# OPPORTUNITIES FOR MANAGING NITROGEN UPTAKE IN ESTABLISHED *PINUS RADIATA* PLANTATIONS ON SANDY SOILS

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## ABSTRACT

In established *Pinus radiata* D. Don plantations growing on sandy soils in southern Australia, nitrogen uptake can be manipulated through thinning, management of residue, and fertiliser use. Thinning, in the absence of above-ground residue, results in a small increase in nitrogen uptake per hectare but can more than double nitrogen uptake per tree. This reflects the capacity of the thinned stand to take up all mineralised nitrogen. Thinning contrasts with clear-felling which results in substantially elevated soil mineral nitrogen concentrations and leaching. Uptake of nitrogen after thinning increases with the quantity of residue retained; all this nitrogen is taken up, there is no leaching. The release of nitrogen from residue is progressive and reflected in the pattern of nitrogen uptake. In contrast, fertiliser results in a rapid, large, but ephemeral increase in nitrogen uptake which is associated with elevated soil mineral nitrogen concentrations and high leaching losses. Patterns of nitrogen uptake after fertiliser application, and simple models of nitrogen leaching and uptake, indicate there is scope for improving the effectiveness of fertiliser use by varying the timing of application with respect to season and thinning schedule. There is probably little scope for influencing nitrogen uptake in established stands by varying the form of nitrogen fertiliser applied or through the use of nitrogen-fixing associations.

**Keywords**: thinning; thinning residue; nitrogen management; nitrogen uptake; nitrogen fertiliser; nitrogen leaching

## INTRODUCTION

The availability and uptake of nitrogen commonly limits forest production (Carlyle 1986) so that the use of nitrogen fertiliser is widespread in managed forests. Nitrogen fertilisers are expensive relative to other commonly applied elements and recoveries by the tree crop can be low due to solution losses, gaseous losses, or both (Mead & Pritchett 1975; Nambiar & Bowen 1986; Melin & Nommik 1988). Consequently, optimising the management of nitrogen availability in production forests is of considerable economic and environmental importance. The efficient management of nitrogen availability and uptake is especially crucial on sandy soils which have low nitrogen reserves and low rates of nitrogen mineralisation, and are prone to nitrogen losses as a consequence of forestry practices (Hunter & Hoy 1983; Beets & Madgwick 1988; Carlyle *et al.* 1990; Smethurst & Nambiar 1990a).

Sandy soils support about 30% of Australia's softwood production. Plantations grown on these soils can exhibit large positive growth responses to nitrogen fertiliser (Fife *et al.* 1993) but this may be associated with substantial leaching losses (Nambiar & Bowen 1986). Sands are particularly prone to leaching losses because of their low cation exchange capacity (Carlyle 1993) and high porosity. The combination of these factors results in large leaching losses of both ammonium and nitrate after fertiliser application or major site disturbances such as clearfelling (Nambiar & Bowen 1986; Smethurst & Nambiar 1990a; Carlyle in press b).

A number of studies have improved our understanding of the impact of management on nitrogen availability and uptake during the establishment of plantations on sandy soils (Gadgil 1979; Jackson *et al.* 1983; Beets & Madgwick 1988; Nambiar & Bowen 1986; Nambiar & Nethercott 1988; Smethurst & Nambiar 1990a, b; Woods *et al.* 1992). However, over half of Australia's softwood plantation area is more than 10 years old and the potential for improving the productivity of these established stands by thinning and fertiliser application is substantial. For instance, Flinn & Turner (1990) estimated that an average increase in MAI of at least 3 $m^3$/ha/year was possible over most of the existing plantation area, equivalent to 1.7 million $m^3$/ha/year or 94 000 ha of new plantations growing at an MAI of 18 $m^3$/ha/year. In order to fully realise this potential we need information on the effect of thinning on nitrogen availability and uptake, the significance of thinning residue to nitrogen supply and uptake, the scope for augmenting native nitrogen supplies with nitrogen fertiliser, and strategies for treating established stands with fertiliser to maximise uptake while minimising leaching. In this paper I focus on these management issues, using as an illustration results from a long-term project initiated in 1988 near Mount Gambier, South Australia, by CSIRO in collaboration with the forest industry.

## MATERIAL AND METHODS

### Soils and Environment

A detailed description of the experimental site where much of the information presented in this paper was obtained has been presented elsewhere (Carlyle in press a, b). The site is representative of softwood plantations in south-east South Australia/western Victoria, virtually all of which have been established on soils with a sandy A horizon of aeolian or coastal origin. These soils generally fall into one of two groups: (1) those with a deep (>2 m) sandy A horizon; and (2) those with a shallow (<2 m) sandy A horizon, which typically overlies a clay B horizon giving a duplex profile. The sandy A horizons of both groups frequently exhibit podsolic features such as an albic A2 horizon, and both may exhibit humic or lateritic features.

Total nitrogen concentrations in the surface 0.15 m of these soils can range from 0.2 to 2.0 mg/g and are highly correlated ($r^2 = 0.94$) with concentrations of organic carbon which range from 3.9 to 45.7 mg/g (Carlyle *et al.* 1990). Concentrations of carbon decline sharply with depth so that the surface soil (0–0.15 m) is the principal reservoir of carbon and organically bound elements (Carlyle 1993). On these soils the distribution of carbon and organically bound nutrients is closely paralleled by that of fine roots, with 90% of the fine root biomass of *Pinus radiata* occurring in the surface 0.3 m (Nambiar 1983).

The region experiences a Mediterranean climate with cool (wet) winters and warm (dry) summers. Average daily temperatures are 5°C (minimum) and 14°C (maximum) in June (mid-winter) and 11°C (minimum) and 26°C (maximum) in January (mid-summer). Annual rainfall at Mount Gambier (latitude 37°49'S, longitude 140°46'E) is 712 mm, about 63% of which falls in winter and spring.

## Experimental Design and Measurement Details

A detailed description of the experiment and measurements performed has been given elsewhere (Carlyle in press a, b). The plantation was planted in 1977 and is the second rotation of *P. radiata* on the site. Logging residues from the first rotation were windrowed and burnt. There has been no input of fertiliser in either the first or the second rotation. Stocking was 1352 stems/ha with a mean spacing of 2.2 m within rows and 3.2 m between rows. Basal area was 36.2 $m^2$/ha in August 1988 (age 10 years), immediately before thinning. The experimental area was thinned during October-November 1988. The thinning systematically removed every fifth row of trees (extraction rows) with a proportion of trees in the area between extraction rows being selectively thinned from below. The thinning reduced stocking by 53% and basal area by 48% from 36.2 to 19.0 $m^2$/ha.

The objectives of the experiment were to quantify the effect of thinning, residue, and application of nitrogen and phosphorus fertiliser on soil nitrogen dynamics and tree nutrient status, water status, and growth. There were eight treatments, each with four replicates:

(1) Thinned and residue removed (forest floor left intact), no fertiliser (zero residue);
(2) Thinned and residue retained, no fertiliser (normal residue);
(3) Thinned and the amount of residue increased with material removed from the zero residue plots, no fertiliser (high residue);
(4) Thinned with normal residue, treated with 80 kg P/ha;
(5) Thinned with normal residue, treated with 200 kg N/ha;
(6) Thinned with normal residue, treated with 200 kg N/ha and 80 kg P/ha;
(7) Thinned with normal residue, treated with 400 kg N/ha and 80 kg P/ha;
(8) Unthinned and no fertiliser.

The normal residue treatment was the control for the treatments with fertiliser. Residue management treatments were installed by December 1988, and fertiliser was applied as a single application in September 1989. For the purposes of this paper I will not consider the treatments with phosphorus applied.

Net nitrogen mineralisation (hereafter referred to as nitrogen mineralisation), leaching, and uptake were estimated by an *in situ* incubation method described by Raison *et al.* (1987). Measurements commenced in January 1989, 71 days after completion of the thinning operation and 49 days after installation of residue treatments. Undisturbed soil columns were confined within 0.35-m PVC cores (internal diameter 50 mm) driven into the forest floor and mineral soil. At the start of each incubation period, three sets of cores were installed side-by-side at eight random locations in each plot. The first set ($C_1$) was removed immediately at the start ($C_{1s}$) of each incubation period. The $C_1$ set of cores also served as the end-of-period samples ($C_{1e}$) for the previous sampling period. The second set ($C_2$) was covered to prevent leaching while the last set ($C_3$) was left uncovered and both sets were retained in the field for a period of approximately 8 weeks. At the end of each measurement period cores $C_2$ and $C_3$ were removed and another set of cores was installed immediately for the next measurement interval. For each set of cores in each plot, mineral nitrogen concentrations were converted to kilograms per hectare using the mass of soil and forest floor.

Inorganic nitrogen uptake and leaching were calculated as follows:

Taking $N_{in}$ as the quantity of inorganic nitrogen, then for a given period—

Nitrogen mineralised $= C_2N_{in}-C_{1s}N_{in}$
Nitrogen leached $= C_2N_{in}-C_3N_{in}$
Tree uptake $= C_2N_{in}-C_{1e}N_{in}-(C_2N_{in}-C_3N_{in})$.

## INFLUENCE OF THINNING AND RESIDUE ON ECOSYSTEM NITROGEN POOLS AND FLUXES

### Nitrogen Pools

Apart from fertiliser application or the use of nitrogen-fixing associations, the greatest impact that plantation management operations have on ecosystem nitrogen pools is associated with clearfelling and thinning. Most research has centred on clearfelling and management of the resultant residues (e.g., Smethurst & Nambiar 1990b); however, thinning has the potential to have a significant impact (Raison *et al.* 1982). For instance, the quantity of nitrogen in thinning residue can be of similar magnitude to the residue from clearfelling operations (Mead 1987). In the study described above (Carlyle in press a), thinning residue contained 128 kg N/ha or 11% of site nitrogen, 66% of which was in needles (Table 1). The quantity of nitrogen contained in thinning residue was 55% of that produced by clearfelling a 37-year-old *P. radiata* plantation of similar basal area and grown on a similar soil (Table 1). The amount in the forest floor was much less, reflecting the young age of the thinned stand and possible differences in decomposition dynamics. Thus, the amount of nitrogen in thinning residue can be large and represent a significant portion of site nitrogen capital.

The proportion of nitrogen in residue contrasts with Swedish studies on *Pinus sylvestris* L., where thinning residue may contain only 0.7% of site nitrogen reserves (Lundkvist 1988), and reflects the low nitrogen content of the sandy soil in this study. Absolute quantities of residue will vary widely between sites, reflecting differences in species, stage of stand development, site fertility and thus growth rate, past management, and thinning intensity. However, the nutritional significance of residue is likely to increase with the proportion of site nutrient capital that it represents (Carlyle in press a).

TABLE 1–Comparison of the quantity of nitrogen (kg/ha, excluding roots) in major ecosystem components after thinning or clearfelling of two plantations grown on podsolised sands in south-east South Australia.

| Ecosystem component | Thinning* | Clearfelling† |
|---|---|---|
| Residual trees | 188 | 0 |
| Residue | 128 | 321 |
| Forest floor | 54 | 491 |
| Soil (0–0.3 m) | 835 | 1235 |

*10 year-old plantation, basal area 36.5 $m^2$/ha, 1352 stems/ha (Carlyle in press a).

†37-year-old plantation, basal area 33.9 $m^2$/ha, 162 stems/ha (Smethurst & Nambiar 1990a).

## Nitrogen Uptake and Leaching

In stands without fertiliser, nitrogen uptake is dependent on the rate of nitrogen mineralisation which is in turn largely dependent on organic matter amount and composition (Carlyle *et al.* 1990), soil moisture, and soil temperature (Gonçalves & Carlyle 1994). In most forests which have not been subject to recent major disturbance, rates of mineralisation are matched by uptake, mineral nitrogen does not accumulate in the soil, and there is no leaching (Carlyle 1986). Forest operations have the potential to influence nitrogen uptake and leaching through either reducing the uptake capacity of the stand (e.g., clearfelling), influencing the variables which control mineralisation rates, or both. Thinning might be expected to increase rates of nitrogen mineralisation due to inputs of mineralisable material both above and below ground, plus changes in soil moisture and temperature. At the same time, tree removal could result in reduced nitrogen uptake resulting in accumulation of mineral nitrogen in the soil, increasing the potential for leaching. However, Carlyle (in press a) found that thinning *per se* resulted in a small increase in nitrogen uptake (Fig. 1); over 4 years, trees in the thinned (zero residue) treatment took up 100 kg N/ha compared to 82 kg N/ha in the unthinned treatment, an increase of 22%. This difference reflected a small increase in soil nitrogen mineralisation after thinning (Carlyle in press a). Similarly, Beets & Pollock (1987) found no effect of thinning on nitrogen uptake by *P. radiata* growing on

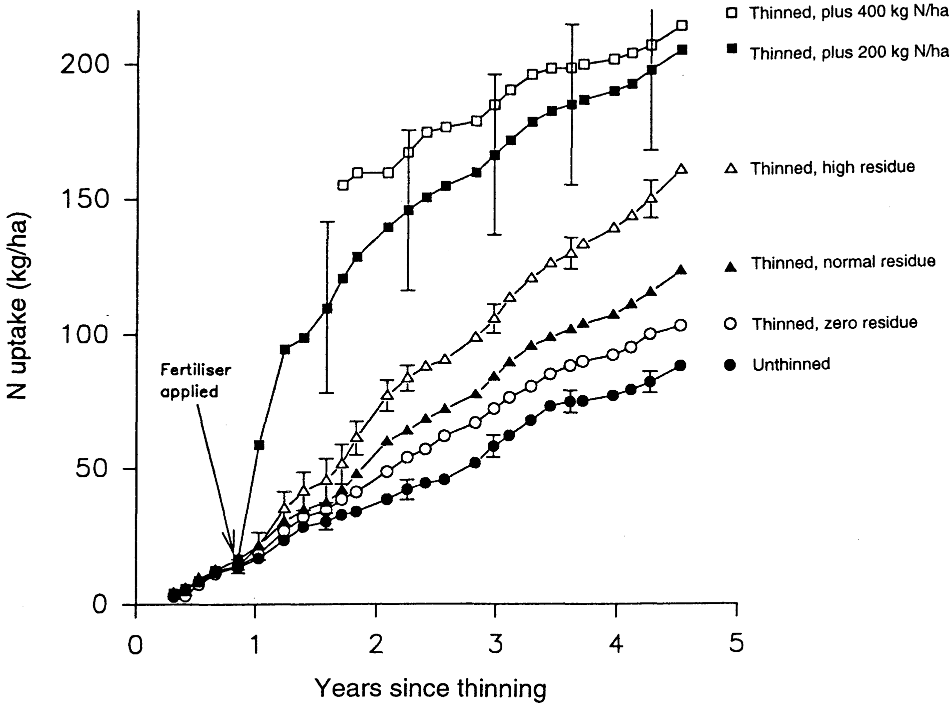

FIG. 1–Uptake of nitrogen from the forest floor plus 0–0.15 m mineral soil in response to thinning, residue manipulation, and fertiliser application. Bars denote standard errors for selected treatments. Uptake of nitrogen was estimated by a sequential soil sampling technique (Raison *et al.* 1987), except for the 400 kg N/ha treatment in the year after fertiliser application when uptake was estimated from a relationship between foliar nitrogen concentration and nitrogen uptake derived for the remaining treatments (Carlyle unpubl. data).

a highly fertile volcanic soil, although thinning was found to reduce uptake on an infertile sand (Beets & Madgwick 1988), the reduction (relative to an unthinned control) increasing with thinning intensity and nitrogen availability (manipulated by nitrogen fertiliser, lupins, or both).

The capacity of the thinned stand to take up all mineralised nitrogen means that while nitrogen uptake per hectare was slightly increased by thinning, nitrogen uptake per tree was increased by a factor of 2.6 over 4 years (Fig. 2). Beets & Pollock (1987) also measured a marked and immediate increase in nitrogen uptake per tree after thinning. Thus, in the Mediterranean environment of south-east South Australia, thinning *per se* did not result in substantially increased nitrogen availability per hectare but distributed the available nitrogen amongst fewer selected trees. The effect of thinning on soil nitrogen fluxes contrasts markedly with that of clearfelling. After clearfelling of a 37-year-old plantation on a similar soil (Smethurst & Nambiar 1990a), rates of uptake were reduced and rates of mineralisation increased, with a resultant increase in soil mineral nitrogen concentrations and leaching (Table 2). In contrast, thinning had little effect on soil nitrogen fluxes or mineral nitrogen concentrations, principally because uptake by the thinned stand was not reduced by thinning, despite removal of 48% of the basal area.

Clearfelling residues can contribute significantly to nitrogen availability (Smethurst & Nambiar 1990b) so that residue removal may be associated with a reduction in tree growth in the subsequent rotation (Balneaves 1990). Similarly, removal of thinning residue has been associated with reductions in tree growth (Lundkvist 1988; Sterba 1988) and nutrient status

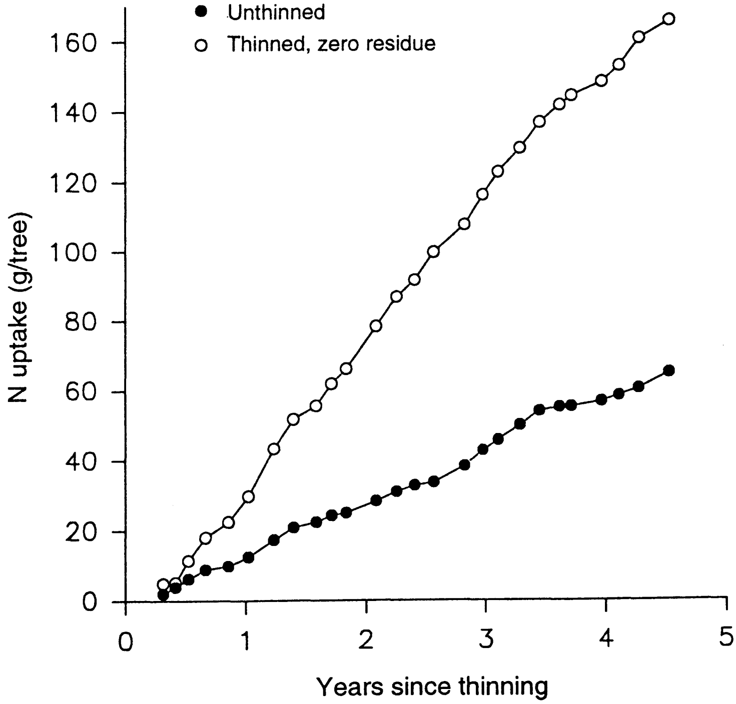

FIG. 2–Effect of thinning on nitrogen uptake (from the forest floor plus 0–0.15 m mineral soil) per tree.

TABLE 2–Influence of clearfelling or thinning on fluxes of mineral nitrogen (kg/ha) in the forest floor plus 0–0.15 m mineral soil for two plantations grown on podsolised sands in south-east South Australia. All harvesting residue was removed from the sites. Fluxes are summed over 3 years; soil nitrogen is the standing pool of mineral nitrogen (kg/ha) measured 18 months after clearfelling or thinning respectively.

| | Clearfelling* | | Thinning† | |
|---|---|---|---|---|
| | Unfelled | Felled | Unthinned | Thinned |
| Mineralisation | 82 | 143 | 58 | 71 |
| Leaching | 0 | 116 | 0 | 0 |
| Uptake | 82 | 27 | 64 | 78 |
| Soil N | 2 | 16 | 1 | 1 |

*37-year-old plantation, basal area 33.9 $m^2$/ha, 162 stems/ha (Smethurst & Nambiar 1990a).

†10-year-old plantation, basal area 36.5 $m^2$/ha, 1352 stems/ha (Carlyle in press a).

(Sterba 1988). However, these studies did not quantify the importance of thinning residue to nutrient supply and uptake directly. In the thinning study outlined above, nitrogen uptake increased with the amount of residue retained (Fig. 1), reflecting increased mineralisation in the presence of residue (Carlyle in press a). Over 4 years, trees in the zero-residue, normal-residue, and high-residue treatments took up 100, 116, and 150 kg N/ha respectively. Thinning with residue retained therefore increased nitrogen uptake per tree by a factor of 3. All nitrogen mineralised was taken up, mineral nitrogen did not accumulate in the soil, and there was no leaching. This indicates that the uptake capacity of the thinned stand was able to cope with the increase in nitrogen availability associated with thinning and residue. That all mineralised nitrogen was taken up by trees in the high-residue treatment indicates that localised high concentrations of residue in thinned stands, that can occur as a result of mechanised harvesting operations, need not be associated with increased leaching as they can be after clearfelling (Rosen & Lundmark-Thelin 1987). It also demonstrates that the thinned stand had the capacity to take up considerably more nitrogen than would be associated with a normal thinning operation. Thus, while thinning *per se* increases nitrogen uptake on a per tree basis but has little effect on uptake per hectare, the input of residue after thinning causes an absolute increase in nitrogen availability and uptake. The commonly reported increase in foliar nutrient concentrations after thinning (e.g., Mugasha & Pluth 1991) is therefore a consequence of increased nutrient uptake per tree, reflecting a reduction in intra-specific competition, and increased availability per hectare. There is no evidence that thinning results in deceased nitrogen availability as a consequence of nitrogen immobilisation by high C:N ratio residue as speculated by Cochran (1968), Beets & Pollock (1987), and Dyck *et al.* (1987). Where thinning results in the development of a vigorous understorey it has been speculated that the resultant competition may reduce nitrogen availability to the tree crop (Beets & Pollock 1987). However, such reductions are unlikely to be significant for *P. radiata* plantations growing on sandy soils in southern Australia where understorey development is normally sparse.

Changes in harvesting technology have resulted in a shift towards fully mechanised first-thinning operations. Such operations can be associated with complete removal of above-ground biomass of thinned trees from the site. In south-east South Australia and south-west

Victoria some 1000–2000 ha per year are subject to complete removal of above-ground biomass at first thinning. The removal of residue after thinning has the potential not only to deplete site nitrogen reserves (Table 1) but also to reduce the availability of nitrogen to the thinned stand with an associated reduction in nitrogen uptake (Fig. 1, thinned with zero residue cf. thinned with normal residue). In fact, for sandy soils, the removal of nitrogen in residue after thinning may have a greater impact on nitrogen uptake and site nitrogen status than removal of an equivalent amount of residue at clearfelling. This is because nitrogen uptake is maintained after thinning and there is no leaching; all nitrogen released from residue is taken up. In contrast, low uptake after clearfelling means that leaching (below 0.3 m) may account for 81% of the nitrogen mineralised (Smethurst & Nambiar 1990a) (Table 2), so that at least a proportion of nitrogen released from clearfelling residue may be lost from the site.

## SCOPE FOR INCREASING PRODUCTIVITY BY FERTILISER APPLICATIONS IN ASSOCIATION WITH THINNING

In established stands thinning is often considered a prerequisite for a growth response to fertiliser (Snowdon & Waring 1990), with unthinned stands often failing to respond (Miller *et al.* 1992). This applies not merely to fertile sites but also to stands which were nutrient-limited prior to canopy closure but which have since outgrown this limitation because of changes in nutrient requirement and increased reliance on internal nutrient cycling. Prior to canopy closure the nitrogen requirement of an aggrading canopy places a high demand on the soil as a source of nitrogen supply. In many managed forests rates of nitrogen mineralisation are low (Carlyle 1986) and must be augmented with nitrogen fertiliser or nitrogen-fixing associations to achieve desired growth rates. Nitrogen requirement is maximum immediately prior to canopy closure; subsequently, foliage biomass and nitrogen content stabilise and may slowly decrease with a concurrent reduction in nitrogen requirement (Beets & Pollock 1987). At the same time a substantial proportion of the annual requirement is met by internal cycling (Miller 1981). Under these circumstances stand growth may cease to be responsive to nitrogen supply, particularly as other resources may become growth limiting, e.g., water and light. Because thinning returns a stand to a period of canopy expansion, it will increase nitrogen requirement and dependence on the soil as a source of nitrogen supply. For this reason Miller (1981) has suggested that on nutrient-limited sites after thinning trees may exhibit nutrient-deficiency symptoms previously manifest at establishment but which the trees had outgrown after canopy closure and increased reliance on internal nutrient cycling. Although thinning with residue retention results in increased nitrogen supply per hectare, and a much larger increase per tree (Fig. 1 and 2) (Carlyle in press a), many sandy sites where nitrogen supplies were growth-limiting prior to canopy closure are also likely to be nitrogen-limited after thinning. This is because rates of soil nitrogen mineralisation will be too low (e.g., 24 kg N/ha/year, Table 2) to support a rapid return to canopy closure. Thus stands which responded, or would have been expected to respond, to nitrogen fertiliser prior to canopy closure should also be expected to respond to fertiliser applications associated with thinning. It is therefore not surprising that a large number of experiments have shown positive growth responses to fertiliser applied in association with thinning (e.g., Mead & Gadgil 1978; Mead *et al.* 1984; Barclay & Brix 1984; Donald 1987; Snowdon & Waring 1990).

Stands where nitrogen supply severely limits leaf area development may be expected to respond to nitrogen fertiliser without the need for thinning. However, in intensively managed plantations in southern Australia such nitrogen-limited stands are becoming increasingly rare.

## INFLUENCE OF NITROGEN FERTILISER ON NITROGEN UPTAKE

In contrast to other plantation management operations, application of nitrogen fertiliser generally results in an immediate and massive elevation of soil mineral nitrogen concentrations (Fig. 3) (Carlyle in press b) which exceed the uptake capacity of the stand and can result in substantial solution or gaseous loss. The problem of leaching is especially acute on sandy soils where cation exchange capacities are often negligible (Carlyle 1993). Under these circumstances the forest manager is faced with a paradox. To increase nitrogen uptake and

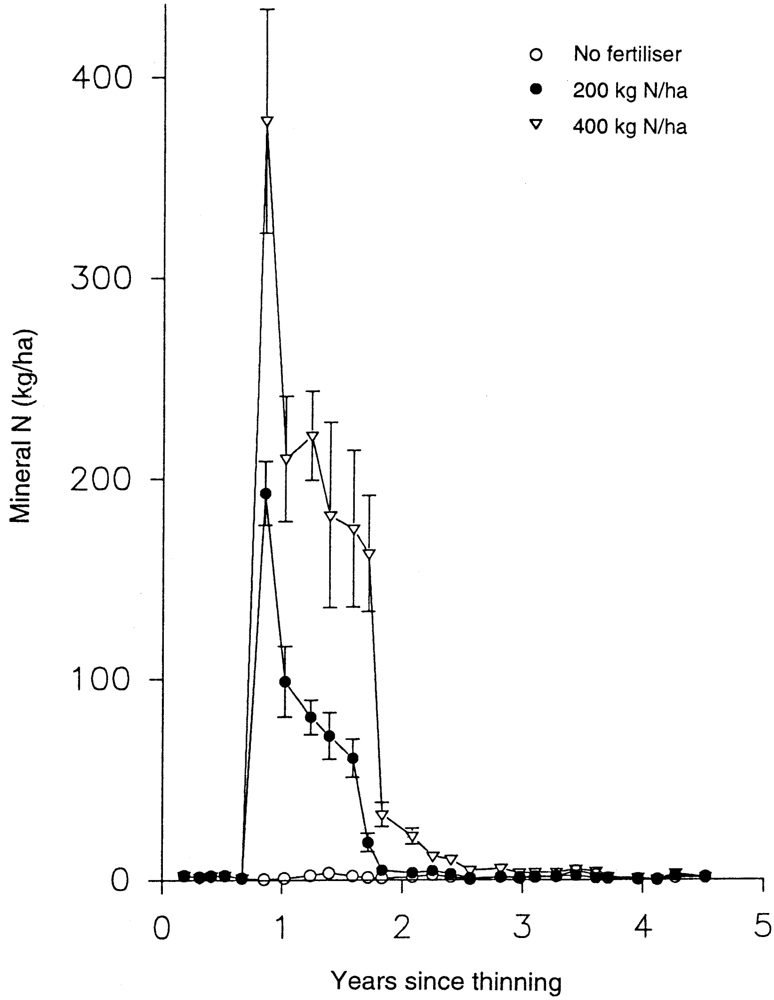

FIG. 3–Effect of nitrogen fertiliser on the standing pool of mineral nitrogen (forest floor plus 0–0.3 m mineral soil). Bars denote standard errors where these are larger than the symbol.

wood yield he must increase the rate of nitrogen supply, but this is difficult to achieve without significantly elevating soil mineral nitrogen concentrations and creating ideal conditions for nitrogen leaching. In theory, a nitrogen addition system which matched the rate of nitrogen supply to the uptake capacity of the stand could increase nitrogen uptake and growth without elevating soil mineral nitrogen concentrations and the risk of leaching. In practice, such a system would need to be based on frequent small fertiliser inputs, e.g., irrigation with soluble fertiliser (Ingestad 1988), slow-release fertiliser, or the use of nitrogen-fixing associations. While multiple fertiliser applications or slow-release fertilisers can be effective experimentally, or for limited areas where the value of production is high, they are not practical for the majority of commercial plantations. The effectiveness of nitrogen-fixing associations has not been demonstrated in thinned *P. radiata* plantations.

There is a marked contrast between the effects of fertiliser and residue on soil nitrogen dynamics and tree nitrogen uptake. Fertiliser results in an immediate, large, but short-lived (c. 1 year) increase in nitrogen uptake (Fig. 1). This is associated with dramatically increased soil mineral nitrogen concentrations (Fig. 3) and leaching (Table 3) (Carlyle in press b). Residue results in a slow but sustained increase in nitrogen mineralisation and uptake (Fig. 1) which is not associated with significantly elevated soil mineral nitrogen concentrations or increased leaching (Carlyle in press a). Uptake of nitrogen during the 15 months after fertiliser application was relatively inefficient (54% of the available nitrogen pool, i.e., fertiliser added plus nitrogen mineralised) compared with uptake of nitrogen released from residue (100% of the available nitrogen pool) over the same period (Carlyle in press a, b). However, the efficiency of fertiliser uptake was much greater than commonly reported for applications at establishment, e.g., 7–18% (Nambiar & Bowen 1986). Greater uptake reflects the presence of an established root system, greater biomass in which to sequester nitrogen, and a reduced potential for leaching because of greater rainfall interception and transpiration. It follows that where the potential for nitrogen loss is high, it would be desirable to treat established stands and minimise fertiliser use earlier in the rotation. In any case, applications of nitrogen fertiliser at planting are probably unnecessary on many sites because of increased rates of nitrogen supply associated with clearfelling and site preparation (Table 2) (Smethurst & Nambiar 1990b).

TABLE 3–Fluxes of mineral nitrogen (kg/ha) in the forest floor plus 0–0.3 m mineral soil in the 15 months after fertiliser application (200 kg N/ha) to a thinned plantation. Soil nitrogen is the standing pool of mineral nitrogen (kg/ha) measured immediately (0) or 15 months (15) after application. Results are taken from Carlyle (in press b).

| | Before fertiliser | 200 kg N/ha |
|---|---|---|
| Leaching | 0 | 142 |
| Uptake | 53 | 171 |
| Soil N(0) | 1 | 194 |
| Soil N(15) | 2 | 5 |

## OPPORTUNITIES FOR MODIFYING NITROGEN FERTILISER USE TO ENHANCE UPTAKE AND MINIMISE LEACHING

Fertiliser practices can be designed to maximise uptake and minimise leaching. Options include varying the timing of application with respect to thinning schedule and season, multiple- *versus* single-dose fertiliser application, and the form of nitrogen applied

## Application with Respect to Thinning Schedule

Established stands have the capacity to rapidly take up large amounts of fertiliser nitrogen (Fig. 1) (Hunter *et al.* 1986; Carlyle in press b). This rapid and large uptake of nitrogen need not be associated with a simultaneous increase in leaf area or growth and reflects storage in existing biomass (Carlyle in press b). Subsequent increases in leaf area and growth are driven by this stored nitrogen (Carlyle unpubl. data) as it is retranslocated to developing needles and shoots. In fact, where annual rates of nitrogen mineralisation are low in comparison to the quantity of nitrogen taken up in the year immediately after fertiliser application, canopy expansion and tree growth may be poorly correlated with subsequent annual nitrogen uptake for several years following (Carlyle unpubl. data).

Because of the significant potential of established stands to store nitrogen in existing biomass, it may be preferable to apply fertiliser to plantations before thinning when the biomass available to sequester nitrogen is greater (Carlyle in press b). Much of the nitrogen taken up by trees that are then thinned will be stored in foliage and branches which are usually retained on site. This nitrogen will become available as the residue decomposes and will provide a second pulse of available nitrogen at a rate able to be totally taken up by the stand. Unthinned stands often fail to respond to fertiliser (Miller *et al.* 1992) so that thinning is generally considered a prerequisite if a growth response to fertiliser is to be obtained (Snowdon & Waring 1990). However, the absence of a growth response does not indicate the absence of fertiliser uptake and it seems probable that pre-thinning applications should result in a growth response once stands are thinned (Carlyle in press b). Pre-thinning application should increase total uptake and reduce leaching, and increase the flexibility available to forest managers in applying nitrogen to established plantations. This hypothesis should be tested experimentally.

## Application with Respect to Season

The amount of nitrogen fertiliser taken up by a plantation can vary with the season of application. For instance, McGrath & McArthur (1990) found greater uptake of nitrogen from spring than from winter application of fertiliser to young pines. Uptake will vary because of seasonal differences in rainfall and evaporation, and therefore leaching. Uptake may also vary because of seasonal differences in the stand's uptake capacity which, in young trees, will be closely linked to growth. At establishment it will be important to match application with a period of active growth because the biomass available in which to sequester nitrogen can be small relative to the increase in biomass over the growing season. Such differences are likely to be less important in established stands where a large storage capacity means that uptake need not be closely coupled with, and therefore dependent on, growth. Experimentally determining the effect of different seasons of application on leaching and uptake of nitrogen can be confounded by variation in rainfall pattern and amount between years. An alternative approach is to construct relationships which predict leaching and uptake from readily measured soil and climatic variables and use these relationships in conjunction with long-term climatic data to assess the average (long-term) effect of different seasons of application. In the thinning study described above, leaching and uptake of nitrogen after fertiliser application could be estimated from simple linear functions (Carlyle in press b)—

$$N_{leach} = 0.021.N_{start} + 0.145.R_{eff} \qquad r^2 = 0.92$$

$$N_{uptake} = 0.018.N_{start} + 0.686.N_{min} \qquad r^2 = 0.91$$

where $N_{leach}$ is the quantity of mineral nitrogen leached below 0.3 m (kg/ha/week), $N_{uptake}$ is the quantity of nitrogen taken up from the 0–0.3 m soil profile over the period (kg/ha/week), $N_{start}$ is the quantity of mineral nitrogen at the start of a period (kg/ha), $R_{eff}$ is effective rainfall (rainfall minus pan evaporation, mm/week), and $N_{min}$ is the quantity of nitrogen mineralised over that period (kg/ha/week).

These simple functions were used to evaluate the effect of varying season of application on leaching and uptake of nitrogen (Carlyle in press b). The predictions must be interpreted with caution since the independent variables were not controlled experimentally but varied simultaneously, making it unreliable to extrapolate outside the particular range of combination of input values used to develop the equations. In addition, the methodology used will over-estimate leaching while the fate of nitrogen leached below 0.3 m is uncertain. With these limitations in mind, spring (September) application is preferable to application in winter (June), when leaching is greater (due to higher rainfall) and occurs at the expense of uptake (Table 4). Raison & Myers (1992) suggested that nitrogen fertiliser should be applied in winter in order to maximise uptake; this seems inappropriate for plantations growing on sandy soils.

TABLE 4–Simulated quantities of nitrogen leached or taken up from the forest floor plus 0–0.3 m mineral soil after application of 200 kg N/ha to a thinned plantation in June (winter) or September (spring). Rainfall is the amount of rain which fell until all applied nitrogen was leached or taken up. Results are taken from Carlyle (in press b).

| | Uptake (kg N/ha) | Leached (kg N/ha) | Rainfall (mm) |
|---|---|---|---|
| June (winter) | 64 | 136 | 620 |
| September (spring) | 88 | 112 | 365 |

## Split Applications

A quantity of fertiliser can be applied as a single dose or as a number of smaller doses on several occasions. It has been speculated that the spilt dose strategy is superior (e.g., Raison & Myers 1992), although Jokela & Stearns-Smith (1993) found no difference in tree growth response to split *versus* single nitrogen applications. Using the uptake and leaching functions described above suggests no difference in leaching and uptake between a single spring (September) application of 200 kg N/ha or two spring applications of 100 kg N/ha in successive years (Fig. 4). This prediction assumes identical rainfall patterns between years and does not consider possible changes in nitrogen uptake capacity as a result of the first dose of fertiliser. Foliage biomass and leaf area can increase substantially after fertiliser application (Brix 1981) so that uptake may be increased if applications are timed to match the increase in storage capacity. Multiple doses may also be superior in regions with highly variable rainfall patterns because they should reduce the risk of very high leaching losses from a single fertiliser application which coincides with a year of unusually high rainfall. Multiple nitrogen applications need not substantially increase the cost associated with fertiliser application because the relatively high cost of nitrogen fertiliser means that application cost

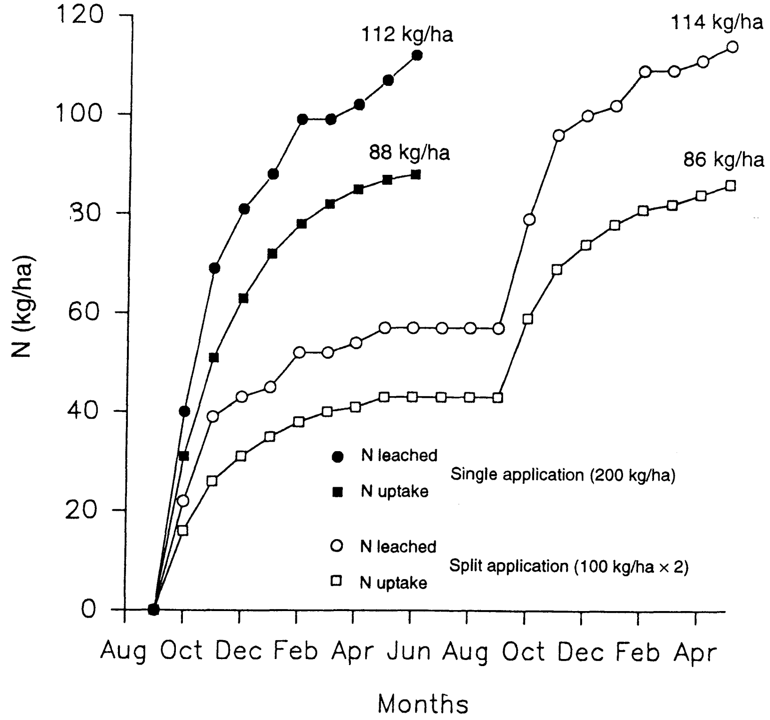

FIG. 4–Simulated comparison of a single application of 200 kg N/ha *versus* two applications of 100 kg N/ha in successive years on cumulative nitrogen leaching and uptake (from the forest floor plus 0–0.3 m mineral soil). Identical rainfall was assumed for the 2 years and no consideration was given to possible changes in nitrogen uptake capacity as a result of the first dose of 100 kg N/ha fertiliser.

may be only 10% of the total operational cost (Carlyle unpubl. data). However, multiple applications increase management complexity and would therefore need to be demonstrably superior to single applications if the strategy were to be widely adopted.

## Form of Nitrogen Fertiliser

Ammonium is readily leached from sandy soils because of their low cation exchange capacity (Smethurst & Nambiar 1990b; Carlyle 1993, in press b). The form of nitrogen applied, ammonium or nitrate, is therefore of little consequence as regards leaching. Both ammonium and nitrate may also be subject to gaseous loss, although such losses are likely to be low in the sandy soils of southern Australia. Gaseous loss of ammonium from ammonium-based fertilisers, after conversion to ammonia, is likely to be negligible from these soils because of low soil pH (Carlyle *et al.* 1990). However, application of nitrogen as urea could lead to high gaseous losses of ammonia. To date, use of urea has been negligible in south-east South Australia/western Victoria, although use is increasing because of the low cost of urea per unit nitrogen. Consequently, there is a need to quantify volatile nitrogen losses from urea applied to forested sandy soils in the Mediterranean environment of southern Australia. Denitrification is unlikely to be important because of low rates of nitrification, absence of anaerobic conditions, and low levels of available carbon. In addition, although some species may exhibit an uptake selectivity for ammonium or nitrate under controlled conditions (Bledsoe & Zasoski 1983), forest trees are almost certainly opportunistic in their exploitation of available nitrogen and probably use whatever nitrogen is available (Wollum & Davey 1975). Thus, the oxidation state of nitrogen in fertiliser is unlikely to significantly influence nitrogen uptake by plantations growing on sandy soils.

Because high inorganic nitrogen concentrations can lead to appreciable leaching from sandy soils, slowly soluble nitrogen fertilisers are conceptually appealing. However, slow-release nitrogen fertilisers are expensive (Oertli 1980) and have not been shown to be effective for forestry on sandy soils (Nambiar & Cellier 1985), partly because of difficulties in obtaining appropriate rates of nitrogen release. Even assuming suitable slow-release fertilisers were available, their use would probably not be well suited to fertiliser treatment in association with thinning. This is because a rapid uptake of nitrogen is desirable to promote canopy development and growth of the residual trees, with the object of reducing rotation length or increasing log size at a given age. Such rapid uptake requires the use of a readily soluble nitrogen form. However, nitrogen uptake by the high residue treatment (Fig. 1) demonstrates that an effective slow-release fertiliser, residue, can substantially increase nitrogen uptake without increasing leaching, although the increase in uptake is less than that achieved with a soluble inorganic fertiliser.

## NITROGEN-FIXING ASSOCIATIONS

A range of nitrogen fixing associations have been successfully used to increase nitrogen supply to plantations at establishment (Gordon 1983; Turvey & Smethurst 1983). For *P. radiata* grown on sandy soils most research and operational practice has focused on the genus *Lupinus* (Gadgil 1979, 1983; Nambiar & Nethercott 1988) with clear demonstrations of high rates of nitrogen fixation and improved tree growth. However, there is little evidence that similar effects can be achieved in established stands after thinning. This is because even quite intense thinning regimes, e.g., 67% reduction in stocking, are insufficient to initiate vigorous lupin regrowth and nitrogen fixation where a lupin crop had been successfully established earlier in the rotation (Beets & Madgwick 1988). For the same reasons, attempts to establish lupins in thinned stands by seeding would probably prove unsuccessful. Thus, although Gadgil (1979) found that lupins fixed at least 160 kg N/ha/year in the first 2 years after establishment, subsequent regeneration and nitrogen fixation declined with no increase in ecosystem nitrogen capital from years 2 to 5. Maintenance of higher tree growth rates in lupin treatments over this time resulted from continued cycling of nitrogen fixed during the first 2 years. Given the dry environment of southern Australia and the intensity of current thinning regimes it is most unlikely that lupins could be successfully established after thinning.

Even if nitrogen-fixing associations could be established successfully after thinning, it is questionable whether they could be as effective as soluble inorganic fertilisers in accelerating canopy development and tree growth for the same reasons as discussed in relation to slow-release fertilisers. These are, principally, that rapid uptake of a readily soluble nitrogen source is required to maximise the rate of canopy development and growth of the residual trees, with the object of reducing rotation length or increasing log size at a given age. It is unlikely that nitrogen-fixing associations could meet this requirement as effectively as soluble inorganic nitrogen fertilisers.

## CONCLUSIONS

Nitrogen uptake in established stands can be influenced by thinning, management of thinning residue, and fertiliser. However, the effect of these operations on nitrogen availability and uptake differs. Understanding the processes and factors which influence uptake allows better assessment of the impact of management practices and increases scope for improving management. Thinning, where residue is retained, increases nitrogen availability and uptake per hectare but results in a much greater increase in uptake per tree. The increase in uptake is sustained and commences immediately after thinning. Nitrogen is released progressively from residue at rates compatible with the uptake capacity of the thinned stand. All this nitrogen is taken up with no accumulation in the soil and no leaching, even where quantities of residue are artificially increased. However, where rates of nitrogen uptake were limiting growth prior to canopy closure, it is unlikely that increased rates of nitrogen uptake after thinning will be adequate to support the rapid canopy expansion, and return to pre-thinning leaf area index, desirable in commercial forestry. This could be supported only by a sudden and large increase in nitrogen uptake of the sort observed after fertiliser application.

Nitrogen fertiliser should be applied in ways to maximise economic benefit and minimise the potential for undesirable environmental impacts such as ground water contamination. Simple empirical models suggest that uptake of nitrogen fertiliser can be increased, and leaching reduced, by spring rather than winter applications. There may be only limited benefit of applying nitrogen fertiliser in split rather than single doses unless the uptake capacity of a stand is substantially increased by an initial fertiliser application, or where there is the possibility of very high leaching losses from a single fertiliser application. The capacity of an established stand to rapidly take up large amounts of nitrogen fertiliser suggests that pre- rather than post-thinning fertiliser application may be effective as a means of increasing nitrogen uptake while minimising leaching. There is probably little scope for influencing nitrogen uptake in established stands by varying the form of nitrogen fertiliser applied or through the use of nitrogen-fixing associations.

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