

# Nitrogen volatilisation from urea fertiliser in mid-rotation *Pinus radiata* plantations in south-eastern Australia

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## Summary

Because of its perceived cost advantage, most N fertiliser applied to mid-rotation *Pinus radiata* in Australia is in the form of urea. However, the potential for large N-volatilisation losses from urea may reduce its cost-effectiveness, and result in significant over-estimation of expected growth responses.

The volatilisation loss of N from urea was compared with that from ammonium sulphate at two sites in radiata pine plantations aged 17 and 27 y, using a mass balance method in which <sup>15</sup>N enriched fertiliser (200 kg N ha<sup>-1</sup>) was applied to microplots. Rainfall was excluded from the plots, but deionised water was added periodically, equivalent to a total of 12 mm over 28 days. Recovery of N from each fertiliser form was determined at 1, 7, 14 and 28 days. After 28 days, 41% of the N applied as urea (equivalent to 83 kg N ha<sup>-1</sup>) had been volatilised, compared with no significant N loss from ammonium sulphate. Significantly, 76% of the total loss of N from urea occurred during the first week. There was a significant difference in N losses between the two sites which may have been related to differences in forest floor mass, moisture content and evaporation rate. After accounting for N volatilisation, urea is still more cost effective than ammonium-based forms of N fertiliser. However, applying urea during winter or in formulations which reduce the rate of hydrolysis could reduce N volatilisation losses and thus improve the cost effectiveness of N fertiliser use in mid-rotation pine plantations.

**Keywords:** forest plantations; nitrogen; urea; ammonium sulfate; volatilization; *Pinus radiata*

## Introduction

Nitrogen fertiliser is widely used across Australia to increase growth of mid-rotation (~12–35-y-old) *Pinus radiata* (D. Don) plantations. Virtually all of this fertiliser is applied as urea alone or in combination with di-ammonium phosphate, in preference to fertilisers with lower concentrations of N (e.g. ammonium sulphate). This preference reflects the lower cost of urea per unit N, and reduced handling and application costs due to lower bulk (higher N concentration). It has been assumed that growth responses will be similar irrespective of N source, but this has not been tested experimentally. Many Australian fertiliser trials with *P. radiata* have used the N sources ammonium sulphate or

ammonium nitrate, both of which have a low potential for volatile N losses (e.g. Fife and Nambiar 1995; Turner *et al.* 1996; Carlyle 1998). Assuming that urea will give responses similar to those obtained with these N sources may result in significant over-estimation of growth response if large volatile N losses occur from urea.

There is anecdotal evidence that uptake of N, and subsequent growth response to N fertiliser applied to pine plantations, may vary considerably depending on the form of N used. In a series of experiments in south-eastern South Australia, growth responses of thinned *P. radiata* plantations to urea fertiliser have been lower than expected, based on previous reported responses to N in the form of ammonium nitrate or ammonium sulphate (Fife and Nambiar 1995; Carlyle 1998; May and Carlyle, unpublished data). Furthermore, in one such experiment, the estimated uptake of N from ammonium sulphate was 42% greater, and growth response to N 35% greater, than the response to N applied as urea (May and Carlyle, unpublished data). These results are consistent with those from agriculture and forestry overseas that show that large losses of N can occur from application of urea fertiliser.

Experiments with agricultural crops have shown that N volatilisation from urea applied to the soil surface can typically account for 20–50% of applied N, with losses tending to be greatest from soils with low cation exchange capacity that are covered in plant residues and exposed to conditions of frequent wetting and drying (Priebe and Blackmer 1989; Lightner *et al.* 1990; Freney *et al.* 1992). Estimates of volatilisation of N following urea application to forest soils range from 0% to 42% (Table 1). Many of these studies have been on acidic and relatively well buffered soils (where the potential for volatilisation is reduced) and have used semi-open or closed sorbers to measure the amount of ammonia lost to the atmosphere, an approach that underestimates total volatilisation losses (Marshall and DeBell 1980). They demonstrate, however, that significant losses of N from urea are possible, even under conditions relatively unfavourable for N-volatilisation. In contrast, many Australian *P. radiata* plantations grow on poorly buffered, sandy soils and where rainfall after fertiliser application can be unpredictable. Under these conditions, losses could be very high. It is important that these losses be properly quantified, so that informed decisions can be made about the cost effectiveness of different N fertiliser forms and different application strategies.

**Table 1.** Reported N volatilisation losses from urea fertiliser applied to the forest floor under various conditions and by various methods

N loss (% N added)	Soil		Duration (d)	Fertiliser		Detection* method	Rain (mm)	Forest type	Age (y)	Reference
	Type	pH		Rate (kg ha <sup>-1</sup> )	Form					
1	Peat	5.4	26	200	Granules	Gaseous NH <sub>3</sub>	41	<i>Picea mariana</i>	70–80	Mugasha and Pluth 1995
9	Silty clay	4.9	41	220	Granules	Gaseous NH <sub>3</sub>	12	<i>Pseudotsuga menziesii</i>	50	Marshall and DeBell 1980
10	Med. loam	3.6–4	17	200	Granules	Gaseous NH <sub>3</sub>	NA	<i>Picea</i> sp.	~50	Voronkova 1981
12	Podsol	4.5	10	224	Granules	Gaseous NH <sub>3</sub>	0	<i>Abies balsamea</i>	70	Bernier <i>et al.</i> 1972
13	Sandy loam	4.7	30	200	Granules	Gaseous NH <sub>3</sub>	1.5	<i>Pinus taeda</i>	50	Craig and Wollum 1982
14	Loamy sand	4.6	45	200	Granules	Gaseous NH <sub>3</sub>	37.6	<i>Pseudotsuga menziesii</i>	40	Nason <i>et al.</i> 1988
17	Silty clay	4.9	41	220	Granules	Gaseous NH <sub>3</sub>	0	<i>Pseudotsuga menziesii</i>	50	Marshall and DeBell 1980
20	Podsollic sod	4.1 <sup>KCl</sup>	50	200	Granules	Gaseous NH <sub>3</sub>	NA	<i>Picea</i> sp.	60	Pobedov and Lebedev 1980
22	Silty clay	4.9	41	220	Granules	<sup>15</sup> N mass bal.	12	<i>Pseudotsuga menziesii</i>	50	Marshall and DeBell 1980
27	Sand	4.3	31	200	Pellets	<sup>15</sup> N mass bal.	14	<i>Pinus sylvestris</i>	90	Nõmmik 1973
30	Sand	4.6	60	300	Granules	Combined	NA	<i>Pinus banksiana</i>	45	Morrison and Foster 1977
31	Podsol	4.5 <sup>1</sup>	14	224	Granules	Gaseous NH <sub>3</sub>	0	<i>Pinus banksiana</i>	45	Carrier and Bernier 1971
42	Silty clay	4.9	41	220	Granules	<sup>15</sup> N mass bal.	0	<i>Pseudotsuga menziesii</i>	50	Marshall and DeBell 1980

\* Gaseous NH<sub>3</sub> = measurement of evolved NH<sub>3</sub> from enriched <sup>15</sup>N using semi-open or closed sorbers; <sup>15</sup>N mass bal = mass balance of enriched <sup>15</sup>N retained in microplots; Combined = estimation of gaseous N losses using combination of total N mass balance in soil and vegetation and measurement of gaseous NH<sub>3</sub> evolution.

NA = no data available; <sup>KCl</sup> = pH measured in 1 M KCl; <sup>1</sup> = pH for forest floor

The experiment described in this paper aimed to quantify the loss of N from urea under worst-case conditions. These were assumed to be where fertiliser was applied to a moist forest floor, but where subsequent rainfall was too low to leach much of the fertiliser into the mineral soil. Nitrogen loss from urea was compared with loss from ammonium sulphate. This information was then used to determine the cost-effectiveness of urea compared with other, non-volatile, fertiliser forms in terms of amount of N remaining in the soil and forest floor.

## Methods

### Study sites

The experiment was replicated at two plantation sites in south-eastern South Australia. The first site (Caroline, 37°55.900'S 140°57.864'E), located on the Victorian–South Australian border, is a first-rotation site, planted in 1970 and thinned in 1986 and 1994. The site has a forest floor 45 mm deep, overlying a grey, sandy A horizon and a yellowish-brown to dark-brown, sandy-clay B horizon at 0.8–1.5 m. The second site (Springs, 37°45.861'S 140°38.545'E) was planted in 1980 and thinned in 1995. The 30 mm deep forest floor overlies a greyish-brown, sandy A horizon, a bleached A2 horizon, and a yellowish-brown to dark brown,

light clay B horizon at 0.3–0.6 m. Limestone occurs at 0.9–2.0 m. Key chemical properties of the soil are listed in Table 2.

### Measurement of N volatilisation

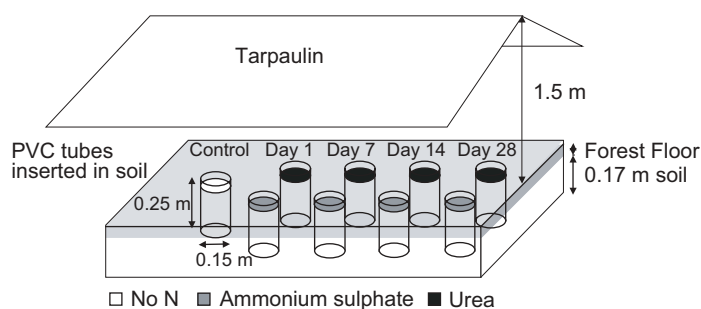
Nitrogen volatilisation was measured using a <sup>15</sup>N mass balance method, similar to those described by Nõmmik (1973) and Marshall and DeBell (1980). Unlike methods that collect ammonia gas, this method does not restrict air flow over the soil and does not require the large plots and assumptions associated with micrometeorological methods (Fox *et al.* 1996). Background <sup>15</sup>N concentrations in the forest floor and soil at each site were determined on eight composite samples, obtained by bulking four cores (50 mm diameter) of forest floor and mineral soil (0–0.15 m) from four locations across each site. Six covered plots (3 m x 1.5 m) were randomly established within an area of 20 m x 30 m at each of the two sites in October 1997 (Fig. 1). Loss of <sup>15</sup>N was measured from PVC tubes (0.15 m diameter and 0.25 m in height) inserted 0.17 m into the mineral soil. Six tubes were inserted in each plot. Urea and ammonium sulphate in powdered form enriched with <sup>15</sup>N (10%) were each applied to the forest floor in three tubes at a rate equivalent to 200 kg N ha<sup>-1</sup>, representing the maximum rate of N normally applied in plantations of this age in the region. In addition, two tubes, one with <sup>15</sup>N enriched urea, and another with

**Table 2.** Selected forest floor and mineral soil (0–150 mm) properties at the two experimental sites at the commencement of the experiment. Moisture content was measured at the start of the experiment after the application of the equivalent of 6 mm rainfall.

Material	Site	Depth (mm)	Mass (mg ha <sup>-1</sup> )	Moisture content (%)	pH	Cation exchange capacity (cmole (+) kg <sup>-1</sup> )	Loss on ignition (%)
Forest floor <sup>1</sup>	Caroline	45	38	64	4.5	NA	57
	Springs	30	25	57	4.7	NA	55
Soil	Caroline	150	1880	8.1	4.7	3.8	3.7
	Springs	150	1868	8.1	4.9	3.8	3.6

<sup>1</sup>Forest floor material includes the soil humus layer.

NA: no data available



**Figure 1.** Plot design showing layout and depth of PVC tubes inserted into soil and height of tarpaulin above the ground surface

$^{15}\text{N}$  enriched ammonium sulphate, were removed from each site immediately after fertiliser application (day 1). Tarpaulins were erected 1.5 m above each plot to exclude natural rainfall, and thus prevent losses of the fertiliser through leaching.

Immediately after application, fertiliser was watered into the forest floor with distilled water equivalent to 6 mm rainfall and an additional amount, equivalent to 3 mm rainfall, was applied after 7 and 14 d. One tube with urea and another with ammonium sulphate were removed from each plot 7, 14 and 28 d after fertiliser application. Temperature, humidity, rainfall and evaporation were measured during the experiment (conducted from early October to early November) at nearby sites outside the plantations (Table 3).

Soil and forest floor (which included the soil humus layer) were removed from each core and separated before being weighed and thoroughly homogenised. Forest floor material and a sub-sample of soil were dried at 40°C and finely ground using a ring mill. The amounts of total N and  $^{15}\text{N}$  in each sample were determined using a Europa 20/20 mass spectrometer interfaced with a Solid-Liquid analyser.

To calculate the loss of N fertiliser applied to microplots, the quantity of  $^{15}\text{N}$  applied plus the original amount in the soil (background  $^{15}\text{N}$ ) was compared with that remaining in tubes. Since leaching and uptake of N were prevented, this difference was assumed to equal volatilisation loss of  $^{15}\text{N}$ . De-nitrification

**Table 3.** Average daily temperature, humidity, wind speed, rainfall and evaporation measured in the open near each site during the 28 d over which N volatilisation was measured

Daily averages		Site	
		Springs	Caroline
Temperature			
Min.	(°C)	4.0	5.5
Max.	(°C)	18.1	20.5
Mean	(°C)	11.9	12.5
Relative humidity			
Min.	(%)	51.5	51.0
Max.	(%)	94.2	99.3
Mean	(%)	75.1	77.3
Rainfall	(mm)	2.9	2.7
Wind speed	(knots)	2.9	3.2

was unlikely to have been significant due to the low concentration of nitrate in the soil, low concentrations of available carbon, the absence of anaerobic conditions, and low rates of nitrification in soils of this type (Carlyle *et al.* 1990). To determine the total loss of N through volatilisation, the amount of  $^{15}\text{N}$  volatilised was multiplied by the isotopic discrimination factor for volatilisation of  $^{14}\text{N}$  relative to  $^{15}\text{N}$ . This factor was calculated from data of Haurat *et al.* (1981) to be 5.08% in favour of  $^{14}\text{N}$  for both ammonium sulphate and urea.

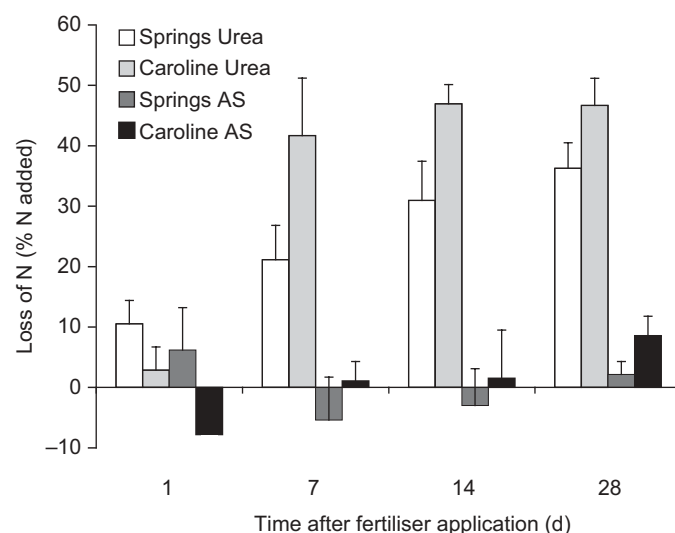
## Analysis of results

Results were analysed using analyses of variance of site  $\times$  fertilizer form  $\times$  time of removal with blocks nested within each site. Differences were classed as significant where  $P < 0.05$  (Genstat Release 3.2). Differences between the amounts of N lost from each fertiliser form for the different time intervals were analysed using Student's *t* tests. Non-linear regressions were fitted to the data for losses of N from urea for the different time periods and were used to investigate relationships between N volatilised and recovered (from the soil and forest floor) and forest floor properties in individual microplots.

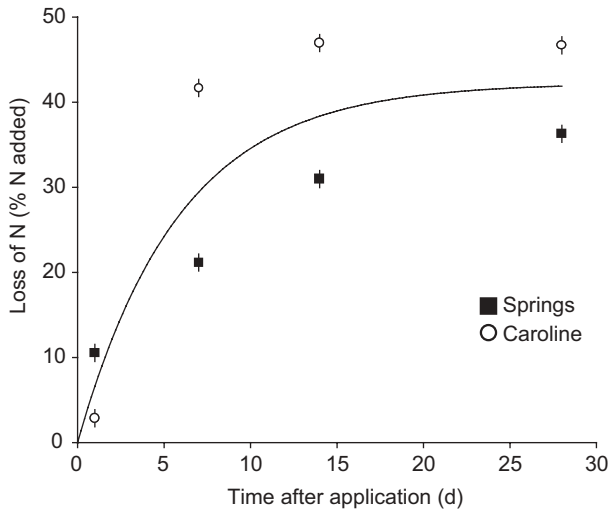
## Results

Volatilisation of N was significantly greater from urea than ammonium sulphate ( $P < 0.001$ , Fig. 2). After 28 d, an average of 41% of the  $^{15}\text{N}$  applied as urea had been lost compared with a loss of only 5% of the N applied as ammonium sulphate, which was not significantly different from zero. Seventy-six percent of the total loss of N from urea occurred within the first week, although the cumulative loss continued to increase between 7 and 14 d after application.

Loss of N from urea after 28 d was significantly greater at Caroline (47%) than at Springs (36%, Fig. 2). However, the rate of N loss over time appeared to decrease more rapidly at Caroline, where



**Figure 2.** Percentage N loss due to N volatilisation at Springs and Caroline from urea and ammonium sulphate (AS) applied at a rate of 200 kg ha<sup>-1</sup>. Error bars represent standard errors of means.

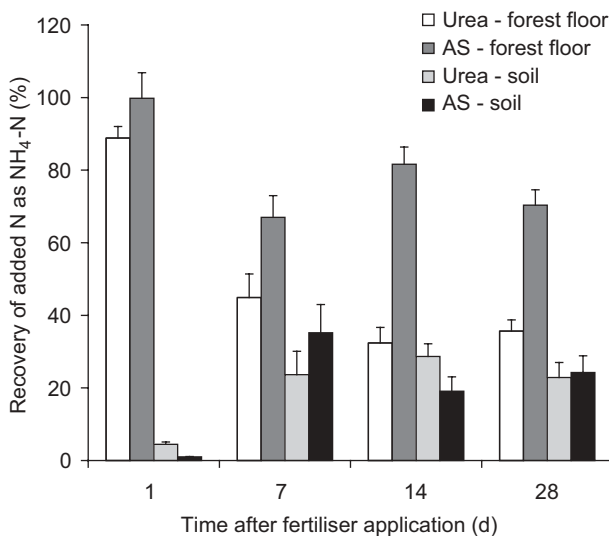


**Figure 3.** Relationships between N loss from urea, at Springs and Caroline, and time (*t*) in days after application. Error bars represent standard errors of means.

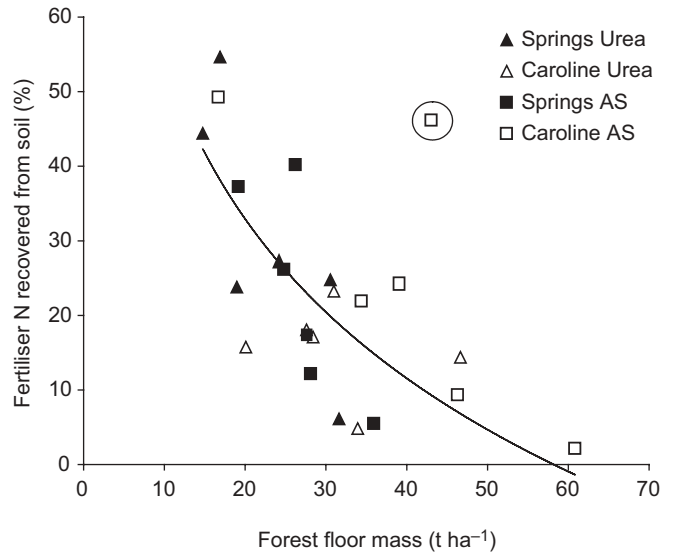
there was no further loss of N from urea between 14 and 28 d, than at Springs, where N loss increased from 31% to 36% over the same time period. However, there were no significant interactions between site, fertiliser form or time of collection. Average loss of N over time followed a predictable pattern that was explained by the following relationship between cumulative N loss and the number of days (*t*) after application (Fig. 3):

$$N \text{ loss} = 42.3(1 - 0.843^t) \quad r^2 = 0.79, \quad SE = 7.5.$$

Changes in the proportion of N recovered from the forest floor and soil over time indicated movement of fertiliser from the forest floor into the mineral soil (Fig. 4). In the forest floor, the amount of N derived from urea or ammonium sulphate fertiliser decreased with time, while the amount in soil increased between day 1 and



**Figure 4.** Percentage recovery of nitrogen applied in urea and ammonium sulphate (AS) treatments from forest floor and soil 1, 7, 14 and 28 d after application. Data are average recoveries from the two sites. Error bars indicate standard errors of means.



**Figure 5.** Relationship between percentage recovery of N fertiliser from soil as total N after 28 d and the mass of forest floor in each plot for urea and ammonium sulphate treatments at Springs and Caroline. The formula for the relationship is:  $N \text{ recovered} = 125 - 30.8 L_n(\text{forest floor mass})$ ,  $r^2 = 0.58$ . One outlier (circled) was excluded from the relationship.

day 7, but stabilised thereafter. Recovery of N fertiliser in the forest floor, after 28 days, was 49% less for urea (71 kg N ha<sup>-1</sup>) than ammonium sulphate (141 kg N ha<sup>-1</sup>), but there was no significant difference between the two fertiliser forms for the amount of N recovered in the soil (46 kg N ha<sup>-1</sup> for urea compared with 49 kg N ha<sup>-1</sup> for ammonium sulphate). Thus, while much of the urea N in the forest floor was lost through N volatilisation, there was no evidence of N losses from the soil.

Significantly more N was recovered from the soil at Springs (30%) than at Caroline (16%) on urea-treated plots 28 days after application. In contrast, there was no significant difference in the amount of N recovered from the forest floor (34% at Springs vs. 38% at Caroline). The amount of fertiliser N recovered from the soil of individual microplots was negatively related to forest floor mass for both urea and ammonium sulphate ( $r^2 = 0.58$ , Fig. 5). Furthermore, there was a significant negative relationship between the amount of urea N volatilised and the recovery of N from the soil ( $r^2 = 0.47$ ). Thus, where there was less forest floor, more fertiliser moved into the soil where N volatilisation losses appeared to be negligible. However, there was no relationship between forest floor mass and N volatilisation from urea, indicating that factors in addition to the amount of material in the forest floor may have influenced N losses.

Other factors that could explain part of the difference in N losses between the sites were difference in moisture contents and evaporation rates from the forest floor. After the application of water at the start of the experiment, the moisture content of the forest floor at Springs was 57% while that at Caroline was 64% (Table 2). However, after 28 d, the moisture content of the forest floor decreased to 30% at Springs and 43% at Caroline despite the addition of a further 3 mm rainfall equivalent on days 7 and 14. From these figures, the estimated evaporation during the course of the experiment was 12 mm at Springs and 14 mm at Caroline. This difference is consistent with the slightly greater temperatures

and wind speeds recorded near the Caroline site (Table 3). Thus, both initial moisture content and evaporation rates were greater at Caroline, possibly contributing to the greater N volatilisation from urea at this site.

## Discussion

### N volatilisation losses

Up to 47% of urea fertiliser was lost due to ammonia volatilisation after 28 d under conditions of simulated low rainfall, compared with no significant loss of ammonium sulphate under the same conditions (Fig. 2). This difference between the two fertiliser forms is consistent with the measured reductions in uptake (42%) and growth response (35%) to N applied as urea compared with N applied as ammonium sulphate at Springs under rainfall conditions similar to those applied in the current experiment (May and Carlyle, unpublished data). Importantly, most of the loss in the current study (69%) occurred in the first week, which is consistent with the pattern of N loss in other similar studies (Nõmmik 1973; Marshall and DeBell 1980). Thus, if urea is applied under conditions similar to those in the current study and little rain falls within the first few days, substantial losses of N can be expected.

The estimated loss of N from urea (42%) is in the upper range of losses reported for forest soils (Table 1) and comparable to those reported in agricultural situations (Priebe and Blackmer 1989; Lightner *et al.* 1990; Freney *et al.* 1992). As already mentioned, most estimates from forest environments are from studies using micrometeorological methods such as closed or semi-open ammonia traps which tend to under-estimate total N volatilisation (Marshall and DeBell 1980). Thus, N volatilisation losses from urea used in forest plantations may be a more serious problem than previously recognised.

The loss of N from ammonium sulphate (5%) was in the range reported for acidic ( $\text{pH} \leq 6.1$ ) agricultural soils (Whitehead and Raistrick 1990). Volatilisation losses from this fertiliser form can be much larger in neutral or alkaline soils, but are normally negligible in soils with low buffering capacity (Du Preez and Du Burger 1988).

### Factors influencing N volatilisation losses

Moisture, chemical and physical characteristics of the soil and surface organic matter, the amount and intensity of rainfall, and the rate of drying are all important factors influencing the rate and amount of N volatilisation from urea fertiliser. Other researchers have demonstrated that plant residues on the soil surface, combined with moist conditions at time of application and alternating wetting and drying conditions, can result in substantial N volatilisation losses from urea where there is insufficient rainfall to wash the fertiliser into the soil (Bacon *et al.* 1986; Prasertsak *et al.* 2002; Freney *et al.* 1992). In particular, the intensity of the wetting and drying cycle strongly affects N volatilisation loss, with  $\text{NH}_3$  evolution being closely related to soil moisture and evaporation (Morrison and Foster 1977; Mugasha and Pluth 1995; Freney 2003). Thus, conditions in the current experiment, where urea was applied to a moist forest floor which then went through a number of cycles of drying and rewetting, probably favoured a high rate of N volatilisation.

However, it is possible that operational losses of N from urea could be even greater than those measured. The covers used to prevent rainfall may have reduced diurnal fluctuations in moisture in the forest floor by reducing dewfall and blocking solar radiation. This, in turn, may have reduced both urea hydrolysis and evaporation and thus affected N volatilisation (Freney 2003). Losses could also be greater if urea is applied from the air, as is frequently the case, due to some fertiliser landing in the forest canopy, where it could be exposed for a longer period to conditions favouring N volatilisation.

The differences in N volatilisation at the two sites were most likely due to a combination of factors including differences in the amount of material on the forest floor, its moisture content and evaporation rates. The shallower forest floor at Springs allowed more urea to pass through into the soil where the potential for N loss through volatilisation was lower. Voronkova (1981) reported that N volatilisation was greater from sites with deeper forest floors. In addition, the greater initial moisture content of the forest floor at Caroline could have increased the rate of hydrolysis of urea into ammonium carbonate, while the higher rate of evaporation at this site would have favoured volatilisation of ammonia. Thus, the amount and depth of the forest floor, its moisture content at time of fertiliser application, microclimate within the stand as well as the prevailing weather conditions may all be important in determining N volatilisation losses.

Soil properties which influence N volatilisation losses from urea include pH, cation exchange capacity,  $\text{H}^+$ -buffering capacity and soil texture (Martens and Bremner 1989; Watson *et al.* 1994). In general, volatilisation is greater for soils with higher pH. However, because hydrolysis of urea itself increases pH, cation exchange or  $\text{H}^+$ -buffering capacity or soil texture are generally better indicators of potential N volatilisation losses from urea applied soil (Ferguson *et al.* 1984; Martens and Bremner 1989). Thus, the amount of N volatilised is dependent on the soil pH attained after application of urea rather than that prior to application (Whitehead and Raistrick 1990). The low  $\text{H}^+$ -buffering capacity (as indicated by the low cation exchange capacity and organic matter content of the soil and low available surface area of the dead pine needles comprising the forest floor) would tend to favour an increase in pH during hydrolysis of urea (Table 2). This theory was tested by measuring the pH of forest floor material before and after application of urea. These measurements showed that average pH increased from 4.8 to 7.8 within 2 d of application, confirming the high potential for substantial N volatilisation from urea fertiliser in the forest floor.

### Operational implications

The high potential for rapid N volatilisation from urea has two important implications for forest management. First, the growth of stands previously treated with urea may be over-estimated if growth responses to N are based on experiments using other N sources, such as ammonium sulphate or nitrate, with low volatilisation potential. Second, although the cost of urea is much less than that for other forms of N fertiliser, volatilisation losses can change the price differentials. However, at current fertiliser prices per kilogram N applied (AU\$0.84, AU\$1.92 and AU\$1.61 for urea, ammonium sulphate and calcium ammonium nitrate respectively: M. Little, Elders, *pers. comm.* 2004) N volatilisation

losses from urea would have to exceed 48% for it to be more expensive than calcium ammonium nitrate even without considering the lower application costs for urea.

Options for reducing volatilisation losses from urea fertiliser include using urease inhibitors (Grant *et al.* 1996), coating urea pellets with sulphur, KCl or plastic (Foster and Beauchamp 1986; Gameh *et al.* 1990; Kong *et al.* 1993) or applying urea together with triple super-phosphate (Carrier and Bernier 1971). These methods operate by reducing the rate at which urea is hydrolysed, and therefore increase the time available for rainfall to wash the fertiliser into the soil. However, their cost-effectiveness for use in forests has not been assessed in Australia. Other approaches include changing the size of fertiliser pellets or the method, rate or time of application. While effective at reducing losses, incorporation of urea into the soil is not practical for forestry situations and the effects of pellet size can be variable (Watson and Kirkpatrick 1991; Prasertsak *et al.* 2002). However, relative N volatilisation losses can be reduced by decreasing the application rate or applying urea during cooler, wetter months when conditions are least favourable for volatilisation (Fenn *et al.* 1982; Watson and Kirkpatrick 1991; Eckard *et al.* 2003). Thus, smaller applications of urea during winter instead of spring, when it is normally applied, may reduce N losses from urea applied to pine plantations. In order to determine the cost-effectiveness of different fertiliser forms, additives, rates and seasons of application differences in N volatilisation, leaching, uptake and growth responses need to be quantified across a wider range of sites and climatic conditions.

It is widely recognised that mid-rotation application of N fertiliser is a flexible and cost-effective means of increasing wood production from Australian softwood plantations. However, it has generally been assumed that the form of N applied is of little consequence. The results from this study demonstrate that this is not necessarily the case, with 42% N lost due to ammonia volatilisation from urea, compared with 5% lost from ammonium sulphate. This loss has potential to seriously affect estimates of growth responses after fertiliser application. Although, at current prices, urea is still cheaper than ammonium-based N forms after accounting for differences in N volatilisation losses, there is a range of application strategies for reducing these losses and improving the cost-effectiveness of N fertiliser application that warrant further research.

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