the maximum values recorded occurred on the first collection.

TABLE 7—Annual average potassium concentrations (mg/l) in soil water at various depths in the soil profile under undisturbed, logged, and logged and burned conditions (standard deviations in parentheses)

Year	Soil depth	Control	Logged	Burned
1977	Surface	4.51 (0.98)	15.25 (4.99)	11.02 (6.86)
	20 cm	2.88 (0.86)	7.39 (1.98)	4.53 (0.89)
	45 cm	2.51 (0.65)	4.48 (1.94)	1.98 (0.59)
	100 cm	1.65 (0.12)	1.70 (0.43)	1.64 (0.18)
1978	Surface	6.59 (2.08)	8.21 (2.64)	1.73 (0.90)
	20 cm	3.42 (1.22)	1.78 (0.90)	1.53 (0.35)
	45 cm	2.43 (1.16)	3.65 (2.31)	1.56 (0.30)
	100 cm	1.14 (0.81)	1.73 (0.57)	1.22 (0.42)
1979	Surface	1.58 (0.43)	6.14 (1.22)	0.81 (0.41)
	20 cm	3.01 (1.16)	2.45 (1.00)	1.18 (0.37)
	45 cm	3.79 (1.00)	4.07 (1.38)	1.59 (0.62)
	100 cm	2.59 (0.33)	2.32 (0.30)	1.42 (0.08)

Soluble Orthophosphate

Phosphate levels responded only slightly to treatment. The maximum monthly mean soil-water concentrations recorded at the soil surface in the logged area and the burned area were 0.119 (May) and 0.291 (April) mg PO₄-P/l respectively, compared to a maximum of 0.121 (June) mg PO₄-P/l in the control area. However, maximum post-logging concentrations may have been missed. Both the 20- and the 45-cm leachates in the logged area showed a small response during 1977 as the annual mean phosphate concentrations were 0.107 and 0.036 respectively, *v.* 0.014 and 0.006 mg PO₄-P/l for the control (Table 8). A definite response was not evident in the burned area at these depths. Results are not shown for the 100-cm depth as the tension-free lysimeters failed to function below 45 cm. The phosphate ion is very immobile in acid soils as it is readily fixed by iron and aluminium oxides (Tisdale & Nelson 1975 p. 199) and thus appears only in low concentrations in mineral-soil leachate.

TABLE 8—Annual average soluble orthophosphate concentrations (mg/l) in soil water at various depths in the soil profile under undisturbed, logged, and logged and burned conditions (standard deviations in parentheses)

Year	Soil depth	Control	Logged	Burned
1977	Surface	0.044 (0.031)	0.066 (0.041)	0.113 (0.087)
	20 cm	0.014 (0.006)	0.107 (0.067)	0.026 (0.029)
	45 cm	0.006 (0.001)	0.037 (0.009)	0.013 (0.007)
1978	Surface	0.002 (0.020)	0.053 (0.006)	0.029 (0.023)
	20 cm	0.014 (0.009)	T*	0.073 (0.111)
	45 cm	T	0.038 (0.052)	T
1979	Surface	T	0.028 (0.021)	T
	20 cm	T	T	T
	45 cm	T	T	T

* Trace (less than 0.010 mg/l)

GENERAL DISCUSSION

The impact of logging, and of burning after logging, on soil-water chemistry was most pronounced during the initial months after treatment. The effects rapidly diminished with time and also with depth in the soil. The exception to this was nitrate. For a number of reasons more attention has been directed in the literature to losses of nitrate than losses of any other ions (Vitousek *et al.* 1979). After a disturbance such as clearfelling, nitrate losses normally increase to a greater extent than losses of other ions, and elevated cation loss occurs in association with increased nitrate loss (Likens *et al.* 1969). As nitrogen supply is often growth-limiting to both terrestrial and aquatic organisms, the behaviour of its mobile forms, particularly nitrate, is of considerable importance to researchers and land managers.

Under undisturbed radiata pine nitrate leaching is very low, as shown in this study and in an earlier study by Knight & Will (1977). Rice (1974) speculated that many tree species, including pines, may inhibit nitrification. As ammonium is much less susceptible to leaching than nitrate, and because within plants nitrate needs to be converted to ammonium prior to the formation of amino acids, inhibition of nitrification provides a mechanism to conserve nitrogen and energy. Logging and slash-burning increased nitrate concentrations at the 100-cm depth, the greatest depth monitored, as well as at shallower depths. In addition, elevated nitrate levels continued for several months longer at the 100-cm depth than higher in the soil profile.

The initial response of calcium and magnesium to treatment was somewhat obscured by high control levels during the second and third years after treatment. The high control concentrations, especially evident in the surface plates, occurred in the autumn of 1978 and again late in the summer of 1979. The high cation concentrations at these times are the result of water flushing the soil after prolonged drought. Early 1978 was exceptionally dry (128 mm of rain in the first 3 months), one of the most severe droughts that has occurred in New Zealand in at least the last 30 years (N.Z. Meteorological Service 1978). The effects of the drought on soil processes are reflected in the unusually high peaks in June in the surface leachate and in August at 100 cm (Fig. 2). Foster & Walling (1978) experienced similar findings in streamwater cation concentrations from pasture after the 1976 drought in England. Levels of calcium and magnesium were found to be abnormally high in response to rain following the drought, whereas potassium concentrations remained relatively unaffected. The authors attributed increased solute levels to a number of factors including the accumulation of readily soluble material during the drought, the deposition of dry fall-out, and the formation of desiccation cracks for soil-water movement.

In the present study it appears that the transpiring forest enhanced the effect of the drought by drying out the soil in the undisturbed stand to a greater extent than in the clearfelled areas. The soil solution would have become more concentrated during the drought through evapotranspiration. According to Donnan Equilibrium theory (Wiklander 1964), the divalent cations calcium and magnesium would have increased in concentration more than the monovalent cation potassium, thus explaining the higher concentrations of calcium and magnesium in soil leachate when the soils were flushed by autumn rains.

Thus, it appears that although the treated areas released greater concentrations of calcium and magnesium to solution immediately after treatment, the undisturbed stand is capable of releasing even higher concentrations of these cations after drying periods. Unfortunately, the absolute amounts (kilograms per hectare) released from each area cannot be determined from this study.

This study indicates that increased nutrient leaching arising after logging and burning in Kaingaroa Forest is likely to be short-lived and to generally occur within 100 cm of the soil surface. Of the nutrients monitored, only nitrogen in nitrate form appears to have the potential to move beyond the rooting zone of radiata pine. The absolute amount of nitrogen being lost in this manner is not known but it is not expected to be great. For an approximation of loss a calculation can be performed. In the burned area the mean nitrate concentration during the first 12 months (March 1977 to February 1978) of monitoring was 1.3 mg NO₃-N/l and the total rainfall was approximately 1400 mm. If we assume that all the precipitation became deep seepage (an obvious gross over-estimate) then the loss of nitrogen would have been of the order of 18 kg/ha the first year. The corresponding loss during the next 12 months would have been less than 6 kg. Subsequent annual losses would have been very much less.

In comparison to total nitrogen reserves of 3351 kg/ha in the litter and the soil (made up of 3049 kg/ha in the soil to a depth of 103 cm and 302 kg/ha in the forest floor (B. D. Webber unpubl. data)), a loss of 18 kg/ha the first year after burning appears very minor. The amount of nitrogen estimated to have been lost from the site in crop removal was 214 kg/ha (B. D. Webber unpubl. data). Thus, nitrogen lost through leaching appears to be unimportant in comparison to that lost in the actual crop harvest and would also be much less than nitrogen volatilised during burning (though this was not measured). The leaching losses of nitrogen estimated in this study lie within the range of nitrogen losses measured in soil water and streamflow after logging and burning in North America.

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APPENDIX
ANALYSIS OF PEKEPEKE SAND

	Layer							
	I	II	III	IV	V	VI	VII	VIII
Thickness (cm)	14	10	8	6	5	5	17	38
pH	5.5	5.7	5.7	5.9	5.8	5.8	5.7	5.8
Conductivity ($\mu\text{S}/\text{cm}$)	25	9	9	8	7	9	13	10
Sand (%)	55	55	64	56	81	64	43	59
Silt (%)	34	35	28	35	11	28	48	33
Clay (%)	11	10	8	9	8	8	9	8
Total N (%)	0.082	0.024	0.012	0.01	0.01	0.01	0.046	0.032
Bray P (ppm)	32.0	45.0	23.0	11.7	8.7	15.6	12.5	13.3
Total C (%)	2.91	0.83	0.49	0.43	0.23	0.44	1.15	0.73
Exchangeable Ca (me/100 g)	2.04	0.44	0.29	0.29	0.37	0.30	0.50	0.46
Exchangeable Mg (me/100 g)	0.89	0.17	0.11	0.16	0.08	0.12	0.34	0.23
Exchangeable K (me/100 g)	0.47	0.14	0.49	0.54	0.50	0.57	1.26	2.76
C.E.C. (me/100 g)	17.6	7.4	6.0	5.8	8.6	8.9	20.0	19.9
Base saturation (%)	19	10	15	17	11	11	10	17