NITRATE LOSSES FROM DISTURBED ECOSYSTEMS IN NEW ZEALAND — A COMPARATIVE ANALYSIS

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ABSTRACT

Tube lysimeters were used to determine the relative potential of several ecosystems to lose nutrients through leaching after disturbance. The ecosystems examined were all on yellow-brown pumice soils and were dominated by species exotic to New Zealand: (1) **Pinus radiata** D. Don (radiata pine), (2) **Pseudotsuga menziesii** (Mirb.) Franco (Douglas fir), (3) **Eucalyptus saligna** Sm., and (4) **Ulex europaeus** L. (gorse). The treatments applied to the systems were trenching and weeding (for 1, 2, and 3), clearfelling (1), clearfelling followed by herbicide application and burning (2), and crushing and burning (4). Soil water was periodically collected from 10 lysimeters in each treated area as well as in undisturbed controls for up to 2 years after disturbance, and analysed for nitrate nitrogen as an indicator of nutrient loss. For the undisturbed systems nitrate loss was in the order gorse >> Douglas fir > **E. saligna** = radiata pine. Nitrate concentrations from the undisturbed gorse area averaged approximately 5 mg NO_3-N/l whereas nitrate from radiata pine averaged 0.006 mg/l. After disturbance relative nitrate loss was in the order gorse >> Douglas fir = radiata pine >> **E. saligna**. In the radiata pine and Douglas fir sites, trenching produced a greater response (max. 10 mg NO_3-N/l for both sites) than clearfelling or clearfelling followed by burning, probably due to rapid revegetation of the clearfelled areas. At two radiata pine sites, one made less fertile through 16 years of litter removal, soil-water nitrate concentrations increased at the same time after trenching; however, the less-fertile site showed greater resistance to nitrate release. The **E. saligna** site responded only very slightly to trenching, possibly because of allelopathic influences.

INTRODUCTION

Forest harvesting and site preparation for planting disrupt normal forest nutrient cycling as plant uptake is reduced or eliminated. Consequently, nutrients released during the accelerated decomposition which normally follows clearfelling (Stone 1973; Gadgil & Gadgil 1978) cannot be utilised and are therefore more susceptible to leaching. Nutrients are lost from a site if they are leached beyond the effective rooting depth of the succeeding tree crop.

Leaching of nitrogen in its most mobile form, nitrate, has received considerable attention in recent years. Nitrogen is often the most growth-limiting nutrient in both terrestrial and aquatic systems. Thus, loss of nitrogen from a forest may reduce site productivity, whereas the addition of nitrogen to an aquatic system may stimulate plant growth possibly to the detriment of that system. Nitrate leaching occurs more consistently and to a greater extent after a disturbance such as harvesting than leaching of other ions (Vitousek *et al.* 1979). Other elements are also lost in association with nitrate (Likens *et al.* 1969) because as the nitrate anion moves in the soil solution it must be accompanied by a cation (Nye & Greenland 1960).

Not all forest ecosystems respond in the same way to a disturbance such as harvesting and some release considerably more nutrients than others (Vitousek & Melillo 1979). The severity of disturbance can also greatly affect the degree to which nutrients are lost, and prolonged devegetation can cause very high levels of nutrient loss from some forest ecosystems (Likens *et al.* 1970).

It is important to recognise the potential for both site deterioration (through nutrient loss) and groundwater and streamwater quality degradation (through nutrient enrichment) arising from the probability of increased nutrient leaching after harvesting and subsequent site preparation. For this reason, a comparative study of nitrate loss was conducted at five sites in the central North Island.

METHODS

Of the five sites investigated in this study (Table 1), one was in radiata pine, two in Douglas fir, one in *Eucalyptus saligna,* and one in gorse (a nitrogen fixer). All sites were on yellow-brown pumice soils in the central North Island. The soils in Cpt 1104 (Douglas fir) and the gorse site were formed from Kaharoa ash, and the soils under radiata pine, *E. saligna,* and the Douglas fir in Cpt 1153 were formed from Taupo Ash (Vucetich *et al.* 1960). Annual rainfall for the region averages 1500 mm (N.Z. Meteorological Service 1979) and mean annual temperature at Kaingaroa Forest headquarters (544 m a.s.l.) is approximately 11°C.

Compartment 69 in Kaingaroa Forest (Table 1) is the site of a litter-removal trial (Ballard & Will 1981) in which debris was removed before crop establishment and radiata pine litter and thinning waste were regularly removed from a 0.16-ha plot for 10 years after the stand was first thinned at age 6. Litter raking resulted in a 12% reduction in stem volume growth as well as a significant reduction in the nutrient status of the site (Ballard & Will 1981), and the area was included in this study to provide a comparison of the effect of disturbance on nitrogen leaching loss from a fertile and a less-fertile site.

TABLE 1—Description of study sites

Dominant vegetation	Location	Age (years)	Stocking (stems/ha)	Topog.	Soils
Radiata pine	Cpt 69 Kaingaroa State Forest	20	250	flat	Kaingaroa silty sand
Douglas fir	Cpt 1104 Kaingaroa State Forest	56	200	flat	Te Rere sand
Douglas fir	Cpt 1153 Kaingaroa State Forest	56	200	gentle slope	Kaingaroa silty sand
E. saligna	Cpt 83 Rotoehu State Forest	18	100	gentle slope	Manawahe coarse sand
Gorse	Rangitaiki River terrace, Fort Galatea	20	dense	flat	Galatea sand

Trenching and lysimetry were used to create and then monitor a disturbance which could readily be repeated.

On the radiata pine site four treatments were applied – control, clearfelled, trenched, trenched and litter-raked; on the Douglas fir site in Cpt 1153 – control, trenched, and in Cpt 1104 – clearfelled and burned; on the *E. saligna* site – control, trenched; and on the gorse site – control, crushed and burned.

The clearfelling treatments represented normal logging operations for Kaingaroa Forest as only logs were removed and tops and branches were left scattered over the site. Because grass growth in the Douglas fir cutover was prolific, a herbicide (2,4,5-T plus paraquat) was applied several weeks prior to burning. The gorse area was burned 1 week before the first sample was collected for analysis and, because of the invasion of grass and regrowth of gorse, the area was sprayed (2,4,5-T) and burned again 11 weeks later. The lysimeters were protected by concrete pipes filled with sand during both the burning of the Douglas fir area and the second burning of the gorse site.

Trenching involved constructing trenched plots similar to those used by Vitousek *et al.* (1979). In our study a trenched plot consisted of a treeless plot of soil, approximately 1 × 2 m in area, isolated from the surrounding forest by a 1-m deep trench lined with polythene (250 micron) and backfilled outside the lining. Vegetation on the plots was severed at ground level and regrowth was prevented by periodic weeding. Five trenched plots were used at each site which included this treatment, and porous cup lysimeters (Grover & Lamborn 1970) were installed in pairs in each plot (i.e., 10 lysimeters per trenched treatment). In the control and clearfelled areas, lysimeters were installed 2 m apart in a nearly straight line. Where possible, lysimeters were at a depth of 70 to 80 cm, well below almost all fine roots and most coarse roots. However, some lysimeters were installed to only 60 cm as it was thought that the coarse lapilli layer present would seriously affect the performance of the lysimeters through poor contact between the lysimeter cups and the lapilli.

Sampling commenced between 29 March and 12 April 1979 on all sites except the clearfelled Douglas fir where, because of logging operations, it was delayed until

11 May. Sampling was normally conducted every 5 weeks but it was more intensive at the start of the study, and weekly sampling was done immediately after burning in the Douglas fir area. The radiata pine, Douglas fir, and gorse sites were sampled on the same days and the *E. saligna* site was sampled a week later. The radiata pine and Douglas fir sites were monitored for 103 weeks, the gorse site was sampled for 67 weeks, and the *E. saligna* site for 56 weeks.

A vacuum of approximately 30 kPa was applied to each lysimeter and soil-water samples were collected the following day. They were preserved with mercuric chloride (40 mg $HgCl_2/l$), returned to the laboratory for analysis, and stored at 4°C if immediate analysis was not possible.

Nitrate nitrogen was determined on each sample by hydrazine copper sulphate reduction (Technicon Corporation 1973). Variation in nitrate concentrations between lysimeters did not approach normal distribution and so differences between treatments were tested statistically by nonparametric methods, viz Kruskal-Wallis and Manning-Whitney tests (Lehmann 1975).

RESULTS

Radiata pine

Soil-water nitrate concentrations under the control plot in the 20-year-old radiata pine stand averaged 0.006 mg NO_3-N/l during the 2 years of monitoring (Fig. 1). Seven weeks after treatments were applied, nitrate concentrations for the clearfelled, trenched, and trenched and litter-raked plots were significantly (p = 0.05) greater than control levels and remained so for the duration of the study. Nitrate concentrations in the clearfelled area never exceeded 2.3 mg NO_3-N/l and at the close of the study were

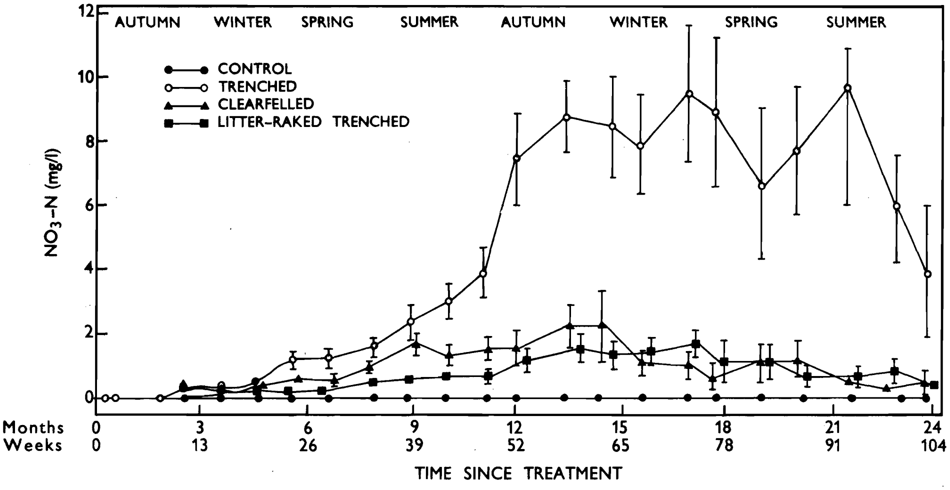

FIG. 1—Response of soil-water nitrate concentrations to disturbance on the radiata pine sites. Values reported are the mean (± S.E.) concentrations. Standard error bars are not shown where smaller than the symbol. Seasons are: Spring - Sept. to Nov.; Summer - Dec. to Feb.; Autumn - Mar. to May; Winter - June to Aug.

around 0.4 mg/*l*. Soil-water nitrate in the litter-raked trenched plots showed a response similar to that in the clearfelled area as concentrations peaked at 1.6 mg NO_3-N/*l* and were less than 0.4 mg/*l* at the end of the study. The response in the unraked trenched plots was the greatest as nitrate exceeded 1 mg NO_3-N/*l* 23 weeks after trenching and reached a maximum concentration of 9.7 mg/*l* after 21 months. This was followed by a fairly rapid decline to less than 4 mg NO_3-N/*l* at the close of the study. Between 15 weeks and the end of the study, nitrate in soil water from the normal trenched plots was significantly ($p = 0.05$) greater than from the litter-raked trenched plots, and after 10 months it was significantly greater than from the clearfelled area.

Douglas fir

Nitrate concentrations in soil water from the control plot in the 56-year-old stand of Douglas fir averaged 0.272 mg NO_3-N/*l* during the 2-year period. Nitrate showed a small response after clearfelling but it was not until the area was burned that concentrations showed an obvious increase (Fig. 2), reaching a maximum of 3.8 mg NO_3-N/*l* by the close of the study. A single sampling after 28 months showed that nitrate concentrations had declined to less than 1.0 mg NO_3-N/*l*. Soil-water nitrate concentrations from the trenched plots 11 weeks after trenching were significantly greater than from the control and remained so throughout the study. Nitrate concentrations did not show a steady increase as in the radiata pine trenched plots but initially peaked at 4.7 mg NO_3-N/*l* after 11 weeks, declined, and reached a maximum of 10.5 mg/*l* 13 months after trenching. This peak was followed by a rapid decline and then a slight increase to 4.2 mg NO_3-N/*l* at the end of the study.

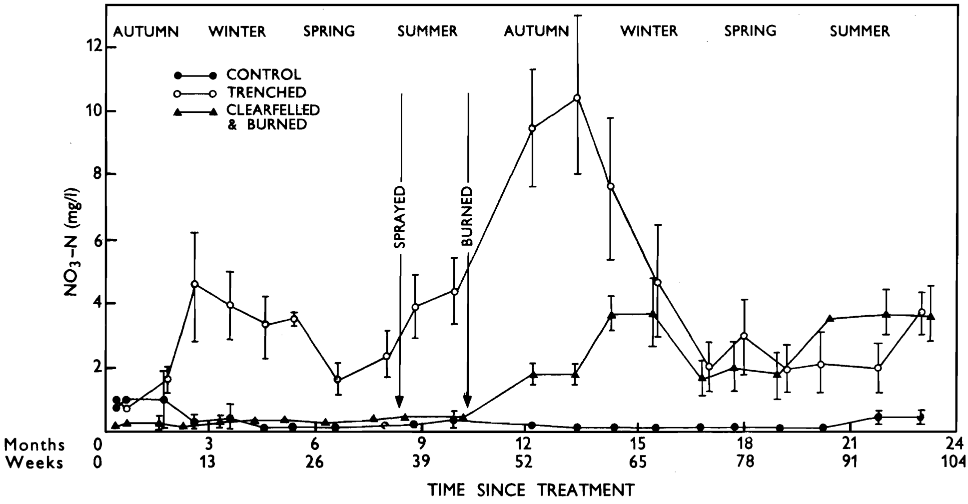

FIG. 2—Response of soil-water nitrate concentrations to disturbance on the Douglas fir sites (see Fig. 1 for definitions of the symbols and seasons).

Eucalyptus saligna

Soil-water nitrate concentrations beneath the control plot in the *E. saligna* stand were generally very low and averaged 0.08 mg NO_3-N/*l* during the year of monitoring (Fig. 3). There was a small (up to 0.6 mg NO_3-N/*l*) but significant ($p = 0.05$) increase in nitrate concentration in the trenched plots starting at 19 weeks and lasting to 37 weeks after trenching.

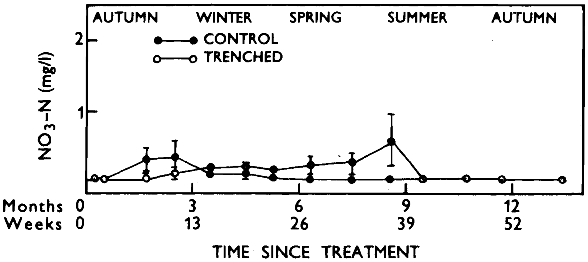

FIG. 3—Response of soil-water nitrate concentrations to disturbance on the **E. saligna** sites (see Fig. 1 for definitions of the symbols and seasons).

Gorse

Nitrate levels in soil water under the control plot in the gorse area averaged 5.1 mg NO_3-N/*l* and showed a winter peak the first year of monitoring and another peak the following autumn (Fig. 4). Concentrations in the crushed and burned area were high at the first collection 1 week after burning, and a maximum recorded value (23.3 mg/*l*) occurred in week 10. Nitrate in soil water increased immediately in response to the second burn but not to spraying, and peaked at 22 mg NO_3-N/*l*. Concentrations then rapidly declined to near control levels.

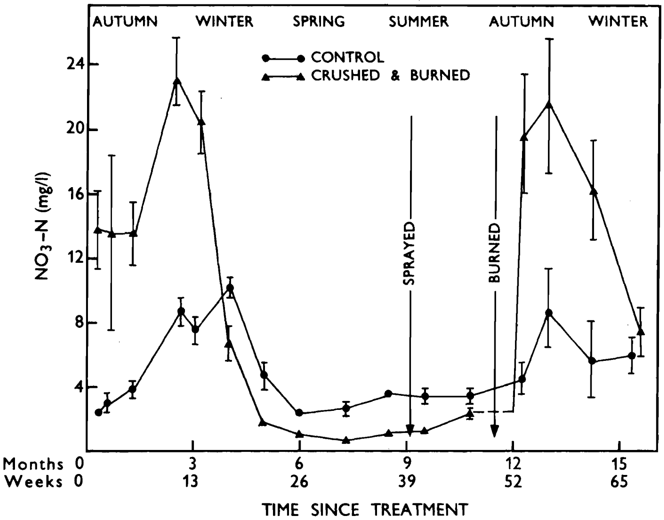

FIG. 4—Response of soil-water nitrate concentrations to disturbance on the gorse sites (see Fig. 1 for definition of the symbols and seasons).

DISCUSSION

In this and other studies (Knight & Will 1977; Dyck *et al.* 1981) nitrate leaching to groundwater under radiata pine forest was low. Clearfelling and trenching resulted in a rapid increase in soil-water nitrate concentrations and there was virtually no lag in nitrate response. It may be that a considerable population of nitrifying bacteria was present in the soil prior to disturbance but it was inhibited in some way (Matson & Vitousek 1981). If nitrification had been proceeding at a high rate prior to disturbance there would probably have been a greater flush of nitrate immediately after treatment rather than the progressive increase observed. The gradual increase in nitrate may reflect a process of change in the organic substrate induced by a gradual release from the inhibition (Gadgil & Gadgil 1978).

The maximum nitrate concentrations recorded in the clearfelled area were substantially lower than in the unraked trenched plots (Fig. 1) and similar to those reported for a clearfelled area in an earlier study (Dyck *et al.* 1981). This is most likely a consequence of nutrient uptake by weeds which rapidly colonised the clearfelled site but may also be partly due to immobilisation of nitrogen by organisms decomposing logging debris. The fairly rapid decline in nitrate concentrations in the clearfelled area compared to the extended high nitrate levels in the unraked trenched plots suggests that a reduced nutrient loss can be expected if logged areas are allowed to revegetate rapidly.

The large nitrate response observed in the unraked trenched plots indicates a large pool of potentially available nitrogen in the forest floor and soil. There was a much smaller response in the adjacent raked area suggesting a smaller store of readily mineralisable nitrogen. Ballard & Will (1981) noted that immediately after thinning (at age 16) foliar nitrogen concentrations in the raked area were lower than in the unraked control ($p = 0.1$). This occurred despite conditions favourable for mineralisation, because the amount of readily decomposable organic matter present was insufficient to fully meet the nitrogen demands of the expanding crown.

Douglas fir may actually require nitrate as it apparently grows very poorly in its natural habitat where only ammonium is available (Krajina 1969) although it has the ability to use both the ammonium and nitrate forms of nitrogen (van den Driessche 1971; Bigg & Daniel 1978). Species with low nutrient requirements, such as pines, appear to favour ammonium as a nitrogen source (Gosz 1981; McFee & Stone 1968; Rice & Pancholy 1972). It may be that radiata pine creates soil conditions (e.g., reduced decomposition rates (Gadgil & Gadgil 1978)) which discourage nitrification in order to keep the nitrogen in ammonium form. This may account for the higher soil-water nitrate concentration in the Douglas fir control plot than in the radiata pine.

The smaller post-clearfelling increase in nitrate concentrations in the Douglas fir plot than in the radiata pine was probably due to greater immobilisation of available nitrogen by weed growth and decomposer organisms in the Douglas fir area. However, a flush of nitrate may have occurred immediately after felling and not been detected because it was impossible to install lysimeters during the logging operation. The almost immediate increase in nitrate concentrations after burning was probably due to the elimination of plant uptake and the creation of soil conditions favouring nitrification (*see* reviews by Tiedemann *et al.* 1979; Raison 1979).

The initial increase in nitrate loss from the Douglas fir trenched plots may have been the result of the leaching of nitrate present in solution prior to disturbance and no longer taken up by vegetation. The decline after the initial flush possibly reflects a lag while populations of decomposers built up and utilised available nitrogen. The large peak would have been the result of the nitrification and subsequent leaching of easily mineralisable nitrogen. The sudden decrease in nitrate leaching after 13 months probably reflects the exhaustion of readily mineralisable nitrogen in the system. This also occurred in the radiata pine trenched plots, although after a longer time.

In a New Zealand study of nine ecosystems involving gorse and associated shrubs and trees, Egunjobi (1969) found that total accumulated nitrogen as well as soil nitrogen content was higher in ecosystems dominated by gorse than in later successional ecosystems. He suggested that the level of soil nitrogen will decrease when the gorse phase is followed by non-nitrogen-fixing species because of plant uptake, leaching, and run-off losses. The results from our study support this theory as it appears that decomposing gorse tissue releases fairly large amounts of nitrate to groundwater. According to Egunjobi (1969) this should continue and soil nitrogen content should decline as gorse is replaced by other species.

Burning would probably have stimulated nitrification through the liberation of basic cations in the ash and an increase in pH. Seventeen weeks after the first burn, nitrate concentrations were lower than in the control plot, indicating that all readily available nitrogen had either been nitrified and leached, or was being immobilised by decomposers or the prolific weed regrowth. The fact that nitrate leaching increased considerably after the second burn (but not after spraying) indicates that a great deal of available soil nitrogen had been immobilised in regrowth. However ,the young gorse regrowth may have also fixed a considerable quantity of atmospheric nitrogen which would have been released after burning.

It was unlikely that denitrification was the reason for the *Eucalyptus* site not releasing much nitrate to soil water as the soils are very well drained and the pH averages 5.5. Chemical inhibition (allelopathy) of nitrification was considered a possibility and the results of a small laboratory experiment suggested that nitrification was inhibited by chemicals leaching from the *E. saligna* foliage (unpubl. data). Work is currently being done to test this hypothesis further.

The results from both the radiata pine and Douglas fir areas indicate the importance of rapid revegetation for controlling leaching losses. Trenching and weeding prevented nutrient uptake and nitrate concentrations increased considerably over those in the clearfelling and control treatments. It seems reasonable to assume that a similar response would occur after clearfelling if revegetation was prevented for a prolonged period – viz Hubbard Brook (Likens *et al.* 1970).

The amount of nitrogen and other nutrients released after a disturbance depends on several factors including the rate of nitrogen mineralisation prior to disturbance, the increase in the rate of mineralisation caused by the disturbance, and the extent to which plant uptake is reduced or eliminated. Also, there are several processes in addition to plant uptake which can prevent or delay solution losses of nitrate. These processes include ammonium immobilisation and volatilisation, nitrate reduction and immobilisation, and lack of drainage water (*see* Vitousek *et al.* 1982).

Vitousek *et al.* (1979) investigated the effect of trenching on nitrate loss from 19 sites throughout the United States, but not the ability of sites to recover after a disturbance. They associated nitrification with more fertile sites and speculated that infertile (nitrogen-poor) sites should have a relatively high resistance (in terms of magnitude of response) to nitrate loss but a low resilience (in terms of rate of recovery), while fertile (nitrogen-rich) sites should be the reverse. Their theory suggests that our gorse site was the most "fertile" owing to its high nitrification rate. As predicted, the gorse site showed the lowest resistance and the highest resilience – after disturbance, nitrate concentrations rapidly fell below levels in the control plot. The Douglas fir site was intermediate in that it showed, at least initially, lower resistance than the radiata pine site and possibly a greater resilience (lower leaching losses in the Douglas fir cutover prior to burning). The radiata pine site showed greater resistance than the Douglas fir or gorse and a high resilience, as indicated by the reduced losses in the cutover. The radiata pine site also showed a more rapid response than North American pine sites (Vitousek *et al.* 1982) possibly because in the United States study the pine sites were on poorer soils and in a less suitable climate.

Two Douglas fir sites were examined in the American study, one of low site quality and the other high. The low-quality site produced a small and delayed lysimeter-nitrate response. The high-quality site responded, after only a slight lag, with a much greater nitrate loss – a response similar to that of our trenched Douglas fir site. However, contrary to the theory of Vitousek *et al.* (1979, 1981) that infertile sites should respond more slowly than more fertile ones, our litter-raked radiata pine site responded at the same time as the more fertile unraked site, although to a lesser extent. Thus, factors such as climate may be more important than available plant nutrients in determining the time to respond; the store of available nutrients is critical in determining the magnitude of the response.

CONCLUSIONS

Nitrate leaching is low in undisturbed radiata pine, Douglas fir, and *Eucalyptus saligna* ecosystems but is much greater under gorse. However, there is a potential for considerably increased nitrate leaching in radiata pine and Douglas fir areas if nutrient uptake is prevented for an extended period. Crushing and burning gorse may result in even greater nitrate leaching.

After a disturbance nitrate leaching should be less from infertile sites than from more fertile ones, although the response time may be the same.

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