NITROGEN AND PHOSPHORUS MINERALISATION IN *PINUS RADIATA* HARVEST RESIDUE SAMPLES FROM A COASTAL SAND

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ABSTRACT

Although nitrogen mineralisation after harvest of *Pinus radiata* D. Don plantation forests has been studied previously, little work has addressed nitrogen and phosphorus mineralisation in stockpiles of harvest residues on coastal sands. We examined, in the laboratory, the mineralisation of nitrogen and phosphorus in dead needles, L/FH materials, and mineral soil (0–10 cm depth) from windrows, and in raked soil, and compared results with those from an adjacent standing forest. Microbial carbon, nitrogen, and phosphorus were also determined. Samples were taken 12 and 32 months after harvest.

Mineralisation of nitrogen was greatest in the dead needles, and was greater in windrow L and FH materials than in corresponding forest samples. The proportion in the nitrate-nitrogen form increased with time after harvest, and became susceptible to leaching loss. Microbial carbon, nitrogen, and phosphorus values were initially highest in the windrow dead needles and L material. These data were consistent with previous results suggesting that net nitrification is likely in *P. radiata* needles with carbon/nitrogen ratios <40, whereas net immobilisation of nitrogen is likely if the ratio is >55. Extractable phosphorus was comparatively high, and carbon/phosphorus ratios comparatively low, in the windrow L and FH materials, which suggests that net mineralisation of phosphorus would readily occur in these materials. Net mineralisation of phosphorus in mineral soil was higher in the windrow and raked soil than in the standing forest. These data are also consistent with previous data suggesting that net mineralisation of phosphorus occurs when the carbon/phosphorus ratio for the FH horizon is <550. Since the nitrogen in the windrows is readily mineralised, and some losses by leaching occur, management practices could be initiated to allow for greater retention of nutrients after harvest on coastal sands.

Keywords: clearfelling; leaching losses; microbial biomass; nutrient availability

INTRODUCTION

When *Pinus radiata* plantation forests are clearfelled and the harvest residues left on site, more than 200 kg N/ha and 30 kg P/ha are potentially available from the residues (Madgwick 1994). Initially, these nutrients are retained in the residues or are immobilised in the microbial biomass (Parfitt *et al.* 1997). After a few months, a proportion of the nitrogen in the post-harvest system is released from needles in the form of mineral nitrogen, and

becomes available in the soil solution, where there is the potential for plant uptake or nitrification and leaching (Dyck *et al.* 1983; Smith *et al.* 1994). Little is known in New Zealand about either the fate of phosphorus in this system or the fate of nitrogen and phosphorus when residues are stockpiled by bulldozing into windrows.

Net nitrate-nitrogen production increased in disturbed mineral soil when slash and LFH horizons were bulldozed after clearfelling of *Pinus taeda* L. (loblolly pine) (Vitousek & Andariese 1986). This may have resulted from the removal of plants which would compete with micro-organisms for nitrogen, and also from increased mineralisation arising from increases in temperature and moisture (Vitousek *et al.* 1982; Smethurst & Nambiar 1990). Where residues are retained on site, soil solution chemistry shows that nitrogen availability increases but, in the first 2 years after harvest, the increased mineral nitrogen is largely lost by leaching (Smith *et al.* 1994). Different harvesting regimes affect the rate of nitrogen mineralisation, partly as a result of the different amounts of mineralisable substrate (Smethurst & Nambiar 1995). Substrate quality is also a major factor influencing litter decay (Heal *et al.* 1997) and nutrient cycling rates in forest systems (Scott & Binkley 1997) . The relationship between litter chemistry and nitrogen cycling probably arises from the fact that soil micro-organisms require carbon (energy) to complete several stages in the soil nitrogen cycle; carbon availability is consequently a major factor controlling nitrogen (and possibly phosphorus) dynamics (Hart *et al.* 1994). However, the presence of branch and stem material with wide carbon/nitrogen ratios does not appear to prevent some nitrogen mineralisation in slash (Parfitt *et al.* 1997).

Little work has addressed the mineralisation of nitrogen and phosphorus in needles, litter, and mineral soil after post-harvest operations, which leave stockpiles of *P. radiata* slash with raked soil between the stockpiles. Here we report on mineralisable-nitrogen and phosphorus, and microbial biomass carbon, nitrogen, and phosphorus concentrations in *P. radiata* residues in windrows, in soil between windrows, and under adjacent 25-year-old trees. We also compare the data with previous hypotheses (Saggar *et al.* 1998; Scott *et al.*1998) that suggested mineralisation of nitrogen from LFH material occurs when the carbon/nitrogen ratio is lower than about 55, and phosphorus mineralisation occurs when the carbon/ phosphorus ratio is lower than about 550.

MATERIALS AND METHODS

Sites and Soil

Himatangi Forest is located at 40°22′S and 175°16′E on recent sand dunes about 30 km west of Palmerston North. Mean annual temperature is approximately 13°C and mean annual rainfall is approximately 900 mm. The soil type is Hokio sand (Cowie & Smith 1958), which is classified as a Recent Soil (Aquic Udipsamment).

From 1950 to 1970, the site was under marram grass (*Ammophila arenaria* L.) and was grazed by stock (Cowie & Smith 1958). *Pinus radiata* was planted in 1970 and was later thinned to a final density of 300 stems/ha. Part of the stand was clearfelled in December 1993, and the slash was line-raked into windrows in April 1994. The area was oversown with red clover (*Trifolium pratense* L. 'Grasslands Pawera') and lotus (*Lotus pedunculatus* Cav. 'Grasslands Maku') in June 1994; replanting with *P. radiata* took place in July 1994 at 800 stems/ha. Weeds were spot-sprayed with glyphosate in August 1994.

Three sites were selected for study:

Site 1—Standing forest: This was a site within the unharvested stand planted in 1970. There was no understorey and the LFH horizons were approximately 5 cm thick. Three plots (7.5 × 15 m) were selected at random and marked out and samples of L and FH material were taken by hand from 20 locations, at approximately equal intervals, in diagonal transects across each plot. Coarse woody debris and twigs >5 mm diameter were excluded because they would have been difficult to assay for biochemical characteristics. The mineral soil was sampled at 0–10 cm depth by taking 25-mm-diameter cores from the same 20 locations. Current-year foliage was collected from lower branches at the edge of the forest stand.

Site 2—Windrows: In each of two adjacent windrows (with the first located approximately 100 m from the edge of the unharvested stand), a 15-m-long sampling area was selected at random. The windrows were about 1 m high and contained branches, cones, and needles on top of soil which had L, FH, and A horizons; there was little weed growth. Ten samples of dead needles not in contact with soil, and of L and FH horizons, were taken by hand from 10 locations in each of these two windrows and pooled to give one sample. The 0–10 cm mineral soil was sampled with a 25-mm-diameter sampling tube from the same 20 locations. This sampling schedule was repeated in the next sets of neighbouring windrows to give a total of three replicate samples.

Site 3—Raked soil between windrows: The raked area between windrows became colonised with herbs, lupin, and pasture grasses, and later some marram grass. The 0–10 cm soil layer contained some LFH material which had been mixed with the mineral soil during raking. Samples of 0–10 cm soil were collected from a 7.5 × 15-m plot between two sampled windrows, using a 25-mm-diameter sampling tube, from 20 locations at approximately equal intervals in diagonal transects. This sampling process was repeated between neighbouring windrows to give a total of three replicate samples.

Samples were obtained on two occasions, viz December 1994 and August 1996. They were transported at ambient temperature and then stored overnight at 4°C in plastic bags. Needles and L material were cut into 2- to 5-mm lengths. All other samples were passed through a 5.6-mm sieve to remove coarse roots. Portions of these samples were air-dried at 30°C, with needles and L material being ground to pass a 1-mm mesh, and the other samples were finely ground for total C and N analyses. The remainder was stored field-moist at 4°C.

Analytical Methods

Results are expressed on the basis of oven-dry (105°C) weight of material. Biochemical analyses began within 7 days after sampling and were made in duplicate.

Soil moisture, pH (in water), total carbon, total nitrogen (by combustion) and total phosphorus, Olsen-phosphorus, and Bray-phosphorus were determined according to Blakemore *et al.* (1987). Microbial carbon, nitrogen, and phosphorus were measured by fumigation-extraction procedures (Brookes *et al.* 1982; Ross & Sparling 1993). Samples were adjusted to 60% water-holding capacity (approximately –5 kPa) immediately before

extraction or fumigation with chloroform for 24 hours. For microbial carbon and nitrogen, the weights of moist samples used were 2.5 g for needles and L horizons and 10.0 g for FH material and mineral soil. For phosphorus, the weights of moist samples used were equivalent to oven-dry weights of 0.75 g for L and FH horizons and 1.5 g for mineral soil. Unfumigated and fumigated samples for microbial carbon and nitrogen were extracted in an end-over-end shaker for 30 minutes with 25 ml 0.5*M* K_2SO_4. The samples for microbial phosphorus were extracted with 25 ml 0.5*M* $NaHCO_3$. Total carbon in the subsequent filtrates was determined on a TOC analyser, total nitrogen by persulphate oxidation, and total phosphorus by the molybdenum-blue method. Extractable-carbon, extractable-nitrogen, and extractable-phosphorus flushes were calculated as the difference between the carbon, nitrogen, and phosphorus extracted from the fumigated and unfumigated samples. The phosphorus values were corrected for sorption of inorganic phosphorus by the mineral soil. The carbon flush values were converted to microbial carbon by using a k_{EC}-factor of 0.33 (based on Ross *et al.* (1995) but adjusted for measurement by the TOC analyser rather than by wet oxidation). For nitrogen, the k_{EN}-factor used was 0.45 (Jenkinson 1988) and for phosphorus the k_{EP}-factor was 0.4 (Brookes *et al.* 1982).

Mineral-nitrogen (min-nitrogen = ammonium-nitrogen plus nitrate-nitrogen) was determined in 2*M* KCl extracts by autoanalyser procedures (Blakemore *et al.* 1987). Net nitrogen mineralisation was estimated by incubating 4.0 g of needles and L horizons, and 10.0 g of FH material and mineral soil at 60% water holding capacity for 14 (or 17) and 56 days at 25°C; the min-nitrogen produced was extracted with 2*M* KCl (1/10 w/v) by shaking for 1 hour.

Net phosphorus mineralisation (ΔP-min) was determined in mineral soil according to Parfitt *et al.* (1994), after labile inorganic phosphorus was first removed from the soil with an anion exchange membrane. The soil was then filtered on GFC papers and incubated moist under aerobic conditions for 7 days at 39°C in the absence of a membrane. The inorganic phosphorus produced during the incubation was then extracted with another resin membrane to give a measure of the phosphorus mineralisation.

The areas for the three replicate plots in the forest were selected at random. The positions of the plots within the windrows and the raked soil were also selected randomly. It is recognised that the study design uses pseudoreplication (Hurlbert 1984), which is not unusual in this type of work; nevertheless, it allows us to make comparisons between samples from forest, windrows, and raked soils. Standard errors of the means are reported in the tables. For each variable, the data were analysed using a Split-Plot Repeated Measures ANOVA. Comparisons were made between means for forest, windrows, and raked samples, and between the samples taken in 1994 and 1996. Before analysis, an appropriate transformation was applied to ensure stability of variances and improve normality for each variable. Pair-wise comparisons of interest were identified for each variable. Because of the multistrata design, the variance of each comparison is dependent on which sampling stratum the means come from. For some properties, only approximate tests were possible, and for these conservative degrees of freedom were chosen (Mead 1988). Variance components used in the comparisons were estimated using REML in S-Plus (S-PLUS 4 Guide to Statistics, Data Analysis Products Division, MathSoft, Seattle). Bonferroni-type adjustments were made to the p-values when multiple comparisons were made for a given variable. The p-values for significant differences are given within the text.

RESULTS

Total Carbon, Nitrogen, and Phosphorus and Olsen-phosphorus

The concentrations of carbon and nitrogen in the soil layers are given in Table 1. The concentrations of nitrogen in the L material (fallen needles) in the standing forest ranged from 7.9 to 9.0 g/kg and were lower ($p<0.02$) than in the L material in the windrows (15.8–19.3 g/kg), and in the current year's growing foliage (11 g/kg). Carbon/nitrogen ratios in the L material were accordingly higher ($p<0.0001$) in the standing forest (56–68) than in the windrows (27–31).

The carbon and nitrogen concentrations of the FH layers (Table 1) were influenced partly by their sand content. The carbon/nitrogen ratios of all FH samples, however, were about 30, and similar to the ratios of the decomposing needles and L material in the windrows. The carbon/nitrogen ratios of the 0–10 cm layer in the raked soil were 23–27, and higher than the ratios of 17–20 in the forest, probably because of the presence of some FH material which had been mixed in during bulldozing of the slash.

Total phosphorus in the L material in the windrows was 1270 mg/kg (C/P = 390), and significantly higher ($p=0.0001$) than the value (863 mg/kg; C/P = 590) in the forest (Table 1). This is consistent with the higher Olsen-phosphorus values in the windrows than in the forest samples (Table 1). In the mineral soil, the acidic Bray-phosphorus reagent extracted more phosphorus than the Olsen reagent, probably through dissolution of primary minerals.

Microbial Biomass Carbon, Nitrogen, and Phosphorus

The microbial biomass carbon and nitrogen values of the L material in the windrows in 1994 were particularly high (24 500 and 2490 mg/kg, respectively; Table 2), but had declined ($p<0.0001$) in 1996. The L material on the forest floor also had higher ($p=0.01$) values of microbial carbon and nitrogen in December 1994 than in August 1996. Values of microbial phosphorus were likewise highest in the 1994 windrow L samples (Table 2). Values of microbial phosphorus were low in mineral soil and differed little between sites and sampling times.

Microbial biomass carbon in the 1994 windrow L material contained 5.0% of the total carbon (Table 3), significantly more ($p=0.003$) than in L material on the forest floor (3.3%). The percentages of microbial nitrogen in total nitrogen, and microbial phosphorus in total phosphorus, were very high in the samples of L material in 1994 (16% and >60%, respectively; Table 3). All these ratios were significantly lower ($p=0.003$) in the FH layers, which contained lower amounts of available substrates such as polysaccharides (R.L.Parfitt & R.H.Newman unpubl. NMR data).

The ratios of microbial carbon to microbial nitrogen ranged from 6 to 16 in the forest samples and were generally higher than in the windrow samples (Table 3). The ratios in the windrow L material and raked soil decreased ($p=0.03$) from 1994 to 1996, probably because of the mineralisation and loss of carbon as carbon dioxide, and the input of little, if any, fresh organic carbon during that period.

The highest microbial carbon to microbial phosphorus ratios (up to 52) were found in the 0–10 cm mineral soil samples (Table 3), which also had the lowest values of available phosphorus, as measured with the Olsen-phosphorus reagent (Table 1). The ratios were

TABLE 1–pH, total carbon (C), nitrogen (N), and phosphorus (P); Olsen-P and Bray-P; standard errors of the means in parentheses.

Sample	pH		Total C (g/kg)		Total N (g/kg)		C/N		Total P (mg/kg)	C/P	Olsen-P (mg/kg)		Bray-P (mg/kg)	
	1994	1996	1994	1996	1994	1996	1994	1996	1994	1994	1994	1996	1994	1996
Forest														
L	5.3	5.3	509	537	9.0	7.9	56	68	863	590	72	22	nd	nd
	(0.1)	(0.1)	(6)	(1)	(0.3)	(0.2)	(2)	(2)	(12)	(12)	(1)	(1)		
FH	4.6	5.2	360	468	11.4	15.2	32	31	673	534	13	14	nd	nd
	(0.1)	(0.1)	(20)	(16)	(0.8)	(0.3)	(0.5)	(0.7)	(12)	(25)	(2)	(1)		
0–10 cm*	6.4	6.3	7	8	0.4	0.4	17	20	330	20	5	2	32	39
	(0.1)	(0.1)	(0.6)	(0.1)	(0.1)	(0.1)	(1)	(0.3)	(6)	(2)	(0.6)	(0.1)	(0.3)	(5)
Windrows														
Needles	nd	6.2	nd	532	nd	19.5	nd	27	nd	nd	nd	nd	nd	nd
		(0.1)		(1)		(0.3)		(0.4)						
L	5.5	6.2	493	542	15.8	19.3	31	28	1270	390	113	44	nd	nd
	(0.1)	(0.1)	(10)	(2)	(0.4)	(0.2)	(0.4)	(0.3)	(44)	(6)	(8)	(3)		
FH	4.8	5.9	157	322	5.2	12.2	30	26	537	287	26	39	nd	nd
	(0.1)	(0.1)	(29)	(34)	(0.8)	(1.2)	(2)	(0.2)	(69)	(18)	(4)	(1)		
0–10 cm*	5.9	6.0	9	13	0.4	0.6	22	22	357	25	14	9	47	32
	(0.1)	(0.1)	(1)	(3)	(0.1)	(0.1)	(2)	(2)	(3)	(5)	(1)	(1)	(1)	(2)
Raked														
0–10 cm*	5.4	5.7	23	16	0.9	0.7	27	23	357	65	12	4	40	40
	(0.1)	(0.1)	(1)	(1)	(0.1)	(0.1)	(2)	(0.4)	(3)	(3)	(0.8)	(0.3)	(1.9)	(4)

nd = not determined,
* = mineral soil.

TABLE 2–Microbial carbon (C), nitrogen (N), and phosphorus (P); standard errors of the means in parentheses.

Sample	Microbial C (mg/kg)		Microbial N (mg/kg)		Microbial P (mg/kg)	
	1994	1996	1994	1996	1994	1996
Forest						
L	17 000 (780)	11 700 (260)	1470 (40)	759 (49)	526 (10)	268 (22)
FH	5 200 (230)	5 410 (900)	478 (9)	874 (181)	231 (12)	354 (32)
0–10 cm*	180 (20)	194 (40)	18 (4)	18 (4)	4 (1)	5 (1)
Windrows						
Needles	nd	12 100 (730)	nd	1840 (160)	nd	nd
L	24 500 (230)	10 100 (630)	2490 (160)	1410 (52)	796 (40)	498 (11)
FH	1 590 (80)	4 270 (740)	170 (15)	638 (40)	74 (10)	268 (19)
0–10 cm*	120 (20)	131 (21)	19 (1)	19 (3)	4 (1)	3 (1)
Raked						
0–10 cm*	341 (10)	209 (17)	29 (2)	25 (4)	8(0.2)	5 (1)

nd = not determined,
* = mineral soil.

lower (about 15–23) in the FH samples and consistent with their higher Olsen-phosphorus values; this could indicate that phosphorus was here more readily available for micro-organisms.

Mineral Nitrogen and Net Nitrogen Mineralisation

Standing forest L and FH layers

The amounts of mineral nitrogen in the forest L and FH layers were lower ($p=0.01$) in winter 1996 than in summer 1994 (Table 4), possibly because of increased leaching during winter; nearly all the mineral nitrogen was in the ammonium form. This is probably the usual situation for most L and FH layers in *P. radiata* production forests where the carbon/nitrogen ratios are wide (Adams & Attiwill 1984). There was no net nitrogen mineralisation in the L material, which is normal for needles with wide carbon/nitrogen ratios (Table 1) where net immobilisation of nitrogen generally occurs (Scott *et al.* 1998).

Windrow needles and L/FH layers

The mineral nitrogen values of 122 and 120 mg/kg in the windrow L material were greater ($p<0.005$) than for forest L samples (Table 4). The needle mineral nitrogen was 39 mg/kg in 1996, 32 months after clearfelling. The mineral nitrogen was predominantly ammonium-nitrogen, which is unlikely to be leached since the A horizon has a cation exchange capacity of 8 cmol/kg. However, nitrate-nitrogen was present in these windrow samples and increased between 1994 and 1996 (Table 4).

In the incubation experiment there was a high rate of net nitrogen mineralisation in the windrow needles and L material, with at least half being in the nitrate form (Table 4). Net nitrogen mineralisation was particularly high in the 1994 L material, with 2700 mg N/kg (equivalent to 17% of the total nitrogen) being produced over the 56-day period; the corresponding values for the 1996 needles were 2790 mg N/kg. More nitrogen was

TABLE 3–Ratios of microbial values to total values, and ratios of microbial carbon to microbial nitrogen and phosphorus; standard errors of the means in parentheses.

Sample	Microbial C/Total C (%)		Microbial N/Total N (%)		Microbial P/Total P (%)	Microbial C/Microbial N		Microbial C/Microbial P	
	1994	1996	1994	1996	1994	1994	1996	1994	1996
Forest									
L	3.3 (0.1)	2.2 (0.1)	16 (0.3)	9.6 (0.3)	61 (0.3)	12 (0.9)	16 (0.9)	33 (2)	44 (3)
FH	1.5 (0.1)	1.2 (0.2)	4.2 (0.3)	5.8 (1.3)	34 (1)	11 (0.6)	6 (0.4)	23 (1)	15 (1)
0–10 cm*	2.7 (0.1)	2.3 (0.3)	4.5 (0.4)	4.2 (0.4)	1.1 (0.2)	10 (0.7)	11 (1.4)	52 (11)	39 (6)
Windrows									
Needles	nd	2.3 (0.1)	nd	9.4 (0.4)	nd	nd	7 (0.2)	nd	nd
L	5.0 (0.1)	1.9 (0.1)	16 (1)	7.3 (0.8)	63 (3)	10 (0.7)	7 (0.4)	31 (2)	20 (1)
FH	1.1 (0.2)	1.3 (0.1)	3.4 (0.4)	5.3 (0.5)	14 (1)	9 (0.5)	7 (1)	22 (3)	16 (20)
0–10 cm*	1.4 (0.1)	1.1 (0.2)	4.9 (0.6)	3.4 (0.3)	1.0 (0.3)	6 (0.9)	7 (0.2)	35 (4)	51 (18)
Raked									
0–10 cm*	1.5 (0.1)	1.3 (0.0)	3.4 (0.1)	3.5 (0.2)	2.3 (0.05)	12 (0.6)	9 (0.7)	42 (1)	50 (11)

nd = not determined,
* = mineral soil

TABLE 4—Net mineral-nitrogen (min-N) produced after 14 (or 17) and 56 days' incubation, and net phosphorus mineralised (ΔP-min) after 7 days' incubation; standard errors of the means in parentheses.

Sample	Min-N (mg/kg)		Rate (mg/kg N/h)				Nitrate-N(×100)/Total min-N				ΔP-min (mg/kg /week)
	1994	1996	0–17days 1994	17–56days 1994	0–14days 1996	14–56days 1996	Day 0 1994	Day 56 1994	Day 0 1996	Day 56 1996	1994
Forest											
L	23 (2)	10 (3)	–6 (0.4)	0	–1 (1)	0	0	0	0	0	nd
FH	22 (1)	13 (2)	21 (0.7)	23 (4)	18 (11)	18 (2)	0	5 (2)	2 (2)	21 (10)	nd
0–10 cm*	3 (0.4)	3 (0.3)	54 (2)	18 (4)	35 (5)	39 (2)	0	88 (10)	17 (3)	90 (1)	3 (0.2)
Windrows											
Needles	nd	39 (3)	nd	nd	81 (4)	118 (9)	nd	nd	3 (0.3)	48 (24)	nd
L	122 (12)	120 (20)	191 (25)	107 (10)	91 (4)	49 (1)	13 (1)	49 (8)	39 (9)	99 (0.2)	nd
FH	59 (18)	115 (17)	38 (7)	34 (4)	50 (3)	61 (3)	18 (17)	92 (2)	25 (6)	99 (0.2)	nd
0–10 cm*	4 (0.7)	2 (0.3)	59 (1)	30 (2)	31 (7)	40 (4)	1 (0.6)	100 (0)	6 (6)	95 (0.6)	8 (0.3)
Raked											
0–10 cm*	3 (0.1)	2 (0.4)	31 (4)	32 (4)	15 (0.3)	42 (4)	0	98 (0.3)	9 (7)	96 (0.4)	7 (0.4)

nd = not determined,
* = mineral soil.

mineralised from the FH layer of the windrows than from the forest ($p<0.005$), and a greater proportion in the windrows was in the nitrate form (Table 4).

Mineral soil

Low concentrations of mineral nitrogen were present in all samples of 0–10 cm mineral soil, which is consistent with the raw nature of this soil (Table 4). Generally, nitrate-nitrogen was not detected in 1994, but a small percentage was present in the 1996 samples. During the incubations for 56 days, similar amounts of nitrogen were mineralised from all the 0–10 cm samples (Table 4).

Net Phosphorus Mineralisation

Net phosphorus mineralisation in the mineral soil was higher ($p<0.0001$) in the windrows and raked soil than in the standing forest (Table 4), and this is consistent with the available-phosphorus (Olsen-P) status (Table 1). The Olsen-P values were also higher in the windrow than the forest FH material. Because the FH material is unlikely to sorb phosphorus chemically, some of this available-phosphorus, in the absence of growing plants, may have been leached into the mineral soil and contributed to the between-soil differences in Olsen-P values.

DISCUSSION

Nitrogen was readily mineralised in the dead needles, L, and FH material from the windrows, whereas it was immobilised in the forest L layer; mineral nitrogen levels also were higher in the windrows (Table 4). These differences were probably due to the age of the windrow and the time of decomposition in the windrow.

Nitrogen in the Needles and L Layers

After clearfelling, nitrogen concentrations increased from 11 g/kg in the current-year foliage to 19.5 g/kg in the dead needles remaining on slash in the windrows after 32 months (Table 1). Thus, the nitrogen content of the needles increased by 80% while the carbon/nitrogen ratio decreased from 39 to 27. Almost half the carbon had therefore been lost from the needles, probably by decomposition by micro-organisms, and by leaching of soluble organic compounds (Johansson 1994). NMR data on needles from windrows showed that O-alkyl groups, including those in carbohydrates, decreased with time of exposure to sunlight, weather conditions, and microbial decay (R.L.Parfitt & R.H.Newman unpubl. data). Nitrogen was probably retained in the microbial biomass on the needles during this period (Table 2) when carbon was being lost. If some of the nitrogen was also lost from needles by leaching (Parfitt *et al.* 1997), then the absolute loss of carbon would have been greater (Will *et al.* 1983; Baker *et al.* 1989). Laboratory incubation of brown needles (L material) from the forest floor on another coastal sand showed that about one-third of the carbon could be lost as carbon dioxide in 1 year at 25°C (Scott *et al.* 1998).

The high percentages of total nitrogen and phosphorus held in the microbial biomass of the 1994 samples of the windrow L materials (Table 3) are also consistent with our suggested mechanism for the retention of nitrogen (and phosphorus) in needles. These values declined with time, probably as a result of the loss of readily available substrates.

Nitrogen Immobilisation and Mineralisation

In the incubation experiment, net nitrogen immobilisation occurred in the fallen needles (L layer) on the forest floor (Table 4), in accord with their wide carbon/nitrogen (>55) and microbial carbon/nitrogen ratios (Tables 1 and 3). These results are consistent with those of Scott *et al.* (1998) from other *P. radiata* forests. During the incubation, heterotrophs would have been likely sinks for any mineral nitrogen produced. The forest FH layer, which had a carbon/nitrogen ratio of about 30 (Table 1), mineralised nitrogen at a rate of about 20 mg/kg N/h. Most of this nitrogen was in the ammonium form, in agreement with the results of Parfitt *et al.* (1997) for similar FH material. The forest 0–10 cm mineral soil, with a carbon/nitrogen ratio of about 18, mineralised more nitrogen than the FH material, per unit of total nitrogen, with most in the nitrate form after incubation for 56 days. The amounts mineralised were close to those obtained by Parfitt *et al.* (1997) in a leaching/incubation experiment with a similar soil.

The mineral nitrogen value of 122 mg/kg in the windrow L material was much greater than for all other 1994 samples. This is consistent with the rapid mineralisation found previously for needles from windrows with trees clear-felled 12 months before sampling (Parfitt *et al.* 1997). More nitrogen was mineralised from the FH layer of the windrows than of the forest, and a greater proportion was in the nitrate form (Table 4). The proportion of nitrate-nitrogen in the windrow L and FH material also increased from 1994 to 1996 (Table 4). The presence of nitrifiers on the slash needles and windrow L material is clearly shown by the large percentage of nitrate-nitrogen in the pools of mineral nitrogen present after incubation for 56 days at 25°C. These incubation data from the L and FH material are consistent with a critical carbon/nitrogen ratio for net nitrification of about 40 (Scott *et al.* 1998).

Between 1994 and 1996 the microbial carbon/nitrogen ratios of all windrow L/FH samples decreased to a value of 7 (Table 3). The narrowing of this ratio may reflect both decreases in the available carbon pool and changes in the structure of the microbial community (Anderson & Domsch 1980).

Leaching of Nitrogen

Lysimeter data at Woodhill and Kaingaroa Forests showed that nitrogen was retained in the system in the first several months after clearfelling *P. radiata* (Dyck *et al.* 1983; Smith *et al.* 1994). This probably resulted from microbial immobilisation of nitrogen (Vitousek & Matson 1984; Vitousek & Matson 1985; Vitousek & Andariese 1986), with the readily decomposable carbon in the residues enabling the microbial biomass to increase (Downs *et al.* 1996). After several months, nitrate-nitrogen was detected in increasing amounts in soil solution (Dyck *et al.* 1983; Smith *et al.* 1994), possibly as a result of decreases in carbon availability and changes in the substrate carbon/nitrogen ratio in the fine fractions of the residues (Scott *et al.* 1998). Where there are large reservoirs of nitrogen, such as in windrows or stockpiles of slash, as at the Himatangi site, increased leaching losses may be expected. Lysimeter data from coastal sands have, in fact, shown that the nitrate-nitrogen concentration in soil solution was 10 times higher under windrows than under raked soil (Parfitt *et al.* 1997), in spite of the presence of branch and stem material with wide carbon/nitrogen ratios. The branch and stem material, however, is physically separated from much of the fine material

and the opportunity for microbial immobilisation of nitrogen by the coarse forest-floor materials may not arise.

Phosphorus Mineralisation

Available-phosphorus, and net phosphorus mineralisation in mineral soil, were higher in the windrows than in the standing forest (Tables 1 and 4). This is consistent with the results of Bekunda *et al.* (1990) who showed labile inorganic phosphorus increased after clearfelling. The total carbon/phosphorus ratios of the L and FH materials were 590 and 534 in the forest compared with 390 and 287, respectively, in the windrows (Table 1). Saggar *et al.* (1998) reported that net mineralisation of phosphorus in pine needles and FH material occurred only when the total carbon/phosphorus ratio was lower than 550, although gross mineralisation occurred readily at wide total carbon/phosphorus ratios. On this basis, net mineralisation of phosphorus should have occurred readily in the windrow materials. The phosphorus released by mineralisation after clearfelling should generally be available for the next rotation.

Implications for Management

Since nutrients in the windrow materials are readily mineralised, and some nitrate-nitrogen (together with magnesium and calcium (Dyck *et al.* 1981)) are likely to be lost by leaching, alternative management practices to allow nutrients to be retained in the system for a following rotation need to be considered. In coastal pine forests, where wind damage is considerable, and large numbers of branches are produced, the large amounts of slash are usually bulldozed into windrows. Our results suggest that it may be better to chop and spread the residues as a mulch. This would give a better distribution of nutrients for plants, reduce water loss from the soil surface by evaporation, and provide microsites for rapid revegetation by other species to reduce the potential losses of nutrients by leaching. A fraction of these nutrients would later become available to the pine trees when the other species are shaded out and decompose.

CONCLUSIONS

Nitrogen was more readily mineralised in the windrow than in the forest L and FH materials, and was also mineralised readily in dead needles attached to windrows. Initially the nitrogen was largely in the ammonium form, which is unlikely to be leached from the soil since it is retained on cation exchange sites. However, the proportion of nitrate-nitrogen increased with time after clearfelling and would be susceptible to leaching, if not taken up by plants. Previous lysimeter data have confirmed that nitrate-nitrogen was present in soil solution under windrows after clearfelling of *P. radiata*. The carbon/nitrogen ratio of needles is a useful guide as to whether net mineralisation or immobilisation of nitrogen will occur during decomposition. Our work here, together with our previous conclusions, suggests that net nitrification is likely in *P. radiata* needles if the carbon/nitrogen ratio is lower than 40, whereas net immobilisation of nitrogen is likely if the ratio is greater than 55.

The available phosphorus in the windrow and raked mineral soil was also relatively high after clearfelling, as a result of net mineralisation, and would be available to plants. The total carbon/total phosphorus ratios were lower in the windrow than in the forest L and FH materials, and suggest that net phosphorus mineralisation in the windrows is likely, based on our previous finding that net mineralisation will probably occur if this ratio is lower than 550.

Since the nutrients in the windrows are readily mineralised, and some losses by leaching will occur, particularly in coastal sands, alternative management practices may be considered which allow for nutrients to be retained in the system. One possibility is to chop the residues and use them as a mulch.

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