DOES CONTACT OF *PINUS RADIATA* SLASH WITH SOIL INFLUENCE POST-HARVEST NUTRIENT LOSSES?

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(Received for publication 9 January 1997; revision 15 December 1997)

ABSTRACT

Although nitrogen dynamics during litter decay have been studied extensively, little work has addressed the contribution of needles in harvest residue to nutrient losses. We examined the decay of *Pinus radiata* D. Don needles on slash and not touching the soil, from compartments clearfelled between 4 months and 4 years previously in Himatangi and Santoft Forests. Fresh foliage was also collected from 25-year-old *P. radiata*, together with soil F, H, and A horizons. The needles and soil samples were incubated, both separately and combined, in suction vessels and leached regularly with water. Most nitrogen was leached from the 4-month and 4-year needles, and amounted to about 8% of the total nitrogen; little nitrogen was leached from fresh foliage. Nitrate-nitrogen was the dominant form of nitrogen leached from the 4-year needles, whereas ammonium-nitrogen was dominant from the 4-month and 1-year needles. More nitrate-nitrogen was produced when the 4-month needles were incubated on top of F, H, or A horizon samples which increases potential for leaching. These data were consistent with field results from lysimeters showing nitrate-nitrogen was leached under 2-year-old windrows and raked soil in Santoft Forest. Net phosphorus mineralisation occurred readily in the older needles and mineral soil, and with time could contribute to the labile pool of phosphorus. Our results suggest that post-harvest losses of nitrogen could increase when large amounts of slash remain in stockpiles. Water-soluble carbon compounds were released from all the foliage samples. Differences in nitrogen losses and forms of nitrogen mineralised are likely to be related to changes in quality of carbon in needles after harvest.

Keywords: clearfelling; leaching; lysimeters; mineralisation; nitrification; nitrogen.

INTRODUCTION

When forests are clearfelled, nitrogen (N) is released into soil solution, and some nitrogen may be leached and find its way into streamwater (Dyck *et al.* 1981; Dahlgren & Driscoll 1994). In New Zealand, soil solution nitrate (NO_3) concentrations under *Pinus radiata* forest have been shown to increase in the period 3–24 months after clearfelling (Dyck *et al.* 1983; Smith *et al.* 1994). This loss of nitrogen may influence streamwater quality and long-term nutrient reservoirs in plantation forests.

Nitrogen loss post-harvest may arise from several sources. The most likely are increased mineralisation of mineral-soil nitrogen, and nitrogen released during decomposition of needles and slash produced during forest harvest (Smethurst & Nambiar 1990a, b; Smith *et al.* 1994). Will *et al.* (1983) studied the decomposition of air-dried yellowish-brown needles of *P. radiata* in litter bags in contact with soil. In open clearfelled sites, needle mass loss rates were less than in plantation sites with closed canopies, and no nitrogen loss occurred during the first 70 weeks. Litter nitrogen concentration increased from 0.7% to1.4% over 4 years. Large amounts of phosphorus (P) and potassium (K) were lost in the first 9 weeks of the incubation. Baker *et al.* (1989) obtained similar results for green needles, except that nitrogen was lost more rapidly (83% in 52 weeks) and no phosphorus was lost in the first 12 weeks. These results suggest that fresh foliage and recent litterfall generally immobilise nitrogen, and are unlikely to contribute to large losses of nitrogen in the first months after harvest.

Substrate quality is a major factor altering litter decay (Heal *et al.* 1997) and nutrient cycling rates (Scott & Binkley 1997) in forest ecosystems. The decomposition rate of *P. sylvestris* L. needle litter was regulated by climate in the initial stages, and in the later stages by the relation between structural carbohydrates and lignin (Johansson 1994). Other studies on *P. sylvestris* have also demonstrated the interaction between lignin decay and litter nitrogen dynamics (Berg & McClaugherty 1987). Over a range of species, litter lignin:nitrogen ratio is generally negatively related to net nitrogen mineralisation (Scott & Binkley 1997). This relationship between litter chemistry and nitrogen cycling is likely related to the fact that soil microbes require energy (carbon) to complete several stages in the soil nitrogen cycle, and so carbon availability is a major factor controlling nitrogen (and possibly phosphorus) dynamics (Hart *et al.* 1994).

Slash remaining post-harvest may contain a large number of needles that do not contact the soil, and which may undergo biochemical changes due to photochemical oxidation or microbial decomposition (Moorhead & Callaghan 1994). These changes in carbon quality or quantity could influence nitrogen dynamics. Although several studies have examined the decay of *P. radiata* needles (Will *et al.* 1983; Baker *et al.* 1989), little work has addressed the decomposition and nitrogen dynamics of needles attached to slash.

In discussing their work on *P. radiata* residues, Smith *et al.* (1994) suggested mineralisation of organic nitrogen contained in partially decomposed forest floor horizons was a likely source of nitrate-nitrogen in the soil. Here we report on the potential decomposition of *P. radiata* needles in residue with different stages of exposure (left attached to the slash for up to 4 years and not in contact with the soil) and their capacity to release mineral-nitrogen and produce nitrate-nitrogen. In a separate study, we examined soil-solution nitrogen concentrations under slash and under raked soil in a recently harvested *P. radiata* plantation. We tested the hypothesis that nitrogen mineralisation in needles increases both with increased time of exposure to photochemical and biological decay processes, and with changes in needle carbon.

MATERIALS AND METHODS

Needles of *P. radiata*, felled 4 months, 1 year, and 4 years previously, were collected from Himatangi and Santoft Forests. The samples were obtained from windrows where the needles were not in contact with the forest floor. Fresh foliage (current year's growth) was also collected from Himatangi Forest. Soil samples of F, H, and A horizons (0–10 cm) from a Hokio sand at Himatangi Forest, under 25-year-old trees (300 stems/ha) on stabilised coastal dunes, were obtained with a 25-mm sample tube. The needles were collected during dry weather and stored at 4°C for a few days. They were then cut to 3- to 5-cm lengths, and samples (8.0 g equivalent dry weight) were loosely placed on 5.5-cm-diameter GFC filter paper in Falcon Bottle-top units to which suction could be applied to remove excess water. Samples of F, H, and A horizons were passed through a 6-mm sieve to remove coarse roots, and 5.0-g samples of F and H and 30-g samples of A horizon materialwere placed on the GFC paper. They were tapped to allow them to settle and make contact with the paper. Samples of the 4-month needles were also placed on top of L, H, and A horizon samples. The experiment was replicated four times and the samples were randomised on a bench and incubated at 21±0.5°C under normal laboratory lighting.

The samples were leached with drops of deionised water (5 ml) three times a week, equivalent to 20 mm of rain per week for a 10-week period. Water was added dropwise and allowed to drain for 2 or 3 hours into 15-ml tubes, after which a suction of 18 kPa was applied to maintain aerobic conditions. All the leachates were collected and frozen for future analysis.

After thawing, the leachate was filtered through 0.2-μm filters and analysed for nitrate-nitrogen and ammonium-nitrogen by auto analysis (Blakemore *et al.* 1987). Potassium was measured using atomic absorption spectrometry, phosphorus by auto analysis, and soluble-organic-carbon using a TOC analyser. The pH of each solution was also measured. Total carbon was measured on the fresh samples using a Leco furnace, and total nitrogen and phosphorus were measured by auto analysis after a Kjeldahl digestion (Blakemore *et al.* 1987).

In May 1994, tension lysimeters (four replicates) were installed at a soil depth of 60 cm at Santoft Forest, both under windrows of slash (cut and raked 2 years previously) and in the raked soil between the windrows. The soil was also a Hokio sand formed on stabilised coastal sand. A second crop of *P. radiata* had been planted in the raked areas between the windrows shortly after harvest. Monthly winter rainfall for 1994 was June 113 mm, July 105 mm, and August 79 mm. The lysimeters consisted of a 25-mm-diameter Millipore GFC filter with a 90-mm-diameter glass filter paper (GFC) wick which was held at a suction of about 10 kPa for several weeks (Stevenson 1978; Stevenson & Beaumont 1984). The suction after 4 weeks was about 5 kPa, and soil solution was continuously collected in glass flasks for up to 4 weeks. The flasks were kept in the dark to avoid the growth of algae. Soil solutions were filtered through 0.2-μm filters and analysed for pH, nitrate-nitrogen, ammonium-nitrogen, and basic cations. The experiment was terminated in September 1994.

RESULTS AND DISCUSSION

Needle Carbon and Nitrogen Composition

Needle nitrogen concentration was greater on trees and branches felled 4 months previously (1.51%) than in fresh foliage (1.13%) (Table 1). The concentration reached 1.68% after 4 years' exposure; therefore, the carbon/nitrogen ratio of the exposed needles on the windrows decreased with time. That there was a greater loss of carbon than of nitrogen in the field was probably due to mineralisation of readily decomposable carbon compounds

TABLE 1–Carbon, nitrogen, phosphorus, and potassium content of pine needles and of horizons of Hokio sand.

Sample	Carbon (%)	Nitrogen (%)	Phosphorus (%)	Potassium (%)	C/N	C/P
Fresh foliage	44.7	1.13	0.124	1.30	39	360
4-month needles	46.4	1.51	0.241	0.98	31	192
1-year needles	47.4	1.63	0.163	0.45	29	291
4-year needles	44.7	1.68	0.111	0.12	27	403
F horizon	41.3	1.16	0.096	0.15	36	430
H horizon	36.0	1.30	0.086	0.18	28	419
A horizon	0.56	0.03	0.033*	0.25	19	nd*

* Includes phosphorus in soil minerals

by heterotrophs to yield carbon dioxide, together with loss of soluble carbon (Baker *et al.* 1989; Johansson 1994). Our unpublished ^{13}C-NMR data on these needles clearly showed loss of carbohydrate with increased time of exposure of needles on windrows, as suggested by Baker *et al.* (1989) for decaying needles.

pH of Leachates

The pH of the leachate from the 4-year needles decreased from 6.8 to 4.4 during the incubation (Fig. 1a). The pH of the 4-month needles decreased slightly, and the other samples of needles showed an initial increase in pH followed by a decrease. The samples of F and A horizon showed little change in leachate pH during the incubation, but the pH of the H samples increased from 4.8 to 5.4 (Fig. 1b). When the 4-month needles were placed over the soil horizons the pH of the leachate decreased even further (Fig. 1c). These decreases were more than for the individual components, suggesting further chemical interactions had taken place. The changes in pH are discussed further in conjunction with discussions of mineralisation.

Fungal Colonisation and Nitrogen Mineralisation During Incubation

During the incubation the fresh foliage lost its green colour by Week 7, and there was obvious fungal colonisation from Week 4. There was also heavy fungal growth on the 4-month needles from Week 6. In contrast, the older needles did not show obvious fungal growth but the colour of the needles became darker during the incubation. The leachate from the 1-year needles was the most highly coloured, and the leachate from the fresh foliage and from the A horizon showed the least colour.

The fresh foliage lost small amounts of nitrogen calculated both on a nitrogen basis (Fig. 2a and 3a) and on a sample weight basis, and this was consistent with the results of Baker *et al.* (1989). Ammonium-nitrogen was the dominant ion (Table 2). Since there was an obvious fungal infection from Week 4, nitrogen was probably immobilised by the fungi. Leachate pH increased from 7.4 to 8.4 in Week 7 (Fig. 1a) and this parallelled the increase in ammonium-nitrogen.

In contrast, the 4-month needles produced large amounts of ammonium-nitrogen per week, up to Week 6 (Fig. 2a). From Week 4, increasing amounts of nitrate-nitrogen were also

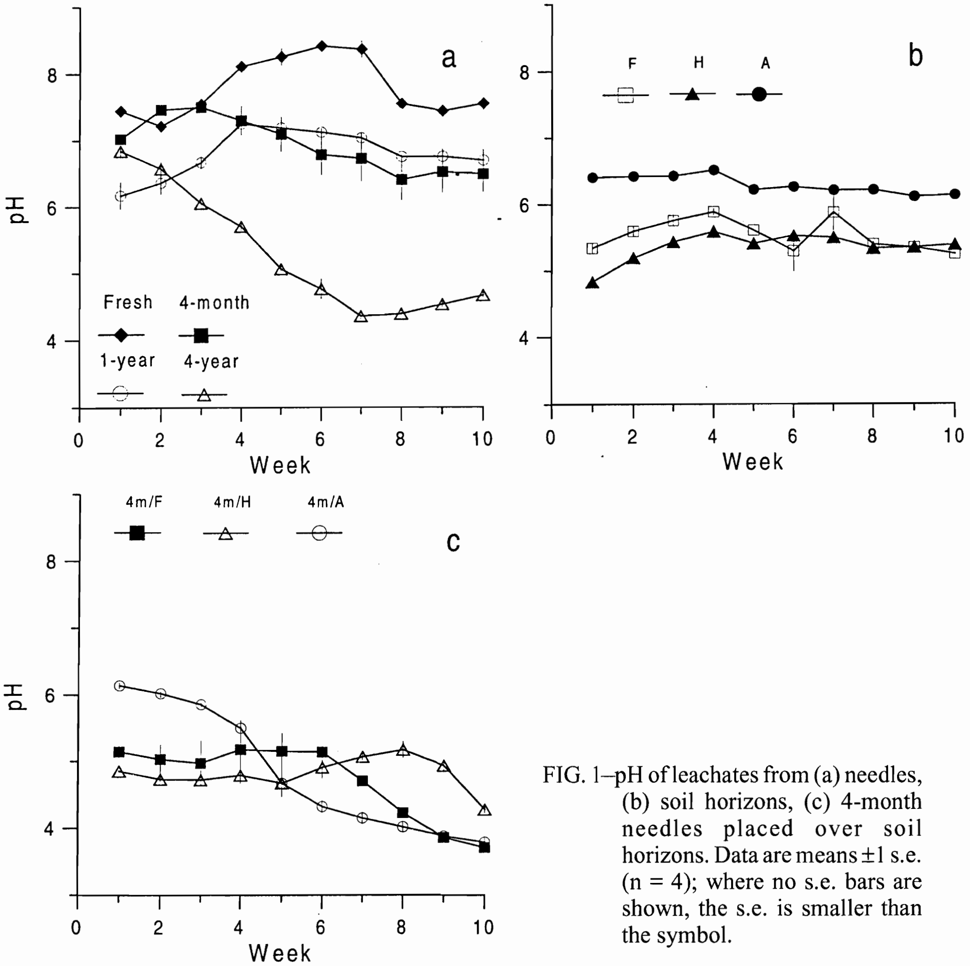

FIG. 1–pH of leachates from (a) needles, (b) soil horizons, (c) 4-month needles placed over soil horizons. Data are means ±1 s.e. (n = 4); where no s.e. bars are shown, the s.e. is smaller than the symbol.

produced (Fig. 3a). The pH of the leachate decreased during this time (Fig. 1a) since protons are produced during nitrification. There was a similar pattern of leaching in the 1-year needles (Fig. 2a and 3a).

The F and H horizon samples initially released ammonium-nitrogen followed by increasing rates of nitrate-nitrogen (Fig. 2b and 3b). The sample of A horizon produced larger amounts of ammonium-nitrogen than the F and H horizons calculated on a nitrogen basis (Fig. 2), but smaller amounts calculated on a sample weight basis. This sample also produced increasing rates of nitrate-nitrogen (Fig. 3b). Active nitrifiers were probably present initially in this horizon, and increased in activity during the course of the experiment.

Most nitrogen was leached from the 4-month and 4-year needles, and amounted to 7–9% of the total nitrogen (Table 2). The 1-year needles lost 3% of the total nitrogen. The A horizon lost 6.6% of the total nitrogen mainly as nitrate-nitrogen, and the F and H horizons lost <1% of the total nitrogen mainly as ammonium-nitrogen. The exposed needles had higher nitrogen contents and narrower carbon/nitrogen ratios than the fresh foliage (Table 1),

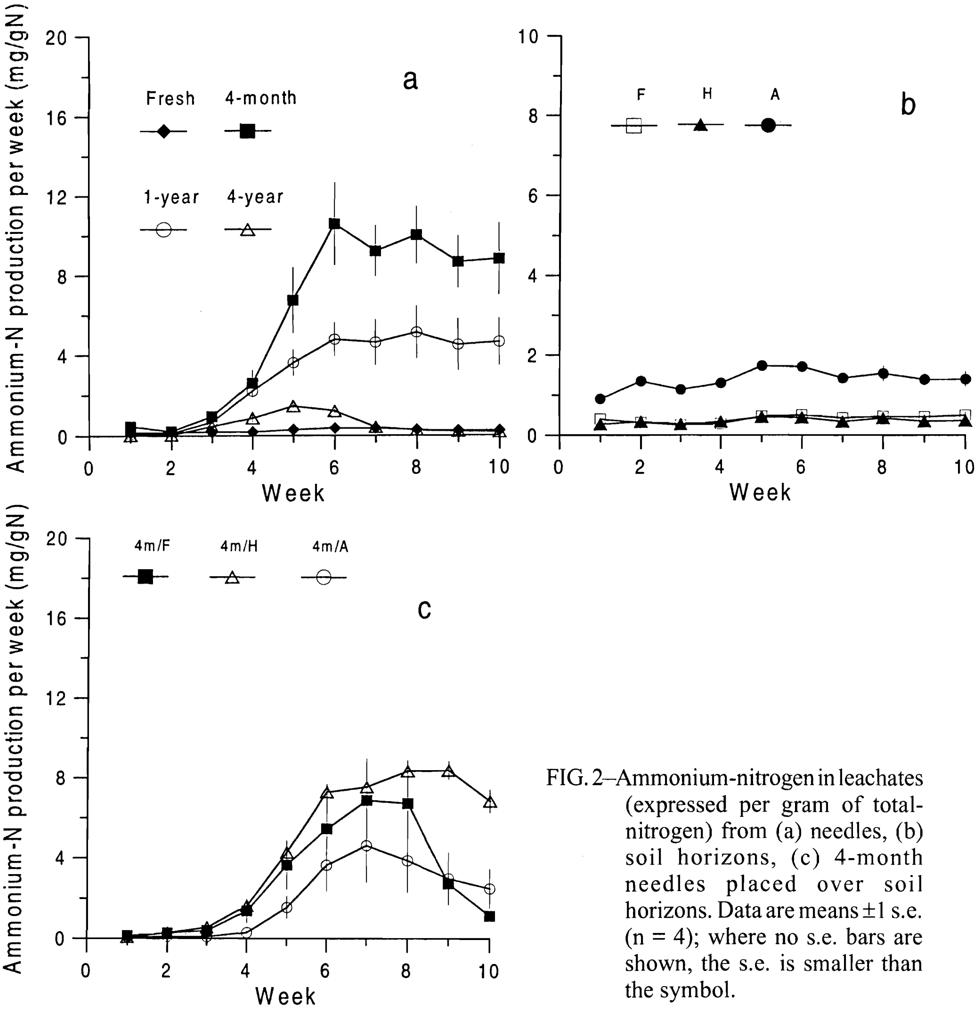

FIG. 2–Ammonium-nitrogen in leachates (expressed per gram of total-nitrogen) from (a) needles, (b) soil horizons, (c) 4-month needles placed over soil horizons. Data are means ±1 s.e. (n = 4); where no s.e. bars are shown, the s.e. is smaller than the symbol.

suggesting that carbon had been lost in the field before the samples were collected. The initial breakdown of the needles (within 4 months) probably was influenced by ultra-violet light, as well as by biological processes (Moorhead & Callaghan 1994). In this laboratory incubation, net nitrogen mineralisation occurred readily when the needle carbon/nitrogen ratio was about 30 (Table 1). The carbon-nitrogen ratio may prove a useful indicator of the quality of substrates available to micro-organisms in needles.

Differences in nitrogen mineralisation for fresh foliage and 4-month needles were consistent with the results of Dyck *et al.* (1983) who observed that nitrate-nitrogen concentrations in soil solution took 3 months to increase after clearfelling. This lag may be related to the time required for the fresh foliage to break down (Polglase, Comerford & Jokla 1992; Polglase, Jokla & Comerford 1992), for mineralisation of readily decomposable carbon, and for retention of nitrogen in increased the microbial biomass. After enrichment of nitrogen in the microbial biomass, nitrogen immobilisation decreases, and net nitrogen mineralisation and nitrification increase. Where needles were placed under 15-year-old

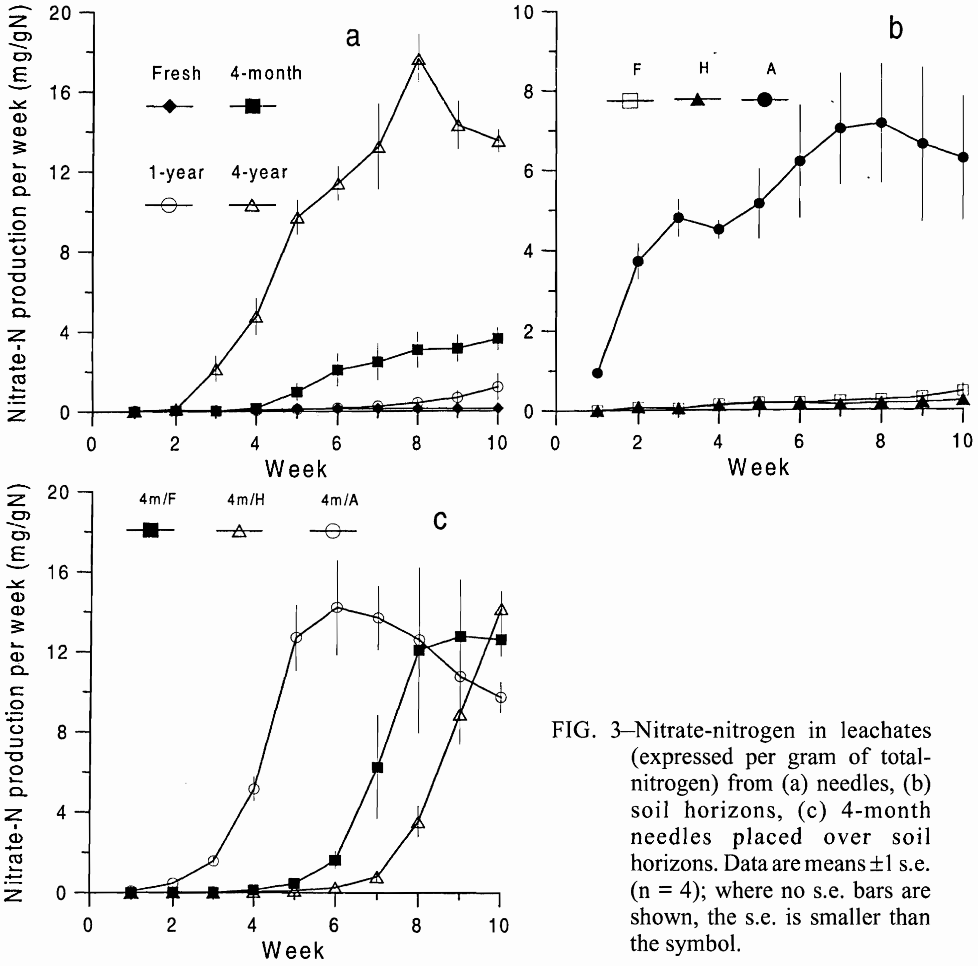

FIG. 3–Nitrate-nitrogen in leachates (expressed per gram of total-nitrogen) from (a) needles, (b) soil horizons, (c) 4-month needles placed over soil horizons. Data are means ±1 s.e. (n = 4); where no s.e. bars are shown, the s.e. is smaller than the symbol.

P. radiata (Baker *et al.* 1989) there was little exposure to solar radiation and decomposition was slower. The decomposition of needles is therefore likely to be enhanced at clearfelled sites (Will *et al.* 1983).

Nitrogen Losses by 4-month Needles Placed on Soil Horizons

When the 4-month needles were placed on samples of the F or H horizon, the leachate ammonium-nitrogen and nitrate-nitrogen concentrations were similar to those of the 4-month needles alone for the first 6 weeks (Fig. 2 and 3). After this time more nitrate-nitrogen was produced at the expense of ammonium-nitrogen (Fig. 2c and 3c), probably as a result of a rapid growth in the population of nitrifiers in the F and H layers. The pH decreased from 5.1 to 3.7 for the F horizon leachate concomitant with the change from ammonium-nitrogen to nitrate-nitrogen (Fig. 1c).

Where the 4-month needles were placed on the A horizon samples, increasing amounts of nitrate-nitrogen were produced up to Week 5, but this was then followed by a slight

TABLE 2–Leachate pH, and percentage nitrogen and phosphorus lost by leaching.

Sample	Leachate pH	Nitrogen lost as NO_3-N (%)	Nitrogen lost as NH_4-N (%)	Total nitrogen lost (%)	Total phosphorus lost (%)
Fresh foliage	7.5	0.1	0.2	0.3	6.0
4-month needles	6.4	1.6	5.8	7.4	32.9
1-year needles	6.7	0.3	3.0	3.3	25.2
4-year needles	4.6	8.7	0.5	9.2	9.8
F horizon	5.3	0.2	0.4	0.6	3.4
H horizon	5.4	0.1	0.4	0.5	4.6
A horizon	6.1	5.2	1.4	6.6	0.1
4-month/ F	3.7	4.6	2.9	7.5	25.8
4-month/ H	4.3	2.8	4.5	7.3	27.3
4-month/ A	3.8	8.1	2.0	10.1	4.0

decrease in the nitrate-nitrogen concentration (Fig. 3c). The pH of the leachate also decreased from 6.1 to 3.8 (Fig. 1c), which may have caused a reduction in the activity of the nitrifiers. The total nitrogen leached was similar to that from the 4-month needles alone, and so needle exposure was a major factor in the release of mineral-nitrogen. For Weeks 7 to 10 of the incubation, the ratio of nitrate-nitrogen to ammonium-nitrogen in the leachate (about 4 to 1) was similar to that in the A horizon sample (Fig. 2b and 3b). These results suggest that after clearfelling, needle carbon is mineralised, and after a lag phase net nitrogen mineralisation begins. Ammonium-nitrogen is then nitrified, mainly in the mineral soil, and contributes to nitrate-nitrogen in soil solution and a possible loss of nitrogen by leaching.

Lysimeters

The concentration of nitrate-nitrogen in the lysimeters under the 2-year-old windrows was about 10 times greater than in the lysimeters under the raked soil (Table 3). No ammonium-nitrogen was detected in the lysimeters. This is consistent with the data from the laboratory incubation which showed that mineral soil produced nitrate-nitrogen, and that more nitrate-nitrogen was produced when needles were placed over the mineral soil. It also indicates that net nitrogen mineralisation occurs in the windrows even though they contain large amounts of branch and stem material with wide carbon/nitrogen ratio. The nitrogen leaching losses in winter under the windrow at 60 cm depth equated to 4 kg N/ha per 100 mm of drainage compared with losses of 0.4 kg N/ha per 100 mm of drainage under the raked soil.

TABLE 3–Concentration of ions (mg/ℓ) in tension lysimeters at 60 cm under windrows and raked soil.

	July		August		September	
	Raked	Windrow	Raked	Windrow	Raked	Windrow
Nitrate-nitrogen	0.4	4.1	0.3	4.7	0.03	2.7
Calcium	54	38	52	50	35	32
Magnesium	9	9	7	12	5	7
Potassium	5	8	4	8	3	4
Sodium	53	74	51	89	30	40

These data show that nitrate-nitrogen can be lost from slash as a result of net nitrogen mineralisation during litter decomposition and not solely from mineral soil disturbance (Vitousek *et al.* 1982; Vitousek & Andariese 1986). The absence of weeds, and therefore nitrogen uptake, in the windrows of slash may also account for the higher levels of nitrate-nitrogen under the windrows (Dyck *et al.* 1983).

The predominant cations in the lysimeters were calcium and sodium (Table 3) and the major anions were chloride and bicarbonate (data not shown). Since the site is close to the sea, there was probably a large input of sea salts both as spray and in rain. The soil at this site contained calcareous shell fragments which are a likely source of the bicarbonate.

Phosphorus

The fresh foliage released phosphorus from Week 2, and the amount released decreased from Week 5 (Fig.4a), which is consistent with dissolution from a labile pool. The 4-year

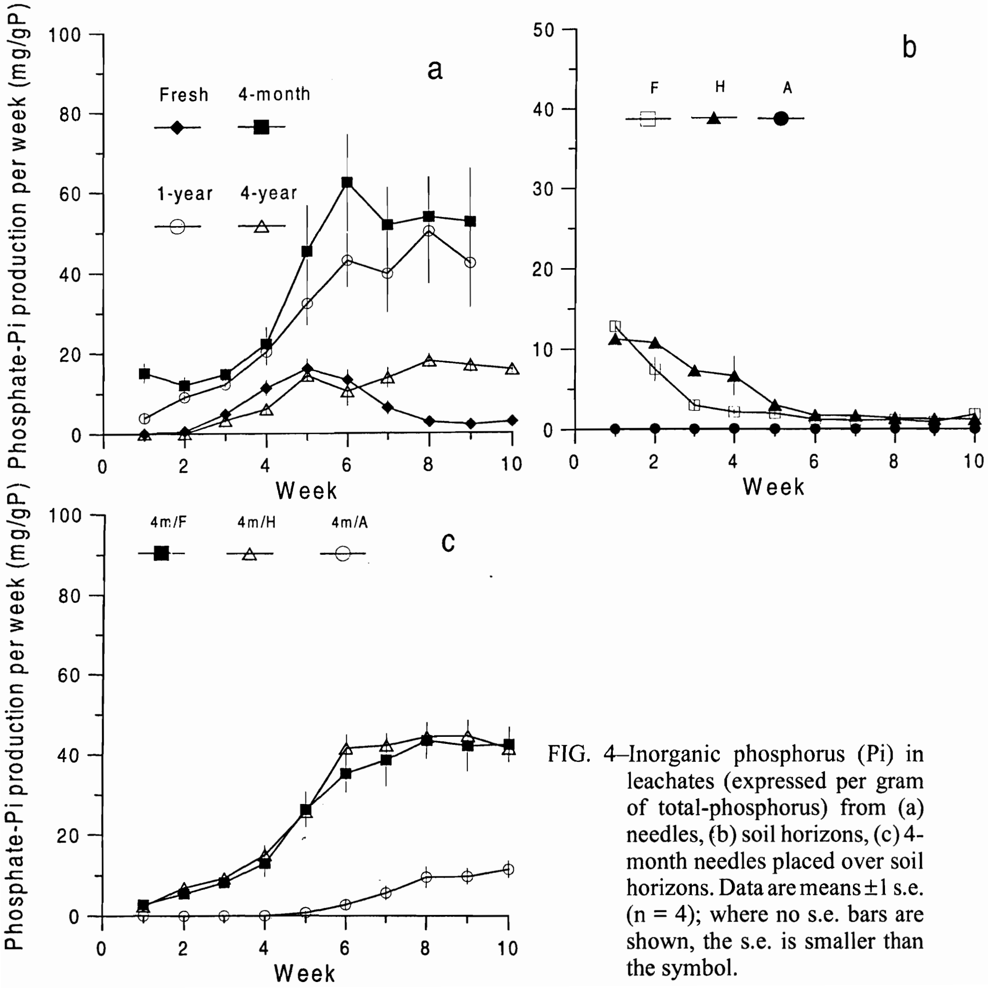

FIG. 4–Inorganic phosphorus (Pi) in leachates (expressed per gram of total-phosphorus) from (a) needles, (b) soil horizons, (c) 4-month needles placed over soil horizons. Data are means ±1 s.e. (n = 4); where no s.e. bars are shown, the s.e. is smaller than the symbol.

needles released small but increasing amounts of phosphorus; the proportion of phosphorus released was 9.2% which was similar to the proportion of nitrogen released (Table 2). The sample of A horizon released small amounts of phosphorus (Fig. 4b). This sample had a small capacity to adsorb phosphorus and probably sorbed some of the mineralised phosphorus. The samples of F and H horizon released decreasing amounts of phosphorus, consistent with the results of Polglase, Comerford & Jokla (1992). When 4-month needles were placed over samples of the soil horizons, the amount of phosphorus released was similar to that from the 4-month needles alone, with the exception of the first 3 weeks when some immobilisation apparently occurred (Fig. 4c).

The pattern of phosphorus release from the needles was generally similar to that of ammonium-nitrogen, and is consistent with microbial mineralisation of phosphorus (Fig. 4a). The 1-year and 4-month needles lost 25% and 33% of their total phosphorus, and these are much greater proportions of the total phosphorus compared with the proportions of total nitrogen lost (Table 2). A large proportion of the phosphorus in needles may be inorganic phosphorus (Pi), which is water soluble (Polglase, Comerford & Jokla 1992). In this experiment the samples were flushed with water three times a week. Since inorganic phosphorus was released in large amounts it suggests that immobilisation of phosphorus is not a rapid process. There is increasing evidence that phosphorus is quite labile in soil LFH horizons, and phosphorus immobilisation may be uncommon in field situations because microbial biomass is not phosphorus limited (Prescott *et al.* 1993; Parfitt *et al.* 1994; Saggar *et al.* 1998). Saggar *et al.* (1998) indicated that the critical carbon/phosphorus ratio for net phosphorus mineralisation of litter was 550, which is consistent with our results (Table 1).

Potassium

Potassium was readily released from the fresh foliage during the first 5 weeks (Fig. 5a) primarily because of the high solubility of potassium (Will *et al.* 1983). The amount released then decreased in a pattern similar to that of phosphorus (Fig. 4a). This suggests that at this stage the labile pool within the fresh foliage may largely have been leached. The pattern of release of potassium appeared to follow the change in pH of the leachate (Fig. 1a) and this may be related to the cation-anion balance. The 4-month needles also showed a similar pattern of release and yielded the most potassium; the 4-year needles yielded the least, probably because leaching of potassium had already taken place in the field (Table 1). The potassium released from the F, H, and A horizon samples decreased with time (Fig. 5b). When the 4-month needles were placed over these samples, less potassium was released initially (Fig. 5c), possibly because of sorption on exchange sites.

Soluble Organic Carbon (SOC)

The pattern of release of soluble organic carbon was similar to that of ammonium-nitrogen and phosphorus (Fig. 6), suggesting that the mineralisation of these elements was occurring together. Mineralisation of organic nitrogen to produce ammonium-nitrogen occurs through the action of microbial heterotrophs, and is therefore influenced by carbon availability (Hart *et al.* 1994). More soluble organic carbon was released initially, which suggests that the source may have been water-soluble carbon compounds in the foliage. The release of soluble organic carbon then increased, which is consistent with the increase in

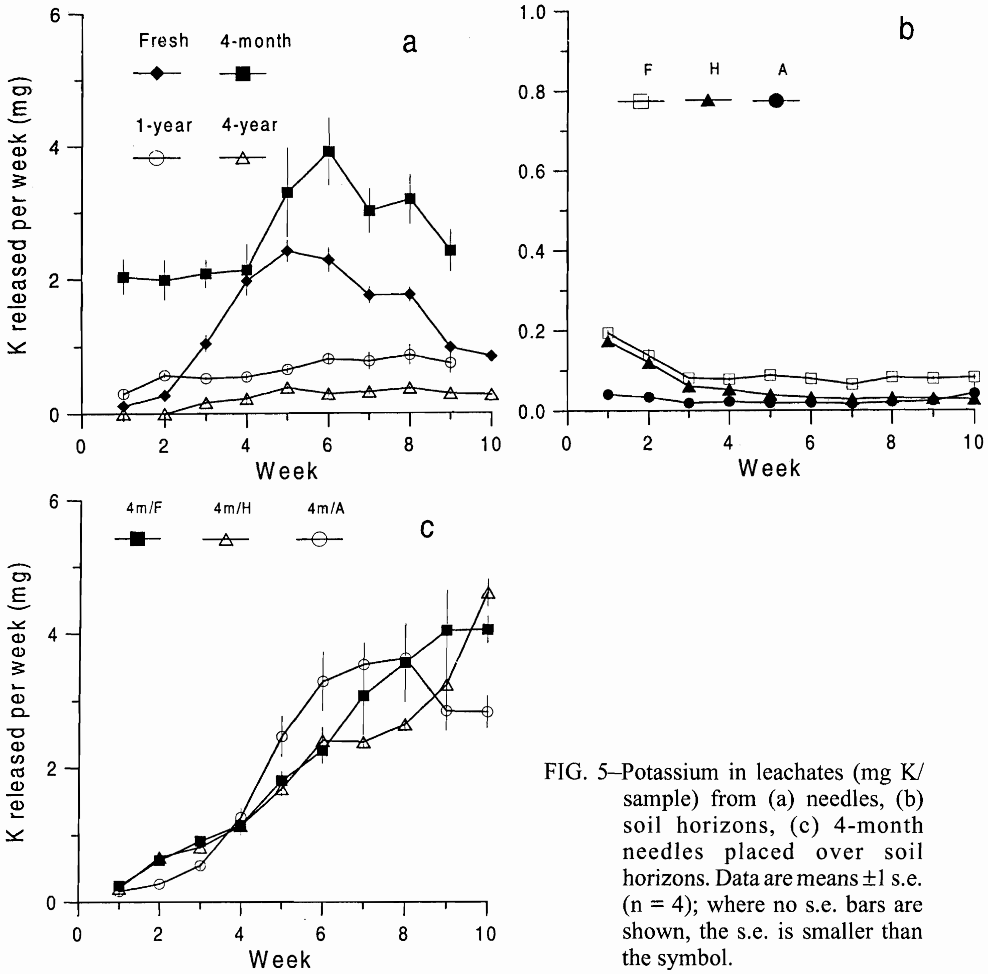

FIG. 5–Potassium in leachates (mg K/ sample) from (a) needles, (b) soil horizons, (c) 4-month needles placed over soil horizons. Data are means ±1 s.e. (n = 4); where no s.e. bars are shown, the s.e. is smaller than the symbol.

microbial decomposition. More soluble organic carbon was released from the 1-year needles than from the 4-month needles (Fig. 6a). Both soluble organic carbon solutions were highly coloured, suggesting the presence of polyphenols, which our ^{13}C-NMR data indicate were proportionately greater in the 1-year needles. When the 4-month needles were placed over the samples of the F and H horizons, the soluble organic carbon released after about Week 6 was lower than from the 4-month needles alone (Fig. 6c). Thus there may have been some metabolism of soluble organic carbon and/or adsorption by soil which would be greater at the lower pH values (Fig. 1c).

Different harvesting regimes can affect both the quantity and quality of readily mineralisable carbon (Smethurst & Nambiar 1990a). Since heterotrophs mineralise carbon and nitrogen there can be interaction between carbon and nitrogen cycles. This suggests that management of carbon inputs could influence net mineralisation of nitrogen and the subsequent nitrification. Thus it may be possible to reduce nitrate-nitrogen losses after clearfelling.

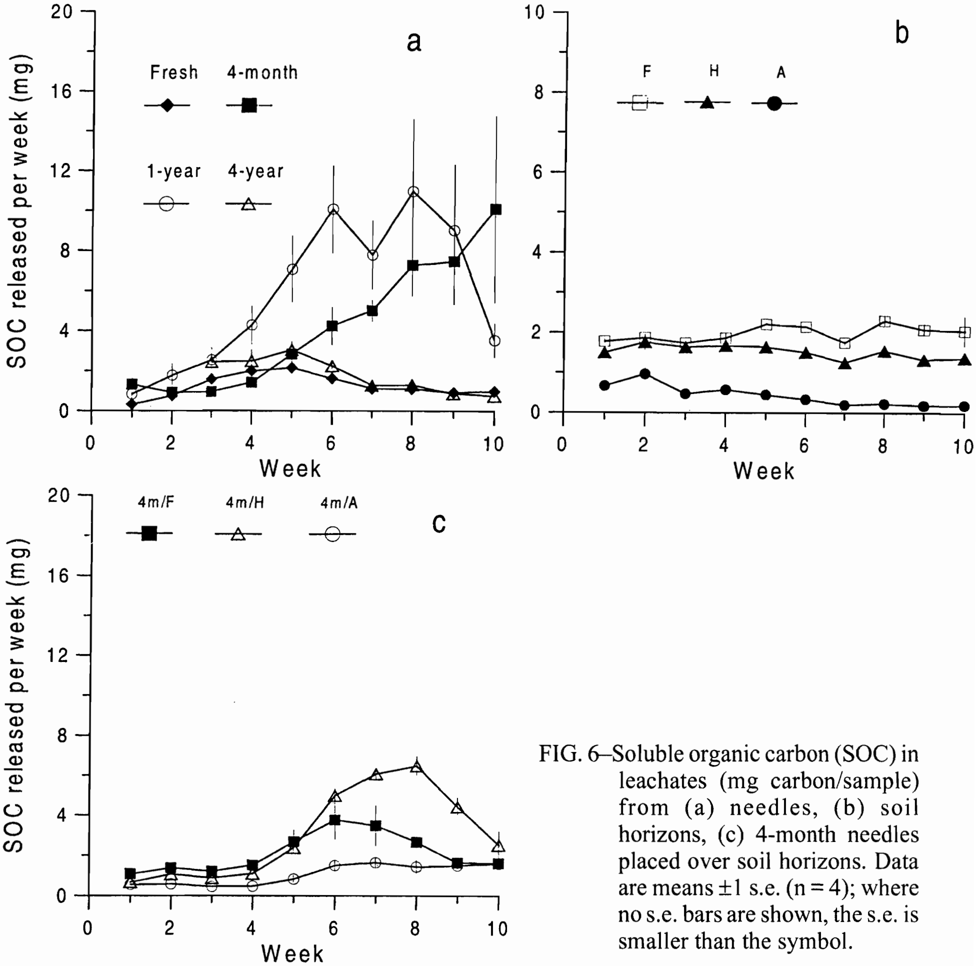

FIG. 6—Soluble organic carbon (SOC) in leachates (mg carbon/sample) from (a) needles, (b) soil horizons, (c) 4-month needles placed over soil horizons. Data are means ±1 s.e. (n = 4); where no s.e. bars are shown, the s.e. is smaller than the symbol.

CONCLUSIONS

Fresh pine needles released very small amounts of nitrogen, thus partly explaining the delay in the release of nitrogen in the field after clearfelling of *P. radiata*. In contrast, the needles exposed on slash for 4 months, which had a higher nitrogen content and a narrower carbon/nitrogen ratio, released large amounts of ammonium-nitrogen as nitrogen was mineralised. When the 4-month needles were placed over A, F, or H horizon samples, nitrate-nitrogen was produced showing that nitrifiers were active in these horizons. These data suggest nitrogen can be lost from needles after a lag of a few months, and can be an important source of the nitrate-nitrogen leached from soil when pine forest is clearfelled.

The result is also consistent with data obtained from lysimeters under windrows in Santoft Forest which showed that 10 times more nitrate-nitrogen was present in soil solution under stockpiles of slash than under raked soil. This indicates that although branch and stem material with wide carbon/nitrogen ratios were present together with needles and forest floor, nitrate-nitrogen can be released into soil solution.

Net mineralisation and dissolution of phosphorus also occurred readily in the exposed needles and mineral soil, and would contribute to the labile pool of phosphorus in soil. The data suggest that immobilisation of phosphorus may not be a rapid process, and are consistent with net mineralisation occurring when the carbon/phosphorus ratio is less than 550.

ACKNOWLEDGMENTS

We are grateful to Pat McCarthy of Ernslaw One Ltd for assistance and for access to Himatangi and Santoft Forests, to Gareth Salt of Landcare Research for the SOC analysis, and to Dr Des Ross of Landcare Research for assistance with the manuscript. This work was supported under Foundation for Research, Science and Technology contract CO4505.

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