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FATE OF ^{15}N UREA FERTILISER APPLIED TO A RECENTLY THINNED RADIATA PINE STAND ON A PUMICE SOIL

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In 1961 a large lysimeter was built in Kaingaroa Forest; together with the surrounding area it was planted with radiata pine (**Pinus radiata**). In the spring of 1974 the 13-year-old stand of trees was thinned, and 3 months later ^{15}N-enriched urea was applied to the Taupo silty sand in the lysimeter and in its immediate surround at a rate equivalent to 200 kg N/ha. In the following 3 years no apparent loss of N by leaching and no change in the rate of leaching of other nutrients was recorded.

The concentrations of KCl-extractable NH_4-N in the surface soil layers showed marked increases 1 week after the fertiliser application, and there were further increases between weeks 2 and 4. After 38 weeks, concentrations had returned to pretreatment levels. Increased NO_3-N concentrations were detected after 2 weeks; these were maintained for the duration of the experiment.

All of the applied N was still present in the litter and top 30 cm of soil 2 weeks after application. The proportion of applied N in the litter and top 30 cm of soil dropped to 60% after 4 weeks and later stabilised at about 50%. It is suggested that tree uptake accounted for a large part of this loss.

INTRODUCTION

The growth rate of radiata pine (*Pinus radiata* D. Don) in the extensive plantations on the pumice soils of the central region of the North Island of New Zealand is high. Until the results reported by Woollons & Will (1975), no serious consideration had been given to increasing growth by the application of fertilisers. Since then, it has become standard practice to apply urea to thinned stands in some forests; these applications now cover about 5000 ha/year. Ballard & Will (1978) estimate that potential use of nitrogenous fertiliser in pumice soil forests is considerably greater.

There are many benefits if forest production is increased, but possible adverse effects must also be considered. One such factor to be considered is fertiliser enrichment of drainage water and the subsequent eutrophication of rivers and lakes. Neary & Leonard (1978) showed that enrichment of surface waters from forest fertilisation is largely related to the amount of fertiliser that falls in or close to stream channels. However, there are few streams and rivers on the volcanic plateau of the central North Island and much of the rainfall percolates through the pumice–ash layers into the underlying ignimbrite rock. Much of this water later emerges in the many springs in

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the district. The present study was undertaken to estimate the quantities of inorganic N that leach through the soil into the ground water after urea fertiliser is applied in a radiata pine plantation.

Since 1962 a lysimeter in Kaingaroa Forest on a Taupo silty sand (W. Rijkse, pers. comm.) has been used to measure the natural leaching losses of plant nutrients from a pumice soil (Knight & Will 1977). Having provided background data on naturally occurring losses, this lysimeter was chosen as the site for studying leaching losses after the application of urea. In addition to leaching losses, distribution of fertiliser within the litter and soil uptake by the trees were included in the study.

The applied urea was tagged with ^{15}N so that maximum information could be obtained on the movement and transformation of the applied N. Several previous studies have emphasised the usefulness of this isotope in forest fertilisation investigations; for example, Overrein (1968) evaluated leaching and volatilisation losses from urea fertiliser applied to a lysimeter; Knowles & Lefebvre (1972) used field microplots to study leaching; and Mead & Pritchett (1975a, b) measured N uptake from ammonium sulphate into a slash pine ecosystem. Hauck (1968) discussed the place for different N fertilisers in growing various crops including trees.

However, to the best of our knowledge this study is the first to have been carried out using a large tree-planted lysimeter where a management-scale thinning and fertiliser application were simulated.

MATERIALS AND METHODS

Lysimeter and tree stand descriptions

Full details of the soil and field lysimeter construction are given by Will (1977): it consists of an 8.56 m^2 concrete drainage water collection pad placed 2.7 m below the soil surface. To allow unrestricted root development, the lysimeter walls extend only a few centimetres above the pad itself. After construction, the multi-layered pumice–ash soil profile was replaced and compacted over the pad and the surrounding excavated area. Trees were then planted. A pipe takes water collected by the pad to a nearby instrument hut. Climate details and the results of analysing leachates collected during the first 12 years of tree growth were reported by Knight & Will (1977).

After 2–3 years a slasher thinning reduced tree stocking to 1350 stems/ha. In 1974, the 13-year-old stand was thinned to 550 stems/ha, which is similar to that preceding responses to N fertiliser in similar aged stands growing on pumice soils (Woollons & Will 1975). Mean dob was 28.7 cm. This thinning of the experimental area included the removal of all slash from the area above and surrounding the lysimeter and was to that extent atypical. There was no understorey and the flat topography, combined with the physical nature of the soil, made overland flow most unlikely.

Fertiliser application

In February 1975 (mid summer), urea enriched with 5.15 atoms % of ^{15}N was applied to the immediate lysimeter area plus a 0.9 m wide surround. One kg of urea was dissolved in 18 litres of distilled water and was applied evenly by watering can. This gave an application rate of approximately 200 kg N/ha. A further 107 litres of distilled water were applied to the treated area on the same day. The combined volume of 125 litres was equivalent to 5 mm of rainfall. The watering with distilled water was to avoid possible losses of gaseous ammonia such as those reported by Pritchett & Smith (1969), when urea is not washed into the soil.

One of the main factors influencing the speed and end products of urea hydrolysis, after application of urea to the soil, is the pattern of rainfall during the first 6–18 days (Cole *et al.* 1975). To avoid an atypical rainfall pattern (either drought or unseasonal storm), a polyethylene tent roof was placed 2 m above the site to exclude natural rainfall; the tent did not influence soil temperatures. For 1 month distilled water was applied by watering can every 3–4 days; the total application was equivalent to 50.5 mm, which climatic records show is the mean rainfall for that period. The tent was removed 3 days after the final watering.

Sampling procedures

Lysimeter leachates: rates and quantities were recorded by a clock-work driven chart recorder coupled to a syphoning device (Knight & Will 1977). Subsamples were collected by a Manning Automatic Sampler.

Litter and soil samples: composite samples of the L, and F + H litter layers and the 0–10 cm, 10–20 cm, and 20–30 cm soil depths were taken from 8 points within a central strip in the fertilised lysimeter surround. Litter subsamples were collected over approximately 0.05 m^2 at each point and soil samples taken from a 2 cm diam. soil core. Any roots were removed from soil samples. Samples were taken on 7 occasions: before the fertiliser was applied and at 1, 2, 4, 38, 89, and 147 weeks after application. Samples for litter weights (kg/m^2) and soil layer bulk densities (g/cm^3) were taken outside the treated plot to avoid disturbance to the lysimeter.

Foliage samples: current season and 1-year-old foliage were sampled from secondary branches in the top and middle thirds of the green crown of one co-dominant tree within the lysimeter area. Samples were taken at the same time as soil samples.

Needle fall samples: nylon mesh litter traps were placed at the 8 soil and litter sampling points. After 38, 89, and 147 weeks needle litter was cleared from the traps and bulked to give composite samples.

Methods of chemical analysis

Leachate samples: after collection in the field, samples were preserved by addition of mercuric chloride and stored at 3°C.

Nitrate-N: determination by AutoAnalyzer method involving reduction to nitrite followed by diazo coupling with sulphanilamide. Any nitrite initially present was thus included in the NO_3-N value.

Ammonium-N: determination by AutoAnalyzer using reaction with sodium salicylate and NAD TT.

Soluble orthophosphate: determination by AutoAnlyzer using molybdenum blue reaction with ascorbic acid as the reducing agent.

Cations: Ca, Mg, K, and Na determinations by atomic absorption techniques.

Soil samples

Total-N: Determination on dried, finely ground samples by a semi-micro-Kjeldahl method modified to include NO_3-N and NO_2-N. Before digestion, acid-permanganate and reduced-Fe were used to convert NO_3-N and NO_2-N to NH_4-N. After distillation and titration to estimate total-N, the distillate was adjusted to pH 3 and reduced to less than 10 ml on a hot plate. After transfer to a 10 ml screw cap vial, samples were evaporated to dryness in a forced-draught oven. The capped vials were stored for ^{15}N determinations (Steele *et al.* 1980).

Ammonium-N and nitrate-N: As soon as possible after sample collections 10 g portions of soil, at field moisture content, were shaken with 80 ml of 2N KCl for 1 hour (Bremner 1965). Extracts were filtered and, when storage was necessary, they were frozen. AutoAnalyzer methods were used to determine (1) NH_4-N (reaction with phenol hypochlorite catalysed by nitroprusside), and (2) NO_3-N (reduction with hydrazine sulphate followed by diazotisation) — any NO_2-N present was included in this value.

Litter and foliage samples: after collection samples were oven dried and ground in a Wiley mill.

Total-N: determinated by micro-Kjeldahl digestion, distillation, and titration. Distillates were prepared for ^{15}N analysis as for soil samples.

^{15}N analyses

^{15}N determinations were made on a double inlet 602 Micromass Mass Spectrometer. The crystalline samples (from micro-Kjeldahl distillation) were reacted with lithium hypobromite and the resulting nitrogen gas samples were analysed for isotopic ratios. A standard ammonium sulphate solution was evaporated to dryness and used as a reference during the ^{15}N analyses (Steele *et al.* 1980).

During sample preparation and analysis appropriate steps were taken to minimise contamination by such substances as ethanol, methylamine, CO_2, N_2O, and air which can cause errors (Martin & Ross 1968).

Calculations

The figures obtained from the mass spectrometer determinations were δ values, i.e.,

$$\delta\,^{15}N = \frac{\text{atom \% }^{15}N\text{ sample} - \text{atom \% }^{15}N\text{ standard} \times 1000}{\text{atom \% }^{15}N\text{ standard}}$$

Atom % ^{15}N in the sample was then obtained from the δ value.

Atom % $^{15}N = (\delta \text{ value} \times 10^{-3} + 1) \times 0.3676$,

where 0.3676 is the atom % ^{15}N of the standard ammonium sulphate.

From the enrichment in ^{15}N it is possible to calculate % N in a sample

$$\text{originating from fertiliser} = \frac{c - b}{a - b} \times 100$$

where a = atom % ^{15}N in fertiliser (5.15)
b = atom % ^{15}N in standard (0.3676)
c = atom % ^{15}N in sample.

RESULTS AND DISCUSSION

Leaching losses after fertilisation

Mean rainfall, lysimeter discharge, and leaching loss values are given in Table 1. There are differences between the 3 years after fertilisation and the 7-year means before the application of urea but these do not appear to have been associated with the fertiliser application. The higher lysimeter discharges, relative to the rainfall in 1975, 1976, and 1977 can be accounted for by changes in interception and transpiration. Nutrient losses, other than N, were higher in 1975 than in other years, but as the amounts of cations were in direct proportion to the leachate volume, there is no reason to think that these were influenced by the fertilisation; similar increases were associated with the high rainfall in 1971 (Knight & Will 1977).

TABLE 1—Rainfall, lysimeter leachate volumes, and nutrient losses before and after the application of urea (200 kg N/ha in February 1975

Year	Rainfall	Lysimeter discharge		Nutrients (kg/ha)						
				NH_4-N	NO_3-N	P	K	Mg	Ca	Na
	(mm)	(months)	(mm)							
1967–73*	1500	July-Oct†	167	Nil	Nil	0.007	4.2	1.6	5.7	12.5
1975	1578	June-Nov	334	<0.001	<0.001	<0.001	6.5	4.0	10.5	20.4
1976	1468	June-Nov	167	0.005	0.006	Nil	3.3	1.5	6.0	11.2
1977	1299	July-Oct	155	0.005	0.002	Nil	3.0	1.5	6.4	10.9

* Mean values from Knight & Will (1977)

† The longest period of flow (May-Dec) was in 1971

The barely detectable concentrations of NH_4-N and NO_3-N in leachates after treatment are consistent with the low concentrations reported by Overrein (1968), Knowles & Lefebvre (1972), and Cole *et al.* (1975). The last mentioned authors suggested that in the US Pacific Northwest conditions in forest soils are such that secondary transformations of nitrogen into the oxidised nitrite and nitrate forms are very slow; the result is a negligible nitrate content in the ground water after urea application. The same situation does not apply to pumice soils in New Zealand where considerable nitrification occurs in the presence allophane in relatively acid conditions (Sarathchandra 1978).

Nitrogen transformations and immobilisation in litter and soil

Litter and soil samples were taken from the middle of the treated surround; the maximum depth to which soil samples were taken was 30 cm. This sampling pattern was adopted to minimise disturbance to the lysimeter and its normal pattern of leaching, and to avoid edge effects as far as possible. Although the study of the movement of the applied N was necessarily confined to the top 30 cm of soil, the results obtained are none the less of considerable interest. In Table 2 extractable NH_4-N and NO_3-N concentrations are summed to give total inorganic-N values which in turn were subtracted from total-N figures to give organic-N values.

TABLE 2—Distribution of N fractions in the soil (ppm)

	Weeks since fertiliser applied						
	0	1	2	4	38	89	147
Depth: 0–10 cm							
Extractable NH_4-N	9.1	235.3	227.7	442.1	12.9	7.6	7.6
Extractable NO_3-N	4.6	1.5	25.0	21.2	16.7	29.6	19.7
Total extractable N (inorganic)	13.7	236.8	252.7	463.3	29.6	37.2	27.3
Non-extractable N (organic)†	1376.3	1593.2	1327.3	1076.7	1630.4	1772.8	1922.7
Total N	1390.0	1830.0	1580.0	1540.0	1660.0	1810.0	1950.0
% inorganic N	1.0	12.9	16.0	30.1	1.8	2.1	1.4
Depth: 10–20 cm							
Extractable NH_4-N	8.4	47.1	30.4	227.1	9.1	7.6	7.6
Extractable NO_3-N	4.6	1.5	24.3	21.2	16.7	27.3	19.0
Total extractable N (inorganic)	13.0	48.6	54.7	248.9	25.8	34.9	26.6
Non-extractable N (organic)†	627.0	931.4	645.3	491.1	714.2	655.1	1223.4
Total N	640.0	980.0	700.0	740.0	740.0	690.0	1250.0
% inorganic N	2.0	5.0	7.8	33.6	3.5	5.1	2.1
Depth: 20–30 cm							
Extractable NH_4-N	7.6	33.4	26.6	*	9.1	7.6	7.6
Extractable NO_3-N	3.8	1.5	24.3	19.7	16.7	27.3	19.0
Total extractable N (inorganic)	11.4	34.9	50.9	—	25.8	34.9	26.6
Non-extractable N (organic)†	588.6	705.1	499.1	—	814.2	655.1	693.4
Total N	600.0	740.0	550.0	530.0	840.0	690.0	720.0
% inorganic N	1.9	4.7	9.3	—	3.1	5.1	3.7

* Poor duplication

† By difference

The application of urea resulted in increased NH_4-N concentrations within 1 week in all 3 soil layers sampled. The largest increase was in the uppermost layer (0–10 cm) where concentrations increased 25 times, and there was a further doubling in concentration by week 4. In the 10–20 cm samples there was an even more marked increase (7-fold) between weeks 2 and 4. The available results indicate that levels at 20–30 cm were similar to those at 10–20 cm. NH_4-N concentrations had returned to pretreatment values at all depths when the layers were next sampled.

In contrast to NH_4-N, NO_3-N concentrations at all 3 soil depths did not rise until week 2. However, after they rose to some 5 times the pretreatment level, this concentration was maintained until the last sampling date at 147 weeks.

Because soil sampling was restricted to one composite sample on each sampling date, no measure of the limits of error for N concentrations is possible. The substantial and consistent changes in concentration of NH_4-N and NO_3-N can be interpreted as above with some confidence but the changes in total-N are erratic and their reality is doubtful. Even the substantial rise in total-N in the 10–20 cm layer between weeks 89 and 147 is likely to be a chance sampling of areas with originally greater mean organic matter contents. The progressive increases in the percentage of N present in inorganic form from the sampling before urea application to those 1, 2, and 4 weeks later are consistent within themselves.

During the period when these changes were taking place in the soil there were also changes in the litter layers (Table 3). One week after the urea application the N concentration in the L litter layer had increased from 1.06 to 1.27%. This increased level was maintained for at least 89 weeks, indicating a retention of the absorbed N. In the combined F and H litter layers there was a rise in N concentration at week 1, a possible further rise at week 2, but a return to pretreatment levels by week 4.

It seems that extra nitrogen retained in the L litter layer at week 1 was held in a bound form as, in the short term, it was not subject to subsequent leaching. In contrast, the additional nitrogen retained in the F and H litter layers at weeks 1 and 2 had been leached by week 4, probably contributing to the peak in NH_4-N in the 0–10 cm soil layer which occurred at that time. This low degree of immobilisation in the litter is in contrast to Scandanavian experience (Overrein 1972).

Fertiliser N movement as indicated by ^{15}N analyses

Before considering the isotope analyses it must be pointed out that this lysimeter study was an unreplicated experiment carried out under somewhat artificial conditions, i.e., reformed soil profile and simulated mean rainfall for the first month. In retrospect, there was also an unfortunate lack of sampling between weeks 4 and 38. However, despite these deficiencies we feel that these results contribute substantially to knowledge in a field which is of considerable economic importance and where present knowledge is meagre. There must be caution in extrapolating from results obtained from a limited number of point-in-time samplings but the overall picture is, we believe, an interesting one.

The total-N concentrations and atoms % ^{15}N in all layers at all sampling times are given in Table 3. The atoms % ^{15}N in the unfertilised litter and soil layers (time 0) are slightly above the mean of 0.32 found for 61 New Zealand grassland top soils (0–7.5 cm) (Steele *et al.* 1980) but above the 0.24 measured in grassland on the same soil type — Taupo silty sand (K. W. Steele, pers. comm.). The similarity of the atoms % ^{15}N in all layers is in contrast to the two New Zealand soils studied in detail by Steele *et al.* (1980) but it does simplify interpretation of results in this study. Bulk density measurements are also given and were used in calculating total-N amounts and the percentage of fertiliser-derived N in the N present in each layer. The percentages of applied fertiliser present in each layer at successive intervals after treatment are shown in Fig. 1.

Of the N present in the litter layers 1 and 2 weeks after the fertiliser was applied, nearly 20% had its origin in the fertiliser. In the F and H layers in particular this fertiliser N must have become interchangeable with the original N present in the litter; this is demonstrated by the fact that after week 2 when the total N content of these layers returned to pretreatment levels there was still about 15% fertiliser-derived N present. A similar interaction of fertiliser N and native soil N was reported by Overrein (1972). At the last sampling dates about 10% of the fertiliser-derived N was still present.

TABLE 3—Nitrogen in the litter and soil as influenced by the addition of 200 kg/ha urea-N tagged with ^{15}N

Time after fertilisation (weeks)	Litter/soil layer (cm)	Wt per plot layer (kg)*	Total N		^{15}N	Fertiliser N		Proportion of fert. N recovered (%)
			conc (%)	Wt (g)	atoms %	(%)	(g)	
0	L	12.96	1.058	137	0.366	—	—	0
	F+H	84.70	1.021	865	0.364	—	—	0
	0–10	1648.00	0.139	2290	0.363	—	—	0
	10–20	1608.00	0.064	1029	0.363	—	—	0
	20–30	1630.00	0.060	978	0.363	—	—	0
								Total 0
1	L	12.96	1.274	165	1.266	18.8	31.0	6.7
	F+H	84.70	1.306	1106	1.117	15.7	173.3	37.3
	0–10	1648.00	0.183	3015	0.751	8.0	241.7	52.0
	10–20	1608.00	0.098	1576	0.437	1.5	22.9	4.9
	20–30	1630.00	0.074	1206	0.377	0.2	2.4	0.5
								Total 101.4
2	L	12.96	1.226	159	1.260	18.7	29.7	6.4
	F+H	84.70	1.396	1182	1.194	17.3	204.2	43.9
	0–10	1648.00	0.158	2604	0.734	7.7	199.5	42.9
	10–20	1608.00	0.070	1126	0.420	1.1	12.3	2.7
	20–30	1630.00	0.055	897	0.379	0.2	2.1	0.5
								Total 96.4
4	L	12.96	1.295	168	1.216	17.7	29.8	6.4
	F+H	84.70	1.010	855	1.071	14.7	125.8	27.0
	0–10	1648.00	0.154	2538	0.569	4.2	106.9	23.0
	10–20	1608.00	0.074	1190	0.386	0.4	4.6	1.0
	20–30	1630.00	0.053	864	0.372	0.1	0.8	0.2
								Total 57.6
38	L	12.96	1.289	167	1.000	13.2	22.1	4.7
	F+H	84.70	1.026	869	0.972	12.6	109.8	23.6
	0–10	1648.00	0.166	2736	0.496	2.7	73.5	15.8
	10–20	1608.00	0.072	1158	0.390	0.5	5.4	1.2
	20–30	1630.00	0.084	1369	0.376	0.2	2.4	0.5
								Total 45.8
89	L	12.96	1.297	168	0.840	9.1	15.3	3.3
	F+H	84.70	1.182	1001	0.853	10.1	101.6	21.8
	0–10	1648.00	0.181	2983	0.515	3.1	91.9	19.8
	10–20	1608.00	0.067	1077	0.402	0.7	7.7	1.7
	20–30	1630.00	0.069	1125	0.376	0.2	2.0	0.4
								Total 47.0
147	L	12.96	1.058	137	0.567	4.2	5.7	1.3
	F+H	84.70	1.171	992	0.819	9.4	93.6	20.1
	0–10	1648.00	0.195	3214	0.475	2.2	72.2	15.5
	10–20	1608.00	0.125	2010	0.436	1.4	28.7	6.2
	20–30	1630.00	0.072	1174	0.388	0.4	5.0	1.1
								Total 44.2

* Calculated using litter weights and soil bulk densities

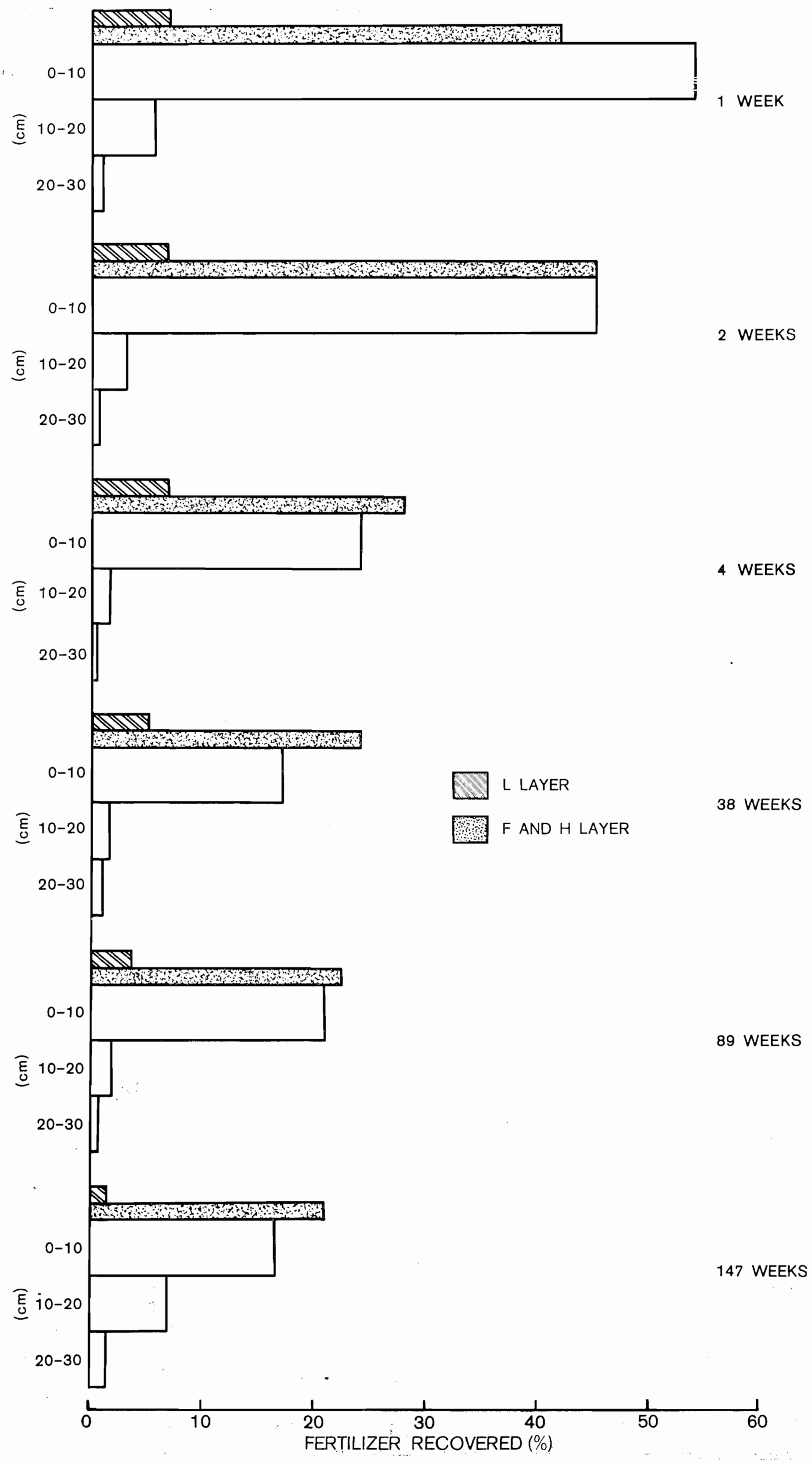

FIG. 1—Percentages of applied fertiliser recovered in each litter and soil layer at successive intervals after treatment

By week 1, fertiliser N had reached all three soil layers sampled. After week 2, the percentage of the total N present, derived from the fertiliser, appeared to progressively decline but with no evidence of a concentration zone moving down through the soil as might be expected if the fertiliser was leached. The higher percentage in the 10–20 cm sample at week 147 corresponds with a higher total N and, as discussed above, this is likely to have been an artifact of sampling rather than a real movement of N.

At both weeks 1 and 2 approximately 100% of the fertiliser could be accounted for but by week 4 only 60% remained in the sampled layers of the litter and soil. This amount declined further to 50% by week 38 and then remained relatively constant until the last sampling date.

This degree of long-term retention of N in the litter and soil is appreciably higher than that reported from some other studies. Morrison & Foster (1977) found that 36% of 300 kg N/ha applied as urea to a boreal pine stand was still in the litter and soil 3 years later. In Florida, Mead & Pritchett (1975b) found that less than 20% of the fertiliser was retained 2 growing seasons after applying 224 kg N/ha as ammonium sulphate to a pine stand on a sand soil. However, Overrein (1972) found that 40 months after applying 250 kg N/ha (as urea) to a podzolic soil 60% of it was still present in the raw humus and upper 5 cm of the mineral soil.

The distribution pattern established by week 1 remained similar for the duration of the study except for the large reduction between weeks 2 and 4 in the amounts present in both the F and H litter layers and in the 0–10 cm soil layer. The possibility that an appreciable part of this "lost" fertiliser moved completely beyond the zones sampled cannot be entirely eliminated but seems unlikely as no indication of inorganic nitrogen was detected in the lysimeter leachate after it began to flow 4 months after fertiliser application.

Overrein (1968, 1969) reported volatilisation losses that amounted to 3.5% of applied urea N but this was when 500 kg N/ha were applied and there were also pH increases of at least 3 units giving final pHs of neutral or slightly alkaline: when 250 kg N/ha was applied the loss was 0.6%. In the present trial, soil pH changes did not exceed 0.5 of one unit and, at the time of the drop in N levels, pHs were about 5.5 (see Table 4).

Morrison & Foster (1977) reported volatilisation losses of 30% in boreal pine forest when pH values in the litter layers rose by 2 and more units to remain mostly above pH 6.0 for 6 months. During the first few weeks they reported very high KCl-extractable NH_4-N levels in the litter and ammonia losses to the atmosphere were highest in the first week after fertiliser application. In the present study, litter pH and NH_4-N levels were not measured but the presence of elevated levels of NH_4-N

TABLE 4—Changes in soil pH after urea fertilisation

Depth	Week after fertiliser application						
(cm)	0	1	2	4	38	89	147
0–10	5.25	5.40	5.50	5.40	5.25	5.25	5.30
10–20	5.35	5.30	5.40	5.50	5.40	5.40	5.50
20–30	5.30	5.30	5.35	5.40	5.50	5.65	5.70

in the soil by week 1 suggests that any rise in NH_4-N in the litter had also begun by that time. The fact that no losses of N from the litter–soil system occurred until after week 2 suggests that the loss was not due to volatilisation. Applying the urea in solution, followed by simulated rain the same day and twice a week thereafter, combined to make volatilisation loss from the litter less likely with time.

If losses by leaching and volatilisation are unlikely explanations for the "disappearance" of 80 kg N/ha, this leaves tree uptake to be considered. The rise in extractable NH_4-N in the soil between weeks 2 and 4, particularly in the 10–20 cm zone (Table 2), suggests that this was a period of abundant supply of N in the soil in a form readily available to tree roots. Although this study was not designed to quantitatively measure N uptake by the trees, it should be noted that by week 4 the first appreciable quantities of fertiliser N were detected in the foliage (Table 5).

Thus, it seems reasonable to propose that during the period between weeks 2 and 4 there was an appreciable increase in mobile N within the trees' vascular system. No sampling of roots or tree stems was undertaken but it seems reasonable to assume

TABLE 5—Concentrations of total N and fertiliser-derived N in foliage

Time (weeks)	Crown position	Age of foliage	% N	% derived from fertiliser
1	Top 1/3	1973	1.25	0
		1974	1.43	0
	Middle 1/3	1973	1.08	0
		1974	1.28	0
2	Top 1/3	1973	1.30	0.1
		1974	1.43	0.1
	Middle 1/3	1973	1.14	0.1
		1974	1.28	0.1
4	Top 1/3	1973	1.36	0.5
		1974	1.50	0.6
	Middle 1/3	1973	1.09	0.5
		1974	1.30	0.6
38	Top 1/3	1973	1.25	4.8
		1974	1.49	5.5
		1975	1.57	8.3
	Middle 1/3	1973	1.22	4.4
		1974	1.42	4.8
		1975	1.70	7.3
89	Top 1/3	1975	1.27	6.2
		1976	1.02	5.5
	Middle 1/3	1975	1.36	6.0
		1976	1.34	5.2
147	Top 1/3	1976	1.18	3.8
		1977	1.12	3.3
	Middle 1/3	1976	1.25	3.9
		1977	1.10	3.3

a high level of root growth and nutrient uptake favoured by (1) the response to thinning 3 months previously, (2) mid-summer temperature and growth conditions, and (3) adequate moisture status after simulated regular rainfall. Although there must remain some question as to whether these environmental and stand conditions could result in an uptake of 80 kg N/ha, this value does not disagree with that reported by Morrison & Foster (1977) for uptake into ground vegetation and pines. Miller *et al.* (1976) concluded that "the efficiency of fertiliser nitrogen usage will depend on ensuring rapid uptake, a large storage capacity, both in foliage and wood, and a high growth potential." It appears that these conditions applied in this study. P. J. Knight (pers. comm.) has found, in a trial in the South Island of New Zealand, that when 168 kg N/ha were applied as urea to a young radiata pine stand the substantial rise in foliage N concentration peaked at about 4 months after treatment.

The data in Table 5 indicate that foliage levels of N never reached far above the satisfactory level (Will 1978). They were highest, and contained the greatest proportion of fertiliser N, in the spring 38 weeks after the fertiliser was applied. By 89 weeks there had been a reduction in foliar N concentrations and by 147 weeks there was an even greater reduction with only one half of the concentrations of fertiliser-derived N.

Therefore, it seems that the availability of the applied N to the trees was directly related to the levels of NH_4-N in the soil, i.e., it was greatest in the period about 4 weeks after the fertiliser was applied and had dropped to zero before week 38.

Although the trees apparently had a sub-optimal N supply, there was not a completely efficient internal recycling and reuse of the fertiliser N. Needle litter-fall samples (Table 6) show that fertilser N was lost from the tree crown beginning in the first year after the fertiliser was applied and reaching a maximum in the second year.

TABLE 6—Total N, ^{15}N, and fertiliser-derived N levels in needle-fall samples

Year	Total N %	^{15}N atoms %	% fertiliser-derived N
1975	1.09	0.456	1.9
1976	1.04	0.548	3.9
1977	0.92	0.506	3.0

CONCLUSIONS

Although lysimeters have been criticised as unsuitable places for growing trees and carrying out experiments designed to give information that can be directly related to forest management practices, the particular lysimeter used in the present study was designed to allow normal tree growth and experimentation throughout the life of a crop of radiata pine (Will 1977). The satisfactory growth of the tree crop and the behaviour of the lysimeter suggest that results can in fact be applied with some confidence to management situations.

The following conclusions can be drawn from the results of this study in which urea was applied in mid summer (February) to a recently-thinned 13-year-old stand of radiata pine growing on a pumice soil:

1. When 200 kg N/ha was applied as a solution of urea leaching losses of N did not occur. Furthermore there were no side effects on the quantities of other nutrients lost by leaching.
2. The application of urea in solution resulted in a slight soil pH rise but this was insufficient to create conditions under which measurable volatilisation losses could be expected.
3. Conversion of urea to NH_4-N began in the soil within the first week after application; production of NO_3-N took place in the second week. KCl-extractable NH_4-N was at a maximum level in samples taken 4 weeks after fertiliser application; when resampled after approximately 9 months, levels had returned to those found before treatment. In contrast, NO_3-N maintained its second week level for at least 3 years.
4. After 1 week most (90%) of the applied N was found in about equal quantities in the decomposing litter and in the top 10 cm of soil beneath it. This distribution pattern did not change with time, but between 2 and 4 weeks after fertiliser application about 40% of the fertiliser N "disappeared" from the litter and soil; further losses were minimal. There was no evidence of leaching, and volatilisation losses appeared unlikely to account for any appreciable part of the 80 kg N/ha which "disappeared". Tree uptake remains the logical explanation of the fate of this N and soil and foliage analyses confirm that this was a period of high availability of N in the soil and of N-movement into the trees.

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