

TRANSFORMATION OF NITROGEN FERTILISERS AND MOVEMENT OF NUTRIENTS FROM THE SURFACE OF A RHYOLITIC PUMICE FOREST SOIL

R. BALLARD

Forest Research Institute, New Zealand Forest Service, Rotorua*

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ABSTRACT

The transformations and movement of urea, diammonium phosphate (DAP), ammonium sulphate (AS), ammonium nitrate (AN), calcium ammonium nitrate (CAN), sulphur-coated urea (SCU) and isobutylidene diurea (IBDU) were followed over a 16-week period using intact cores from the surface 10 cm of a rhyolitic pumice forest soil. Fertiliser was applied at equivalent to 200 kg N/ha and the cores were leached with 5 cm of distilled water per week.

AS, AN and CAN exhibited similar, rapid leaching rates with over 90% of the applied N passing through the cores in 10 weeks: 50% of the N applied as $\text{NH}_4\text{-N}$ passed through in this form while the remainder was nitrified and passed through as $\text{NO}_3\text{-N}$. Urea and DAP showed a slower initial leaching, but this increased as nitrification peaked at 7 weeks. After 16 weeks about 70% of the N applied in urea and DAP had passed through the cores with about 70% of this as $\text{NO}_3\text{-N}$. The two slow-release fertilisers, SCU and IBDU showed steady leaching patterns, identical to each other. About 50% of their N was leached over the 16 week period, nearly all as $\text{NO}_3\text{-N}$. Very little unhydrolysed urea was leached from any of the urea-based sources. The bulk of the residual fertiliser N appeared to be in organic form, but it was readily mineralisable.

All fertilisers greatly increased the leaching rate of Ca, Mg and K, with AS having the greatest and DAP the least effect. The fertilisers had little effect on the movement of P in this soil.

The practical implications of the results are discussed.

INTRODUCTION

The use of nitrogen fertilisers in New Zealand's exotic forests has increased dramatically over the last decade and is expected to show further large increases during the next decade (Ballard and Will, 1978). Urea has been the main N source used in the past, with lesser amounts of diammonium phosphate (DAP) and calcium ammonium nitrate being used. The selection of N sources has been based principally on their cost and availability and to a lesser extent on results of a limited number of field trials which have compared responses from a number of N sources (Mead, Ballard and Mackenzie, 1975).

There has been little work in New Zealand on the transformations of different

*Present address: Department of Forestry, N.C. State University, Raleigh, NC 27650, U.S.A.

N sources in soils which could influence their suitability as fertilisers. This lack of interest has resulted from the traditional reliance in New Zealand on inputs of N from symbiotic N fixation, rather than from N fertilisers, to maintain or increase the N status of agricultural and some production forestry ecosystems (Ball, 1969; Gadgil, 1976). The transformation and movement of N fertilisers in forest soils and factors to consider in the selection of N sources for forestry have received considerable attention overseas and have been the subject of several extensive reviews (Hauck, 1967; Pritchett and Smith, 1969; Beaton, 1973; Bengtson, 1973 and 1976). However, as these reviews stress, the reaction of N fertilisers in soils will vary between sites depending on the soil, climatic conditions and the particular N source used. Thus a research programme was initiated to examine the transformations of a range of N sources in our major forest soil types with the aim of putting the selection of N sources on a sound biological and chemical as well as economic basis.

This paper presents the results, for a yellow-brown pumice soil, of an examination of the transformations and movement of a number of N sources available on the New Zealand market.

MATERIALS AND METHODS

Soil

Soil for the lysimeter study was collected from a 1×1 m area under an unthinned 15-year-old stand of *P. radiata* in Cpt 69, Kaingaroa Forest. The soil type is Kaingaroa silty sand, a yellow-brown pumice soil formed from rhyolitic ash deposited by the Taupo eruption of ca. 150 A.D. (Vucetich, 1960). The soil type is typical of those in the central pumice plateau on which most of New Zealand's exotic forest resource is concentrated. Currently some 2000-3000 ha/yr of forests on these soils are being fertilised with N, mainly as urea. Properties of the surface 10 cm of soil at the collection site are: pH (H₂O) 5.36, pH (KCl) 4.35, carbon 3.73%, total N 0.170% (C/N = 22), Bray 2 P 42 ppm, cation exchange capacity and exchangeable K, Ca and Mg (NH₄OAc, pH 7) 13.32, 0.36, 0.84 and 0.28 me/100 g respectively. A litter layer of about 2 cm depth covers the soil at the collection site and has the following chemical analysis: 1.063% N, 0.088% P, 0.029% K, 0.356% Ca and 0.068% Mg.

Lysimeter Experiment

Fifty "undisturbed" soil cores, 10 cm deep and 4.2 cm diameter, were collected by driving 4.2 cm internal diameter, 15 cm-long pieces of PVC piping into the mineral soil to a depth of 10 cm. The litter layer was retained on the surface of each core (the litter was "cut" prior to driving the PVC tubes into the soil using a sharpened aluminium tube of the same diameter as the PVC tubes). The tubes were removed from the soil by excavation and cutting the soil flush with the leading sharpened edge.

Each PVC-encased core was seated into a Nalgene filter unit with a 0.20 micron membrane to which 10 g of acid-washed sand had been added. Immediately upon setting up the units in the laboratory, 5 cm (69.3 ml) of distilled water was added to the surface of each core and drawn through under an applied suction of one-third atmospheres. After drainage was complete the 40 most compatible units, in terms of drainage time, were selected and the weight of each was recorded. One week later the units were adjusted back to weight using distilled water and another 5 cm of distilled water added

and drawn through under suction. The leachate from each unit was collected, the volume recorded, 0.5 ml phenyl mercuric acetate added and then stored at 4°C while awaiting chemical analysis. Following this leaching the fertiliser treatments were applied and the above leaching procedure repeated once weekly for 15 weeks. Immediately after the last distilled water leaching, the cores were leached with 5 cm of 2N KCl to extract all remaining exchangeable NH_4 ions. Following the KCl extraction the units were dismantled and the soil separated into mineral and organic layers, air dried, weighed and ground in preparation for total N analysis.

Seven N fertiliser sources available commercially in New Zealand (Table 1) were broadcast on the surface of the cores at a rate equivalent to an application rate of 200 kg N/ha. Two of the fertilisers (urea and ammonium nitrate) were also applied under the litter layer in a small slit in the mineral soil. This latter method was designed to emulate the localised placement method used when fertilising seedlings at planting. Each of these fertiliser treatments and an untreated control were assigned at random to 4 cores. During the study period the laboratory temperature was maintained in the range 18-24°C.

TABLE 1—Fertiliser treatments

Fertiliser	Application method	Symbol	Total N (%)	Application rate per core (mg)
1. Urea	Broadcast (B)	Urea (B)	46	60.2
2. Urea	Slit	Urea (S)	46	60.2
3. Ammonium nitrate	Broadcast	AN (B)	35	79.1
4. Ammonium nitrate	Slit	AN (S)	35	79.1
5. Calcium ammonium nitrate	B	CAN	22*	125.9
6. Ammonium sulphate	B	AS	21	131.9
7. Diammonium phosphate	B	DAP	18	153.9
8. Sulphur-coated urea	B	SCU	32	86.6
9. Isobutylidene diurea	B	IBDU	31	89.4

* Value given on label; analysis showed it to contain 26% N.

The seven fertilisers were also applied in quadruplicate, using the same amounts as above, to filter units containing only 10 g of acid-washed sand. These units and four controls were also leached weekly with 69.3 ml of distilled water, subject to a final leaching with 2N KCl and the remaining sand and fertiliser analysed for total N content. At each leaching the distilled water was left in contact with the sand and fertiliser for 10 minutes before applying suction which rapidly pulled the water through the filter. This time period was the mean residence time of free water on the surface of the soil cores.

Analytical Methods

Leachates were analysed for NH_4 -N, NO_3 -N and NO_2 -N, urea-N, orthophosphate, and inorganic K, Ca and Mg. KCl extracts were analysed only for NH_4 -N, the assumption

being that all the water soluble $\text{NO}_3\text{-N}$ and urea-N would have been removed by the distilled water as neither is retained in an exchangeable form in the soil. Orthophosphate, $\text{NH}_4\text{-N}$, $\text{NO}_3\text{-N}$ and urea-N were determined by automated colorimetric methods: orthophosphate was determined as the phospho-molybdate complex using ascorbic acid as the reductant: $\text{NH}_4\text{-N}$ was determined using the nitroprusside catalysed indophenol reaction: $\text{NO}_3\text{-N}$ was determined as $\text{NO}_2\text{-N}$, after reduction by hydrazine sulphate, using the sulphanilamide method: Urea-N was determined using the diacetyl monoxime method. Total N of soil, sand and litter samples was determined as $\text{NH}_4\text{-N}$ following reduction of N by Kjeldahl digestion. Potassium, Ca and Mg in leachates were determined by atomic absorptions spectrophotometry using strontium chloride as a releasing agent.

RESULTS AND DISCUSSION

Nitrogen Leaching in Sand

The nitrogen in the totally water soluble fertilisers, urea, DAP, AS, AN and CAN, was nearly all collected in the first leachate (Fig. 1). As expected the nitrogen came through in the form in which it was applied with little indication of urea hydrolysis or nitrification (Table 2).

The two controlled release fertilisers tested, IBDU and SCU, showed different release characteristics. SCU showed a fairly rapid release of N during the first four leachings, with about 60% of the applied N being solubilised. Thereafter it showed a very slow release rate. Such a release pattern can be attributed to variability in the porosity of the sulphur coating around the urea granules (Davies, 1976). IBDU, which relies on a low water solubility for its controlled release, showed a slow, consistent release rate. Nearly all the N released from the SCU and IBDU granules was recovered as urea (Table 2).

The excessively high recovery of CAN (Table 2) was due to an error in the stated composition of the fertiliser: the manufacturer's label indicated 22% N, but a check after the high recovery values were observed in this experiment showed it in fact to contain 26% N. The somewhat low recovery value for DAP may have been due to tition to the moist sand: in saturated solution DAP has a pH of 7.9 which favours conversion of ammonium to ammonia (Wollum and Davey, 1975). The low recoveries for SCU and IBDU cannot be attributed to volatilisation losses as this first requires hydrolysis of urea to ammonia, which did not occur (Table 2). However with both these fertilisers significant residual quantities of N were detected in the sand by total N analysis, and some difficulty was experienced in duplicating analyses because of the discrete nature of the residual fertiliser granules and the small sample sizes used in the analysis. Thus the values quoted for residual N in the sand must be interpreted with some caution and this could account for the low recovery values.

Nitrogen Leaching in Soil

In terms of patterns for cumulative amounts of N ($\text{NH}_4\text{-N} + \text{NO}_3\text{-N} + \text{urea-N}$) leached through the Kaingaroa soil, the fertilisers fall into three fairly distinct groups (Fig. 1). The first consists of CAN, AS and AN, which all exhibited rapid movement of N through the soil cores with close to 100% recovery of the applied N in the leachates (Table 3). It is notable that despite the relatively high CEC of the soil and

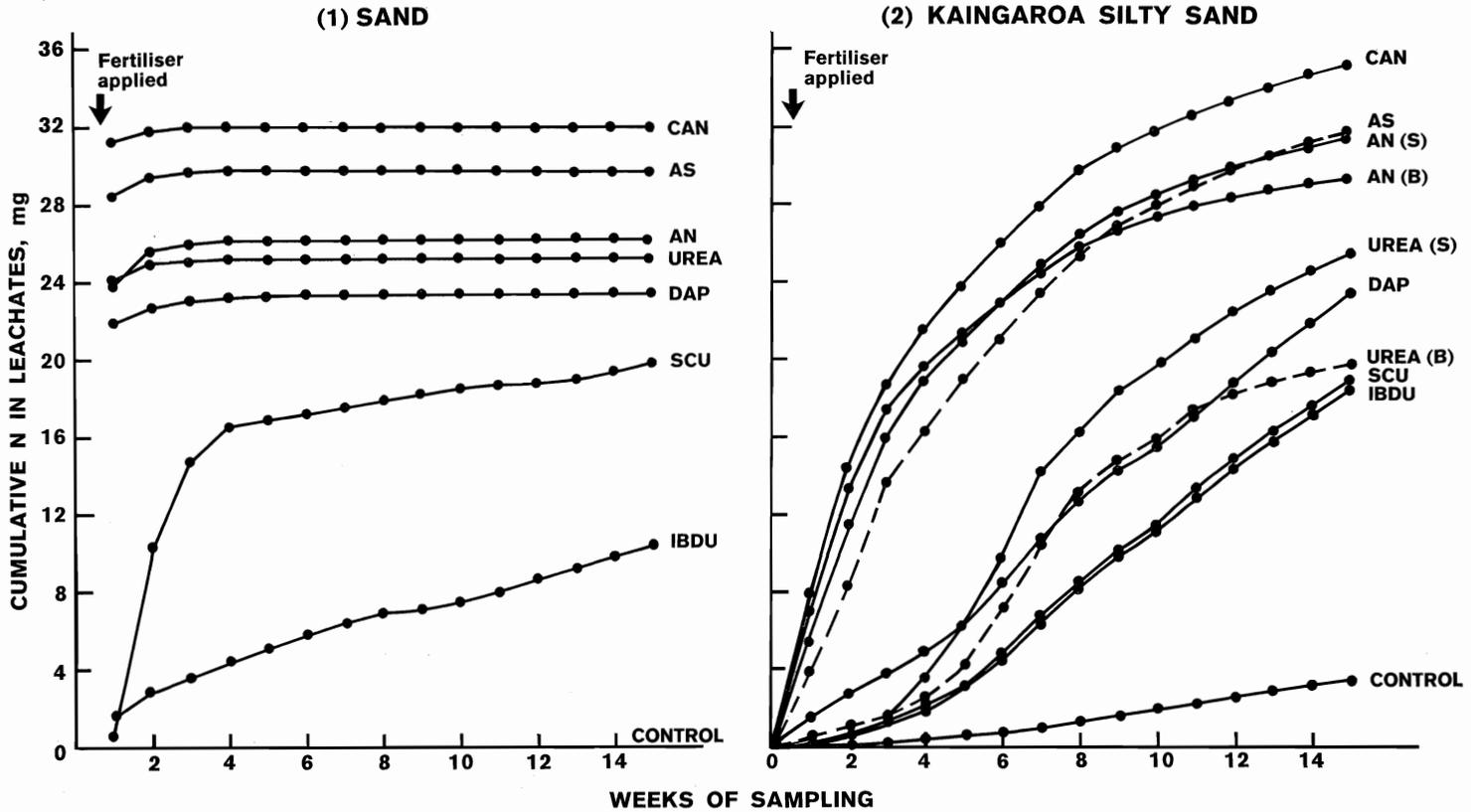


FIG. 1—Cumulative leaching of N ($\text{NH}_4\text{-N} + \text{NO}_3\text{-N} + \text{Urea-N}$) from cores of Kaingaroa silty sand and acid washed sand to which 27 mg N was added as various N fertilisers (32 mg N in the case of CAN).

TABLE 2—Mean (\pm S.E.) amounts of leached and residual fertiliser N, 16 weeks after application to acid-washed sand

Fertiliser	Leached				Residual*			Recovered	
	NH ₄	NO ₃	Urea	Total	KCl extrac.	Sand	Total	Amount	%
	----- (mg N) -----								
Urea	0.67 \pm 0.35	—	24.52 \pm 0.40	25.19	—	0.17 \pm 0.07	0.17	25.36	94
AN	12.59 \pm 0.21	13.60 \pm 0.22	—	26.19	—	0.02 \pm 0.01	0.02	26.21	97
AS	29.80 \pm 5.60	—	—	29.80	—	0.12 \pm 0.05	0.12	29.92	111
DAP	23.50 \pm 0.22	0.02 \pm 0.00	—	23.52	0.07 \pm 0.01	0.12 \pm 0.03	0.19	23.71	88
CAN**	15.79 \pm 1.91	16.29 \pm 0.10	—	32.08	—	0.02 \pm 0.01	0.02	32.10	119
SCU	0.95 \pm 0.14	0.06 \pm 0.01	18.76 \pm 1.43	19.77	0.09 \pm 0.02	4.20 \pm 1.10	4.29	24.06	89
IBDU	0.33 \pm 0.02	—	10.02 \pm 0.31	10.35	0.05 \pm 0.01	12.18 \pm 0.66	12.23	22.58	84
Control	0.04 \pm 0.01	0.01 \pm 0.00	—	0.05	0.01 \pm 0.00	1.03 \pm 0.05			

* All values reported for fertilisers are net values, having been corrected for amounts in the control.

** Applied at 32 mg N per core in contrast to 27 mg N per core for all other fertiliser sources.

TABLE 3—Mean (\pm S.E.) amounts of leached and residual fertiliser N, 16 weeks after application to Kaingaroa silty sand

Fertiliser	Leached*				Residual*			Recovered		
	NH ₄	NO ₃	Urea	Total	KCl extrac.	Sand	Total	Amount	%	
	----- (mg N) -----									
Fertiliser	NH ₄	NO ₃	Urea	Total	KCl extrac.	Soil	Litter	Total	Amount	%
Urea (B)	1.14 \pm 0.30	14.56 \pm 1.96	0.54 \pm 0.44	16.24	—	0.37 \pm 5.04	2.91 \pm 2.40	3.28	19.52	72
Urea (S)	4.70 \pm 1.07	17.03 \pm 1.92	0.11 \pm 0.04	21.84	—	14.23 \pm 7.84	2.04 \pm 2.48	16.27	38.11	141
AN (B)	8.52 \pm 0.75	17.25 \pm 0.67	—	25.77	—	0.35 \pm 10.67	0.50 \pm 3.09	0.85	26.62	99
AN (S)	8.68 \pm 0.28	19.12 \pm 1.26	—	27.80	—	-3.35 \pm 4.65	-0.38 \pm 2.57	-3.73	24.07	89
AS	17.49 \pm 1.36	10.73 \pm 0.41	—	28.22	—	0.15 \pm 10.91	0.06 \pm 1.78	0.21	28.43	105
DAP	5.90 \pm 0.74	13.99 \pm 0.73	—	19.89	0.29 \pm 0.09	17.63 \pm 7.18	2.52 \pm 1.52	20.15	40.04	148
CAN**	10.22 \pm 0.38	21.47 \pm 1.70	—	31.69	—	2.83 \pm 4.37	-3.29 \pm 3.29	-0.46	31.23	106
SCU	0.96 \pm 0.28	14.09 \pm 0.83	0.36 \pm 0.15	15.41	0.22 \pm 0.05	7.18 \pm 4.47	-1.63 \pm 3.44	5.55	20.96	78
IBDU	0.41 \pm 0.20	12.91 \pm 3.00	1.65 \pm 0.28	14.97	0.30 \pm 0.15	2.98 \pm 2.90	3.43 \pm 3.10	6.41	21.38	79
Control	0.09 \pm 0.03	3.40 \pm 0.43	—	3.49	0.07 \pm 0.04	150.49 \pm 6.47	30.64 \pm 4.77	181.20		

* All values reported for fertilisers are net values, having been corrected for amounts in control.

** Applied at 32 mg N per core, in contrast to 27 mg N per core for all other sources.

low base saturation (see materials and methods) quite large quantities of NH_4^+ ions leached through the soil. In the case of cores fertilised with CAN, AS and AN, about 50% of the N applied as NH_4^+ leached through in this form with most coming through during the first four leachings (Figs. 2 and 3). The remaining $\text{NH}_4\text{-N}$ was apparently nitrified to $\text{NO}_3\text{-N}$ and was leached in this form. Nitrification appeared to reach a peak 7 weeks after fertiliser addition (Figs. 2 and 3).

The second group exhibiting similar leaching patterns comprised urea and DAP. They released considerably less N than CAN, AS and AN over the first 6 weeks (Fig. 1), due in the main part to the low quantities of NH_4 and urea leached. After 6 weeks the leaching rate increased concurrent with the increased nitrification (Fig. 2 and 3). Kaingaroa silty sand, in common with most agricultural and forest soils (Wollum and Davey, 1975), exhibits significant urease activity; very little of the water soluble, highly mobile urea was leached from any soil columns receiving it (Fig. 2 and 3, Table 3). In DAP fertilised cores only 22% of the N applied as NH_4^+ leached through in this form. If we assume complete urea hydrolysis to NH_4^+ , then only 4% of the NH_4^+ from urea leached in this form (Table 3). These low NH_4^+ leaching values are in contrast to those of about 50% for CAN, AS and AN. The temporary increase in pH usually associated with the dissolution of DAP and hydrolysis of urea probably contributed to the lower leaching losses of $\text{NH}_4\text{-N}$: raising the pH of soils increases their cation retention capacity, stimulates microbial activity (N-immobilisation) and enhances nitrification (Wollum and Davey, 1975). Losses as $\text{NO}_3\text{-N}$ from urea and DAP were greater than those from AS which produces an acid solution on dissolution. In the case of DAP, the presence of phosphate may also have contributed to the lower $\text{NH}_4\text{-N}$ loss as phosphate also increases the cation retention capacity of soils (Ryden *et al.*, 1977).

The third group comprised the "slow release" fertilisers SCU and IBDU, which showed almost identical leaching patterns (Fig. 1). Over the 15 week leaching period, both released less N than other fertilisers although they did lose over 50% of their N (Table 3) and were only marginally superior to DAP and urea in this respect. Nearly all the N leached from both the SCU and IBDU treated cores was in the NO_3^- form (Table 3, Fig. 3). In this respect these urea-based fertilisers behaved very much like urea (B), although it is noticeable that there was a pronounced flush of nitrate production in the urea treated cores whereas nitrate was released more steadily from the SCU and IBDU cores (Figs. 2 and 3).

The different methods of application of urea and AN had only a small effect on leaching patterns (Fig. 1) and forms of N leached (Fig. 2). The effects were slightly greater for urea than AN. In the case of urea, the lower losses from the broadcast application were associated with a quite pronounced reduction in the loss of NH_4^+ and a small reduction in the loss as NO_3^- . The lower NH_4^+ losses were probably associated with the well documented microbial immobilisation of nitrogen in urea treated litter layers (Salonius and Mahendrapa, 1975). The detection of residual N in the litter layer of the urea (B) treatment (Table 3) lends some support to this contention. There was little evidence of any immobilisation in the litter layer where AN(B) was used. The apparent immobilisation of urea but not AN in litter layers has been an important factor in the swing from the use of urea to AN for fertilising coniferous forests in Scandinavian countries (Bengston, 1976).

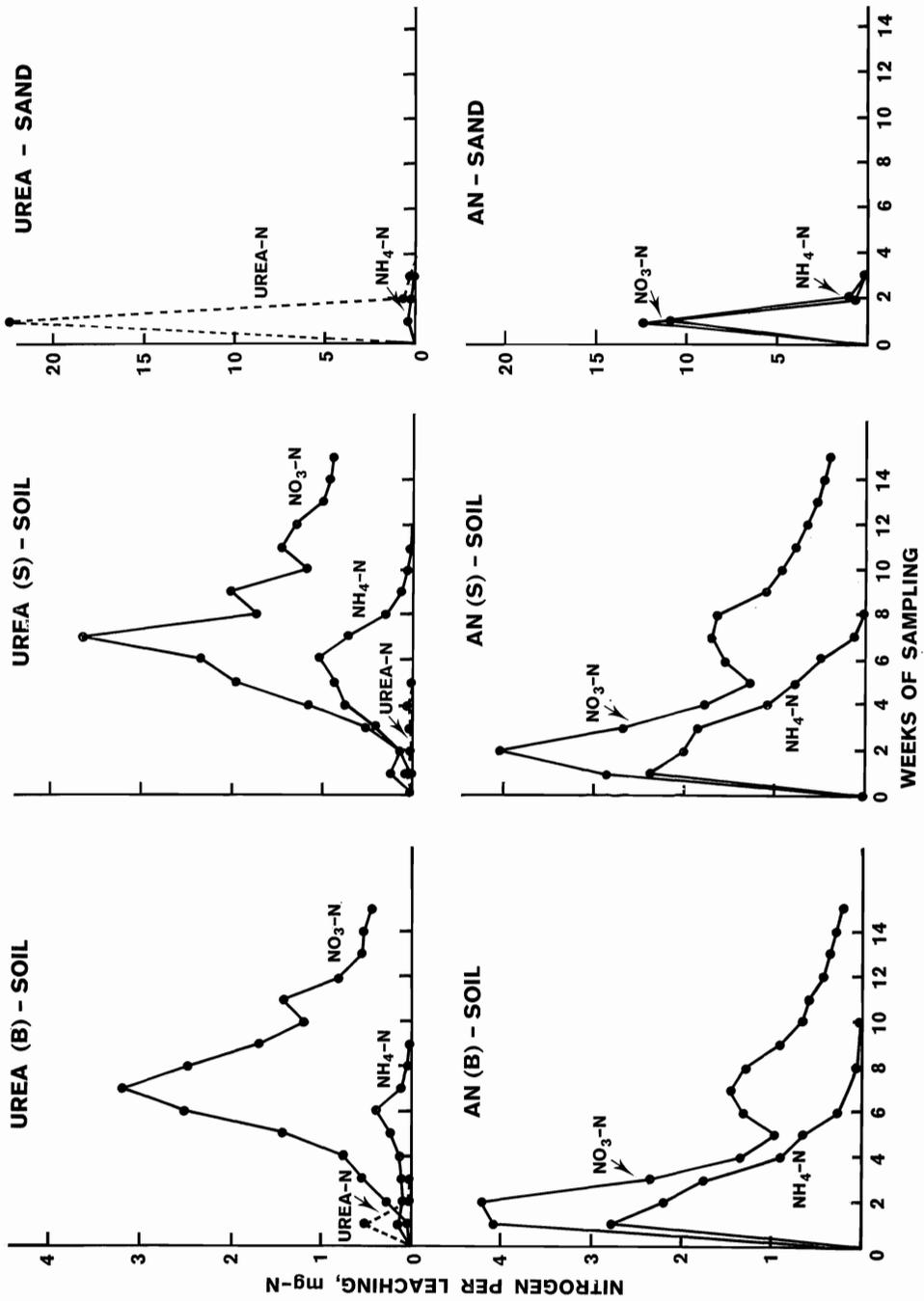


FIG. 2—Effect of fertiliser placement and contact medium on the amounts of NH₄-N, NO₃-N and Urea-N leaching from urea and ammonium nitrate.

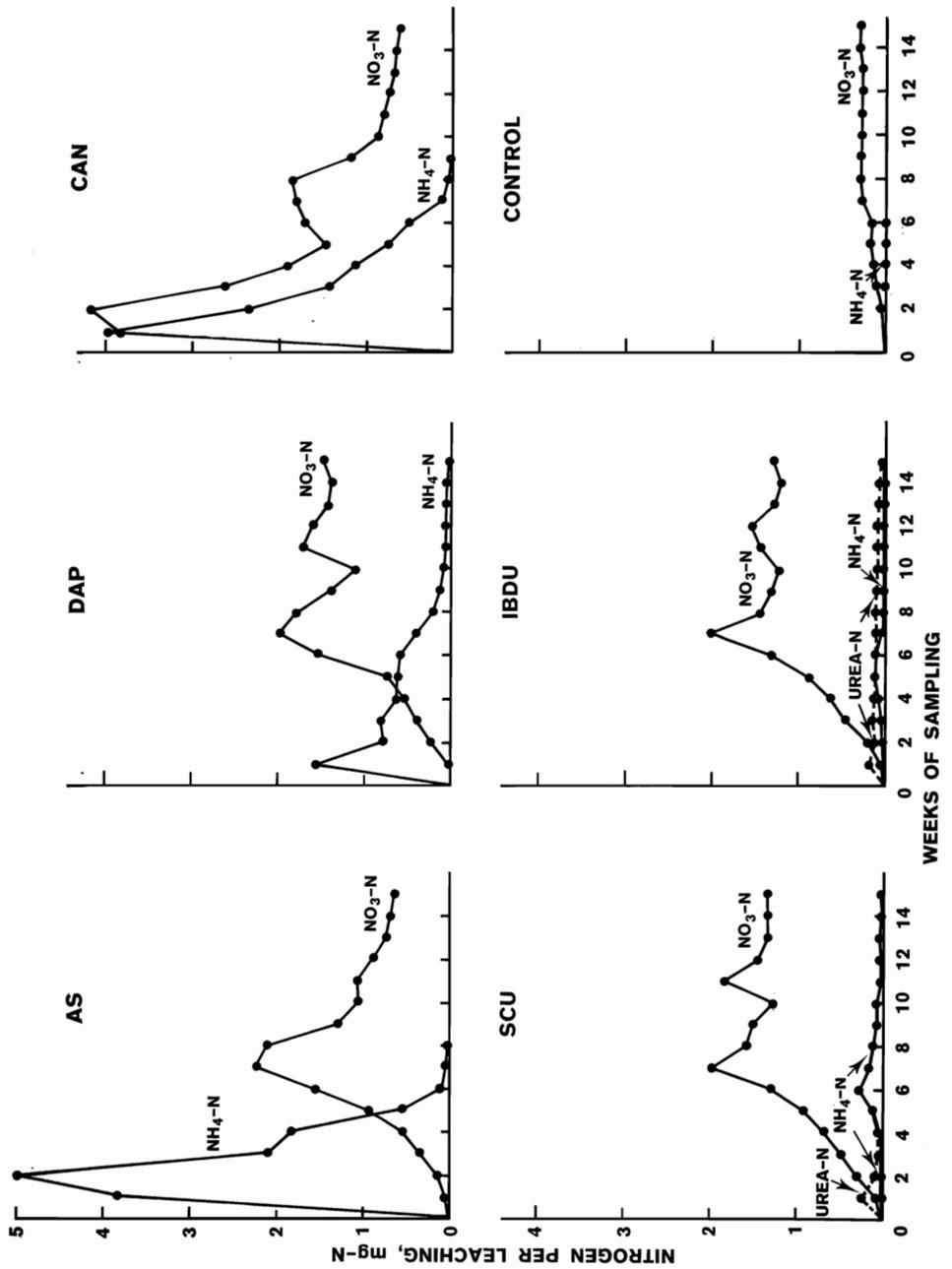


FIG. 3—Amounts of $\text{NH}_4\text{-N}$, $\text{NO}_3\text{-N}$ and Urea-N per leachate obtained from cores of Kaingaroa silty sand fertilised with different N fertilisers at 27 mg N/core (32 mg in the case of CAN).

Residual Fertiliser N in Soil

After 15 weeks' leaching there was very little KCl-extractable (exchangeable) NH_4^+ in any of the cores (Table 3). Trace amounts were obtained from the DAP, SCU and IBDU cores. The lack of exchangeable NH_4^+ and the relatively large amounts of $\text{NO}_3\text{-N}$ still being extractable from many of the treated cores at the last leaching (Fig. 2 and 3) indicate that (1) most of the residual fertiliser N had either been converted to an organic form or in the case of slow release fertilisers still persisted in the original fertiliser form, and (2) the nitrification step in mineralisation of organic N was not rate limiting in these soils, at least not after addition of N fertilisers.

One disadvantage of using intact soil cores is that one has no direct control over the uniformity of the soil and litter between cores. This reflected itself in the variation between cores in total N of both soil and litter which led to poor estimates of residual fertiliser N in these two components (Table 3). The problem was aggravated in the soil where the residual N was such a small fraction of the total soil N. Nevertheless, there was some indication of residual fertiliser N in the litter of cores treated with urea (B), DAP and IBDU. The values for the soil, although more variable, suggest some of the fertiliser N from urea (S), DAP, SCU and to a lesser extent from IBDU and CAN was still present in the soil after 15 weeks' leaching. The form of the residual N is debatable, but it is apparent from the sustained $\text{NO}_3\text{-N}$ release in the cores containing residual N (Figs. 2 and 3) that it is still in a readily mineralisable form.

The poor estimates of residual N in the soil and litter make presentation of accurate figures for the recovery of fertiliser N impossible. However, despite the poor accuracy of the recovery figures presented in Table 3, it is perhaps noteworthy that the lowest recovery values were for the urea-based N fertilisers from which volatilisation losses are most likely. The extremely high recovery values for DAP and urea(S), both of which can lose N through volatilisation (Wollum and Davey, 1975), is most probably due to a high estimate of residual N levels in the soil (Table 3).

Leaching of Other Ions

The leaching of Ca, Mg and K was increased by all fertiliser treatments (Table 4). The amount of Ca leached was increased by 3.3 to 5.1 times, that of Mg by 1.6 to 3.4 times, and that of K by 0.7 to 1.3 times that leached from the control cores. On average the extra Ca, Mg and K leached represented close to 50% of the estimated amount of the exchangeable form of these cations in the soil cores (calculated at 17 mg, 3.4 mg and 14 mg for Ca, Mg and K respectively using NH_4OAc extractable values and the average weight of the cores). The strongly acidifying fertiliser, AS, had the most pronounced effect on the leaching of cations, a phenomenon also observed by Cole and Gessel (1965) and Sarigumba *et al.* (1976), while DAP generally had the least effect. The apparent conservation effect of DAP is probably associated with the phosphate ion increasing the cation retention capacity of the soil; of the 30 mg of P added to the Kaingaroa soil, which has a moderate P-retention capacity (Ballard, 1978a), only 2.2 mg were leached (Table 4). The moderate P-retention capacity of this soil undoubtedly contributed to the insignificant effect the fertilisers had on P leaching losses.

Practical Implications

The results of this study indicate that, in the absence of intercepting roots, the N from most commercially available N fertilisers will move fairly rapidly through at least

TABLE 4—Mean (\pm S.E.) amounts (mg) of additional Ca, Mg, K and P leached from Kaingaroa silty sand and acid-washed sand as a result of N fertiliser application

Fertiliser	Kaingaroa Silty Loam				Sand			
	Ca	Mg	K	P	Ca	Mg	K	P
Urea (B)	7.61 \pm 0.74	1.51 \pm 0.17	4.91 \pm 0.46	—	—	—	0.07 \pm 0.03	—
Urea (S)	8.66 \pm 1.55	2.03 \pm 0.26	7.23 \pm 1.44	0.07 \pm 0.04				
AN (B)	6.99 \pm 1.08	1.74 \pm 0.25	5.62 \pm 0.17	—	0.10 \pm 0.02	0.03 \pm 0.01	0.11 \pm 0.07	—
AN (S)	6.68 \pm 0.70	1.30 \pm 0.10	5.54 \pm 0.31	—				
AS	10.42 \pm 0.44	2.29 \pm 0.33	7.20 \pm 1.47	—	0.09 \pm 0.02	0.03 \pm 0.01	0.05 \pm 0.03	—
DAP	7.31 \pm 1.90	1.07 \pm 0.25	4.50 \pm 0.12	2.24 \pm 1.00	0.21 \pm 0.04	0.10 \pm 0.02	0.39 \pm 0.04	29.02 \pm 3.86
CAN	10.74 \pm 0.85	2.20 \pm 0.19	6.37 \pm 0.78	0.01 \pm 0.01	3.07 \pm 0.10	0.05 \pm 0.01	0.09 \pm 0.02	—
SCU	10.50 \pm 0.45	2.05 \pm 0.18	5.87 \pm 0.61	0.01 \pm 0.01	0.02 \pm 0.01	—	—	—
IBDU	9.94 \pm 2.20	1.87 \pm 0.43	4.00 \pm 1.47	—	0.01 \pm 0.01	—	0.10 \pm 0.04	—
Control	2.05 \pm 0.37	0.68 \pm 0.10	5.62 \pm 0.63	0.03 \pm 0.01	0.26 \pm 0.02	0.06 \pm 0.01	0.23 \pm 0.04	0.03 \pm 0.01

the surface 10 cm of the Kaingaroa soil. Additionally, the movement of N considerably increases the movement of cations in this soil. However a number of investigators have shown in both field (Cole and Gessel, 1965) and glasshouse lysimeter (Sarigumba *et al.*, 1976; Terman and Allen, 1970) experiments that in the presence of growing plants, and thus active roots, leaching losses following addition of N fertilisers are reduced dramatically. Cole and Gessel (1965) reported that while 93% of AN and 85% of urea applied to a forest soil in Washington State at 224 kg N/ha moved through the surface 2.5 cm of the forest floor in 30 days, less than 0.2% reached the normal maximum rooting depth of the trees in 10 months. However, these authors recorded little nitrification in this soil, a process which is obviously active in the Kaingaroa soil following fertilisation with ammoniacal fertiliser sources. Current studies with a large field lysimeter in Kaingaroa forest (Will, 1977), to which ^{15}N enriched urea has been added, should give a good indication of the extent to which fertiliser $\text{NO}_3\text{-N}$ is likely to pass through the rooting zone of trees in the Kaingaroa soil: Knight and Will (1977) observed that for a 7-year period after canopy closure of the radiata pine stand on this lysimeter, inorganic N forms in the leachates were consistently below the detection threshold, indicating conservation of natural soil nitrogen.

The significance of cation mobilisation under field conditions is difficult to ascertain. Nitrogen fertilisation in the absence of an intercepting root mat, which would occur when applying fertiliser to newly planted seedlings on well prepared land, could lead to leaching of cations and loss of soil cation status. On the other hand, in the presence of intercepting roots, the increased availability of the cations may be beneficial: Ballard and Mead (1976) reported a significant increase in foliage Mg of young radiata pine treated with urea in Riverhead Forest.

The problems of applying N fertilisers at establishment of plantations have been giving concern for some time. Mead, Ballard and Mackenzie (1975) reported that N fertilisers applied in a slit 15 cm from the seedling 2 months after planting on a Kaingaroa soil had only a short term effect on foliar N levels. Further, these authors found the slow release SCU and IBDU fertilisers showed no advantage over urea and DAP in terms of growth response or maintaining foliar N levels. Ballard (1978b) also reported that establishment applications of urea at 60 g/seedling to eucalypts on pumice soils were only effective for one year. These results are hardly surprising in view of the volatilisation losses of ammonia following dissolution of the DAP pellets after application with which most N fertilisers apparently move through pumice soils and the limited root development of seedlings in the first 6 months after planting. Further attention needs to be paid to this practice in order to co-ordinate fertilising timing, position of application and quantity applied with root activity and N demand. Selection of N source appears to offer little major opportunity of improving efficiency of uptake when considering time periods of 2 to 3 years. Nevertheless, the data suggest that sources such as urea and DAP may have some advantage over AS and AN. The slow release fertilisers IBDU and SCU are unlikely to improve the efficiency of uptake by young seedlings as their leaching patterns were similar to those of urea and DAP — their only advantage would be the opportunity to place the fertiliser closer to the young root system without causing tissue dehydration. The recent production of IBDU in large briquettes (Hamamoto, 1976), which release only *ca* 50% of their N over 2 years in the soil compared with *ca* 80% released over 6 months for the pelleted type in this

current study, may offer an opportunity for improving the efficiency of establishment N applications in terms of N uptake and duration of response.

As well as leaching losses, two other processes which tend to reduce N fertiliser efficiency, volatilisation and immobilisation, have received considerable attention overseas and have had a significant effect on N fertilisation practices in forestry (Wollum and Davey, 1975; Bengtson, 1976). Although not evaluated under field conditions, it appears that the immobilisation of N fertilisers producing an alkaline reaction, such as urea and DAP, will occur in New Zealand forest soils but that the immobilised N is readily remineralised. Bengtson (1976) in reviewing world literature on this problem of immobilisation concluded that most reports of immobilisation limiting fertiliser efficiency, in terms of tree response, were from regions with cooler climates and soils characterised by low biological activity (mainly in coniferous forests in northern latitudes). Thus it appears that this is unlikely to be a problem in most New Zealand forest soils and in fact it may be advantageous, in terms of reducing leaching losses, to deliberately use fertilisers which do become temporarily immobilised in a soil's organic N pool.

The data from this study provide no real indication of the extent of likely volatilisation losses from susceptible fertilisers. However extensive overseas evidence indicates that losses must be expected from applications of solid urea to forest soils (Wollum and Davey, 1975). Nevertheless the large research effort into this problem has effectively defined conditions which control the extent of volatilisation losses (Wollum and Davey, 1975). Nitrogen fertiliser applications during cooler periods of the year, and when rainfall can reasonably be expected within 3 to 4 days of application, should considerably restrict volatilisation losses. Of particular interest to New Zealand, where combined N and P deficiencies often occur in forests, is the report that addition of P with urea-N can considerably reduce volatilisation losses (Wollum and Davey, 1975).

CONCLUSIONS

It appears that the poor performance of past fertiliser applications at tree establishment on pumice soils can be attributed to the rapid movement of N through these soils, before developing root systems can effectively intercept them. This problem has probably been aggravated by the considerable nitrification capacity of these soils. Until fertilisers with release characteristics compatible with seedling demand over at least a 2 to 3 year period are available in New Zealand, careful attention to the timing and amounts of N fertiliser in relation to root activity and demand offers the best promise of improving the efficiency of establishment applications. However, use of fertilisers containing a significant part of their N as NO_3 , or which did not stimulate retention of N by microbial or other means should be avoided.

Provided volatilisation losses can be minimised, it appears that urea or ammoniacal fertilisers with an alkaline reaction should be preferred over other ammoniacal and nitrate fertilisers for broadcasting in forests on pumice soils. Also, where there is a need for both N and P, every effort should be made for their application to coincide.

The findings and conclusions from this work are only valid for the Kaingaroa silty sand and closely related pumice soils. It is quite possible that in other forest soils with different chemical and biological properties, particularly in nitrification capacity, the relative leaching rates of the fertilisers may be quite different. This possibility is being examined in an extension of this work to other major forest soils in New Zealand.

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