Available online at www.sciencedirect.com

SCIENCE DIRECT®

Forest Ecology and Management 193 (2004) 63–80

Forest Ecology and Management

www.elsevier.com/locate/foreco

Nitrogen management in *Eucalyptus nitens* plantations

Philip Smethurst[a,b,*], Greg Holz[a,c], Martin Moroni[a,d], Craig Baillie[a,b]

[a]*Cooperative Research Centre for Sustainable Production Forestry, Private Bag 12, Hobart TAS 7001, Australia*
[b]*CSIRO Forestry and Forest Products, Private Bag 12, Hobart TAS 7001, Australia*
[c]*31 Poimena Road, Burnie TAS 7320, Australia*
[d]*Canadian Forest Service, Atlantic Forestry Centre, P.O. Box 960, University Drive, Corner Brook, Nfld, Canada A2H 6J3*

Abstract

Low nitrogen (N) availability commonly limits the growth of *Eucalyptus nitens* plantations on ex-forest sites in Tasmania, Australia. We summarise here a decade of mechanistic and empirical research that has improved the basis for N management of these plantations. Twenty-two fertiliser experiments were used to define relationships between tree growth and methods of N fertilisation, i.e. timing, frequency, form, rate and placement. Pools and fluxes of mineral N were monitored at five sites. Potential deficiencies of N between planting and 10 years of age were indicated by the concentrations of soil NH_4, NO_3, total N and total phosphorus (P). Appropriate timing of N fertilisation depended on when N demand started to exceed supply from soil reserves, and was indicated by soil total N. Plantations on low-N sites experienced N deficiency during the first few years of growth, but others experienced it later or not at all. High cumulative rates of N fertilisation (at least 500 kg N ha^{-1}) were needed to maximise growth at many sites, but there is no evidence to suggest that any individual application in excess of 200 kg N ha^{-1} is warranted. Hence, multiple applications will be needed to maximise growth. Urea was the preferred form of N, because it was relatively cheap and at least as effective as other N forms. Limiting N application to the crown drip line of 6-year-old trees with small crowns did not increase growth compared to a totally broadcast application. Soil N availability increased for 1–2 years following most N-fertiliser applications. Tree growth rates increased significantly for the same period followed by several years of less significant responses during which re-applications promoted a more sustained response in growth. This research has fostered an increase in the use of N fertilisers to increase productivity, and it should improve the basis for evaluating the economics of options for N fertilisation. Although applications of N fertilisers at rates up to 200 kg N ha^{-1} and at intervals of several years are unlikely to be a threat to water quality, especially if urea is used, research is needed to determine the environmental risks associated with long-term and higher intensity uses.

Keywords: Fertiliser; Fertility; *Eucalyptus*; Nitrogen; Nutrition; Plantations

---

1. Introduction

Productivity of *Eucalyptus nitens* Deane and Maiden plantations grown for pulpwood in Tasmania, Australia, is commonly limited by low nitrogen (N) availability, especially when established on ex-forest sites (Bennett et al., 1996; Cromer et al., 2002; Smethurst et al., 2003), but high-productivity sites can yield about 30 m^3 ha^{-1} per year mean annual increment (MAI) in stem volume (Mummery and Battaglia, 2001). Because of its frost tolerance, *E. nitens* is generally grown in cooler and wetter conditions than most other high-productivity eucalypt species. *Pinus radiata* D. Don, the other species

---

[*] Corresponding author. Tel.: +61-3-6226-7953;
fax: +61-3-6226-7942.
E-mail address: philip.smethurst@csiro.au (P. Smethurst).

0378-1127/$ – see front matter. Crown Copyright © 2004 Published by Elsevier B.V. All rights reserved.
doi:10.1016/j.foreco.2004.01.023

planted in these conditions in Tasmania, generally grows more slowly than *E. nitens* during the first decade after planting. Differences in growth habits therefore conferred doubt about the transferability of N management experience from *P. radiata* to *E. nitens*. Apart from frost tolerance, the ranges of environmental tolerance (temperature and rainfall) of *E. globulus* and *E. nitens* are broadly similar such that both are suitable options in cool temperate regions that experience only mild frosts (White et al., 1996). However, even for *E. globulus*, which is now much more extensively planted than *E. nitens* in environments with a low risk of frost, many questions related to N management have not been addressed.

Knowledge of N supply and demand underpins the judicious use of fertilisers in forest plantations (Nambiar, 1995). Annual rates of net N mineralisation (NNM) in the top 0–10 cm of Tasmanian plantation soils cover a wide range (18–182 kg N ha^{-1} per year; Moroni et al., 2002), and potential mineralisation rates in subsoils suggest total-profile rates of NNM in the range 54–910 kg N ha^{-1} per year (maximum depth 120 cm; Moroni, 2001). High-productivity eucalypt plantations have uptake rates of about 200 kg N ha^{-1} per year as they approach canopy closure (Cromer et al., 1993; Periera et al., 1996; Misra et al., 1998b). Therefore, the N status of Tasmanian eucalypt plantations of similar potential productivity will range from highly deficient (inadequate N supply) to supra-optimal, and a means of predicting a site's N status would aid N management.

Earlier work indicated that soil solution nitrate (NO_3) was more discriminatory between sites of contrasting rates of N supply than was KCl-extractable NO_3, particularly at low concentrations (Moroni, 2001), probably because extraction of soil solution by the paste method involves less dilution of the liquid phase and hence easier detection of mineral N. The usefulness of concentrations in soil solution is also supported by a strong theoretical basis on which to interpret values as indicators of N availability (Sands and Smethurst, 1995; Smethurst, 2000). These results encouraged further assessment of concentrations of NH_4 and NO_3 as indictors of N deficiency.

Apart from the prediction and diagnosis of N deficiency using estimates of N supply and uptake and soil chemical indicators, key N management issues are the form, placement, rate, frequency and timing of fertilisation, return on investment, and environmental impacts. Regarding N form, there was evidence that *E. nitens* and *E. globulus* have a preference for the ammonium (NH_4) form of N (Shedley et al., 1993; Garnett et al., 2001), but the relative usefulness of NH_4- or NO_3-based fertilisers had not been compared under field conditions. Regarding placement, rates and timing, the potentially rapid development of eucalypt roots (Misra et al., 1998a) might reduce the need for localised placements of N fertiliser (spots or strips), but relatively high N demand might require high rates of N fertilisation early in the crop cycle. In other countries, some N management issues of eucalypt plantations have been addressed, but these mainly involved low rates of N applied during the first year (Attiwill and Adams, 1996), and differences between Australian and overseas conditions in soils, climate and species, limit the quantitative transferability of results.

The rate and timing of fertilisation are two important factors that need to be considered together for managing N fertilisation, because split applications can have positive or negative effects on fertiliser efficacy and economics. Timing is related to the age of the stand and season of application, whereas rate is related to the rate of each individual application and cumulative amount. There are numerous possible combinations of these and other N management factors, but based on our knowledge of N dynamics, these can be reduced to practical combinations for testing.

Intensive production of eucalypts on low-N sites can be expected to require an average application of 30–40 kg N ha^{-1} per year over a 15- to 25-year rotation, and some growers have operationally commenced such regimes. Long-term N inputs of this order can lead to N saturation, which is characterised by a higher risk of NO_3 leaching, base cation losses, increased soil acidity and aluminium toxicity (Magill et al., 1997). Hence, managers of N fertilisers need to be aware of these risks and use regimes that keep them at acceptable levels, but the significance of these issues has not been studied in relation to N fertilisation of eucalypt plantations.

Research summarised here evaluated soil-based indicators of N deficiency for *E. nitens*, and methods of managing N fertilisers, including form, placement, rates, timing and frequency. New data are presented in conjunction with recently published information to provide a synthesis of our experience.

2. Methods

2.1. Sites

We used data from 22 experiments located at 16 sites in Tasmania, Australia: one ex-*P. radiata* plantation site, two ex-pasture sites, and the remainder were converted from native forests (Table 1). The sites experienced a cool, temperate climate with annual rainfall in the range 850–2000 mm, which peaked in winter (June–August) and included rain in all summer months (generally in excess of 50 mm per month). The high elevation sites (>400 m) experienced frequent frosts during winter and had a mean annual maximum temperature of about 12 °C and minimum of about 3 °C, and occasionally a mild summer drought. Low elevation sites (<300 m) experienced few frosts, had a mean annual maximum temperature of about 15 °C and minimum of about 6 °C, and summer droughts were more common and pronounced than at higher elevations.

The soils were mainly derived from basalt, but parent material also included dolerite, alluvium and granite (Table 2). Surface soils (0–10 cm depth) had clay-loam textures, except at Bluegum, which had a coarse sand texture. All soils were acidic (pH_{water} 5–6) and of low conductivity.

Sites were prepared by harvesting the previous forest (if present) and the debris was cleared into windrows which were burnt. Soil was cultivated with rippers and formed into rows 3–4 m apart with a mound plough. Knockdown (glyphosate) and residual herbicides (atrazine or simazine) were applied pre- and post-planting uniformly across each site. All sites were planted with *E. nitens* seedlings on the mounds during winter or spring between 1986 and 1995 at a stocking of 1100–1500 trees ha^{-1}. Fertilisers containing about 20 g of both N and P per tree were applied at planting unless other rates of application at this time were part of the experimental design.

2.2. Experimental designs

All 22 experiments were of a randomised block design with at least three replicates, and included a minimum of 10 measured trees per plot surrounded by a buffer of at least 1.5 m. Some designs included factorial combinations of treatments. Characteristics of the experiments at each site are summarised in Table 3, i.e. ages and types of treatments, and main variables studied.

Concentrations of total N, total P, and mineral N (KCl extractable and soil solution), and rates of N mineralisation in surface soil (0–10 cm depth) were

Table 1
Characteristics of sites used for N fertiliser experiments in *E. nitens* plantations

Site name	Longitude east	Latitude south	Elevation (m a.s.l.)	Rainfall (mm per year)	Previous vegetation	Year planted
Allensbush	146°47′	40°16′	225	850	*E. amygdalina* native forest	1992
Basalt	145°51′	41°21′	580	1570	*E. delegatensis*-myrtle beech native forest	1986
Basils	145°39′	41°19′	550	1800	Myrtle beech native forest	1993
Blue Gum	145°50′	41°11′	350	1255	*E. obliqua* native forest	1990
Boulder	145°50′	41°12′	390	1400	*P. radiata* plantation	1993
Chromys	145°39′	41°10′	300	1640	Pasture	1987
Hurds	146°40′	41°21′	170	1039	*E. amygdalina* native forest	1990
Middlesex	145°45′	41°27′	620	2000	*E. delegatensis* native forest	1994
Nunamara	147°15′	41°23′	400	1180	*E. viminalis* native forest	1993
Old Park	145°46′	41°23′	640	1913	*E. delegatensis*-myrtle beech native forest	1990
Potters	145°45′	41°09′	510	1570	Pasture	1995
Rabbits	145°46′	41°24′	630	1913	*E. delegatensis* native forest	1993
Sugarloaf	145°48′	41°15′	400	1400	*P. radiata* plantation	1994
Talbots	145°43′	41°27′	650	1913	*E. delegatensis*-myrtle beech native forest	1989
Tim Shea	146°28′	42°40′	430	1444	*E. regnans* native forest	1993
Wages	145°44′	41°22′	620	1913	*E. delegatensis*-myrtle beech native forest	1991

Table 2
Soil characteristics of the sites used for N fertiliser experiments in *E. nitens* plantations (0–10 cm depth for chemical analyses)

Site name	Parent material	Australian soil classification (Isbell, 1996)	Soil taxonomy (Soil Survey Staff, 1990)	Total C (mg g^{-1})	Total N (mg g^{-1})	Total P (mg g^{-1})
Allensbush	Dolerite	Chromosol	Alfisol	29	1.14	0.2
Basalt	Basalt	Ferrosol	Oxisol	108	5.7	1.4
Basils	Basalt	Ferrosol	Oxisol	133	7.4	3.2
Blue Gum	Granite	Kurosol	Ultisol	74	1.0	<0.1
Boulder	Basalt	Ferrosol	Oxisol	67	2.7	0.5
Chromys	Basalt	Ferrosol	Oxisol	85	4.9	1.7
Hurds	Alluvium	Hydrosol	Inceptisol	39	1.8	0.3
Middlesex	Basalt	Ferrosol	Oxisol	93	5.6	1.6
Nunamara	Basalt	Ferrosol	Oxisol	34	2.1	0.8
Old Park	Basalt	Ferrosol	Oxisol	100	5.0	1.5
Potters	Basalt	Ferrosol	Oxisol	91	6.5	4.1
Rabbits	Basalt	Ferrosol	Oxisol	88	5.1	1.8
Sugarloaf	Basalt	Ferrosol	Oxisol	102	4.8	1.1
Talbots	Basalt	Ferrosol	Oxisol	71	3.8	1.5
Tim Shea	Mudstone	Kurosol	Ultisol	61	3.5	0.8
Wages	Basalt	Ferrosol	Oxisol	88	5.1	1.7

related to the age of a growth response to N fertiliser during the first few years after planting. Five experiments were designed to indicate the age at which N deficiency developed, but only at two of these (Tim Shea 1 and Nunamara 1, Table 3) were NH_4 and NO_3 measured before and after the growth response was first measured. Even when a growth response was first measured it was difficult to precisely identify when N deficiency had first affected growth, but we knew that N-deficient *E. nitens* plantations respond rather quickly to N fertilisation because at seven sites a positive growth response ($P < 0.1$) occurred within 6 months of N application to 4- or 6-year-old plantations. Where N was applied annually we therefore defined the 'onset of N deficiency' as being 1 year before a positive growth response was first recorded.

We used a combination of factors (age, season, fertiliser rate and frequency of application) based on our knowledge of N dynamics in these plantations to select treatments allowing the assessment of timing and rate of N fertilisation on growth (Wang et al., 1998; Smethurst et al., 2001a; Moroni et al., 2002; Paul et al., 2002). Fertiliser N and P were confounded in two experiments (Middlesex and Sugarloaf, Table 1) that addressed timing of application during the first year, but in several other experiments we examined responses only to N applied in various combinations of rates and ages of application during the first 3 years.

2.3. Measurements

Pools and fluxes of mineral N were measured using the in situ core technique and paste methods as described by Smethurst et al. (2001a) and Moroni et al. (2002). At sites where N fluxes were measured, soil samples (0–10 cm depth) were taken at about 2-month intervals for a 2- or 3-year period after planting. To test mineral N as an indicator of N deficiency in nine experiments in older plantations (3–10 years of age), we sampled soils (0–10 cm depth) in control (unfertilised) plots in these plantations at 4–11 years of age (September 1997), which was 1–4 years after fertilisation of the treated plots. Concentrations of total N and P in soil were measured by Kjeldahl digestion and colorimetry. Soil total C was measured directly using an induction furnace or colorimetric measurements of oxidisable C, or estimated by the loss-on-ignition method (Wang et al., 1996). Tree heights and stem diameters (at 15 cm height or 1.3 m height) were measured at 1–3-year intervals, and where experiments were installed in established plantations that had not previously been measured, trees were first measured within 1 month of the application of treatments.

Table 3
Characteristics of the N fertiliser experiments in *E. nitens* plantations used for the current study

Site name	Age first treated (years)	N treatments[a,b]	Number of replicates	Measured trees per plot	Main variable studied or common N form[b]				
					N fluxes	Form	Placement	Rate	Timing
Allensbush 1	6	Rate: 0, 100, 200, 400 Placement: 2 m diameter or broadcast	4	20		U	✓	✓	
Allensbush 2	6	Form: none, AS, $Ca(NO_3)_2$, NH_4NO_3, U	3	10		✓			
Allensbush 3	6	Frequency: 0.5-yearly, 1-yearly, 2-yearly 3-yearly, nil (rate 200)	4	10		U		✓	✓
Basalt	10	Rate: 0, 200	3	16				✓	
Basils	0, 1, 2	Rate year 0: 0, 25 Rate year 1: 0, 50, 100, 200 Rate year 2: 0, 50, 100, 200	4	12	✓			✓	✓
Blue Gum	3	Rate: 0, 200	3	17		AS		✓	
Boulder	0, 1, 2	Rates in year 0: 0, 25 Rates in year 1: 0, 50, 100, 200 Rates in year 2: 0, 50, 100, 200	3	8	✓			✓	✓
Chromys 1	9	Rate: 0, 200 Placement: 1 m radius or broadcast	3	14			✓	✓	
Chromys 2	9	Rate: 0, 50, 100, 200 Placement: 1 m radius or broadcast	3	13			✓	✓	
Hurds	3	Rate: 0, 200	3	18		AS		✓	
Middlesex	0	Rate: 0, 36 Timing (year 0 + months): 1, 2, 3, 5, 7, 9	4	9		DAP			✓
Nunamara 1	1, 2, 3	Rate year 1: 0, 25, 50, 100 Rate year 2: 0, 50, 100, 200 Rate year 3: 0, 125, 150, 200	3	25	✓	U		✓	✓
Nunamara 2	4	Rate: 0, 400	3	15		U		✓	
Old Park	3	Rate: 0, 200	3	20				✓	
Potters	0	Rate: 0, 25, 50, 100	3	12	✓				
Rabbits	0, 1, 2	Rate year 0: 0, 25 Rate year 1: 0, 50, 100, 200 Rate year 2: 0, 50, 100, 200	4	29				✓	✓
Sugarloaf	0	Rate: 0, 36 Timing (year 0 + months): 1, 2, 3, 5, 7, 9	4	9		DAP			✓
Talbots	7	Rate: 0, 200 Placement: 1 m radius or broadcast	3	17			✓	✓	
Tim Shea 1	1, 2, 3	Rate year 1: 0, 25, 50, 100 Rate year 2: 0, 50, 100, 200 Rate year 3: 0, 125, 150, 200	3	25	✓	U			✓
Tim Shea 2	4	Rate: 0, 400	3	15		U		✓	
Wages	2	Rate: 0, 200	4	22		AS		✓	
Wattle	5	Rate: 0, 200	3	15		AS		✓	

[a] Rate unit is kg N ha^{-1}.

[b] N forms were AS: ammonium sulphate, DAP: diammonium phosphate, U: urea.

2.4. Statistical analyses

All data were analysed by ANOVA methods using standard statistical software and the $P = 0.05$ significance level, unless otherwise indicated. Covariates were included when available, e.g. initial tree size if treatments were not applied at planting. Quantitative variables were also analysed by linear or non-linear regression and only significant regressions reported ($P < 0.05$).

3. Results

3.1. N status indicators

3.1.1. N budgeting and soil total N, P and C

The N budgeting approach, i.e. comparing N supply (mineralisation) with potential N demand (maximum uptake), correctly predicted that (1) trees at the Potters and Basils sites were not N deficient between ages 1 and 4 years; (2) those at Tim Shea became N deficient in year 3; (3) those at Nunamara were marginal in year 2 and N deficient in years 3–4; and (4) those at Boulder were N deficient throughout this age range (Fig. 1). However, this analysis was based on several assumptions and intensive measurements.

Nitrogen-deficiency during the first 2 years after planting occurred at sites where concentrations of total N in surface soil (0–10 cm depth) were <4 mg g^{-1}, whereas a concentration of 5.1 mg g^{-1} total N was associated with N deficiency being delayed until 4 years of age (Fig. 2). The relationship between N deficiency and total P was not well defined, but total $P < 1$ mg g^{-1} indicated that N deficiency occurred during the first 2 years after planting.

In another study, we examined the usefulness of total N, P and C for predicting the growth response (minimum of 2-year response period measured) to a single application of 200 kg N ha^{-1} in 0- to 10-year-old plantations at 14 sites. Soil total N explained 64% of the variation, total P 71% and organic C 26% (Fig. 3). Responses of 10–30 m^3 ha^{-1} could be expected for soil total $N < 3$ mg g^{-1} or total $P < 1$ mg g^{-1}. The likelihood of no response increased at higher concentrations, and there was no evidence of responses at concentrations in excess of 6 mg g^{-1} total N and 3 mg g^{-1} total P.

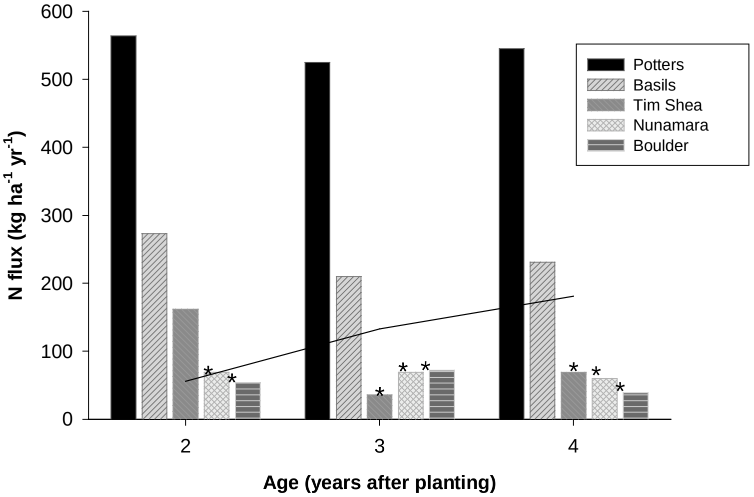

Fig. 1. Comparison of estimated rates of N mineralisation (bars) and uptake (line) for five sites where soil N fluxes were measured in the surface soil (0–10 cm) of unfertilised plots of N fertiliser experiments. This analysis assumes N mineralisation for the whole profile is three times that measured in the surface 10 cm (Moroni, 2001), and that potential uptake of a high-productivity *E. nitens* plantation is consistent with that estimated for above-ground components for high-productivity *E. nitens* (Moroni, 2001) and *E. globulus* (Periera et al., 1996), and that below-ground N is 0.4 of that above-ground (Misra et al., 1998b). Mineralisation in year 4 at Potters was estimated as the average of that measured in the two previous years. Asterisks indicate that N deficiency was indicated by a significant, positive growth response to N fertiliser.

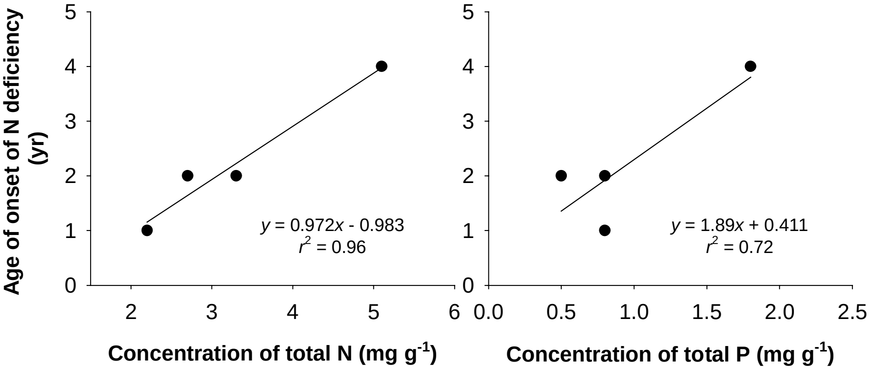

Fig. 2. Relationships between concentrations of total N and P in surface soil (0–10 cm depth) and age of onset of N deficiency in four *E. nitens* plantations (Boulder, Nunamara, Rabbits, and Tim Shea). A fifth site, Basils, with a similar experimental design and with higher concentrations of total N and P did not respond to N fertiliser.

3.1.2. Soil mineral N

At Tim Shea and Nunamara, soil solution concentrations of NH_4 decreased markedly below suggested critical levels (0.05 mM) within a year of the onset of N deficiency (Fig. 4). A similar decrease also occurred for NO_3 at Tim Shea, but the decrease in NO_3 concentrations at Nunamara was not as marked. Hence, the decrease in concentrations of soil solution NH_4 and NO_3 did not precisely coincide with the onset of N deficiency.

Results from the one-time sampling of nine sites indicated that the N sufficient sites had high average concentrations of KCl-extractable NO_3 relative to the N deficient sites, but variability was high, and these classes of sites were also not distinguishable using KCl-extractable NH_4 (Fig. 5). In contrast, concentrations of both soil solution NH_4 and NO_3 were significantly higher at the N sufficient sites than at the N deficient sites.

3.2. Fertiliser management options

3.2.1. Form and placement of N

At Nunamara, a growth response to urea application occurred although concentrations of NO_3 in soil solution were relatively high (>0.1 mM; Fig. 4), suggesting soil NO_3 could not be fully utilised by the trees. However, trees responded to both NH_4 and NO_3 forms of N fertiliser at Allenbush where concentrations of both NH_4 and NO_3 were very low (Fig. 6). Although growth responses to calcium nitrate and ammonium nitrate were not significantly different to the responses to ammonium sulphate or urea, trees responded significantly better to urea than to ammonium sulphate.

Urea application at Allensbush was not significantly more effective when spread within about 1 m radius of the stem than when broadcast over the entire plot area (Fig. 7).

3.2.2. Rate and timing of application

In two experiments, the response to 200 g diammonium phosphate was maximised when applied within 3 months of planting in mid-spring (Fig. 8). On sites that were deficient in N at age 1–2 years, and where up to 100 kg N ha^{-1} was applied at planting and up to 200 kg N ha^{-1} per year at later ages, there was an approximately linear relationship between cumulative rate of N applied (up to about 500 kg ha^{-1}) and subsequent tree growth (Fig. 9). However, at a site fertilised only once at 6 years of age, the response was asymptotic with a plateau at about 200 kg N ha^{-1} (Fig. 7).

3.2.3. Duration of response

Where growth responses occurred, growth rates increased markedly for 2–3 years and less markedly for a further 2 years (e.g. Fig. 10). Re-applications within this time-frame promoted a more sustained response in growth rate, such that the growth response was positively related to the frequency of application (Fig. 11) and cumulative N rate (Fig. 9).

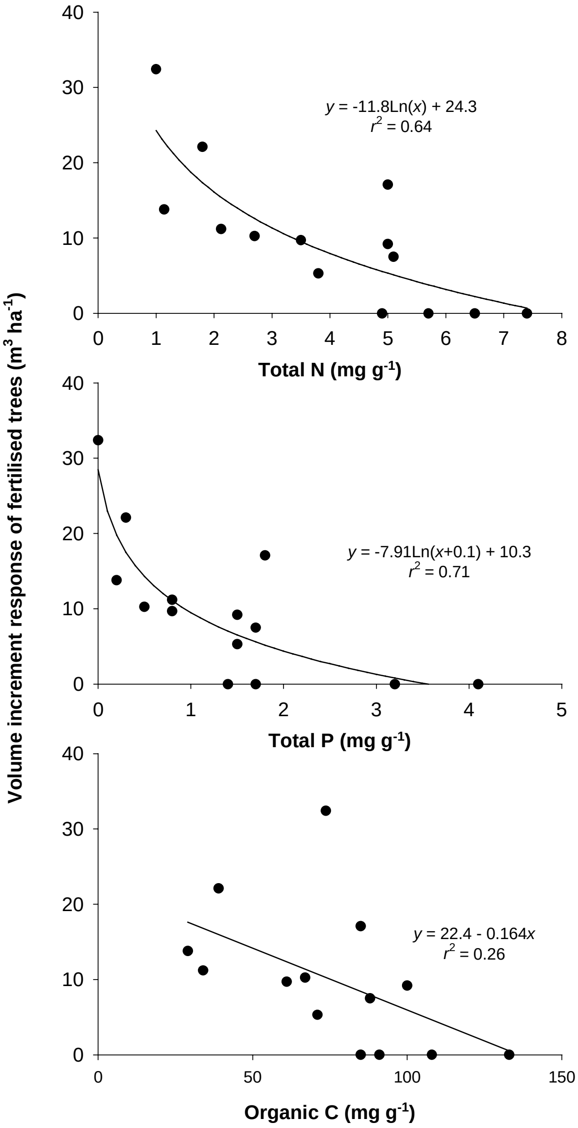

Fig. 3. Relationships between concentrations of total N, P and C in surface soil (0–10 cm depth) and maximum response in volume increment observed in trees receiving 200 kg N ha^{-1}. Data are from 14 *E. nitens* plantations aged 0–10 years, and growth responses were measured over a minimum of 2 years after fertiliser application.

4. Discussion

4.1. N status indicators

4.1.1. N mineralisation

Despite inaccuracies in estimating NNM in the total profile, potential nitrogen uptake and the amount of mineral N leached beyond the root zone, the crude budget based on a comparison of maximum N supply and demand provided an accurate indication of the sites and ages of N deficiency where these measurements were made (Fig. 1). We accept this result as validation of the N budgeting approach, but we also recognise that such measurements are not possible outside a research context. It follows that if a budgeting approach is to be useful, reliable, simple methods of estimating NNM and potential N uptake are needed.

Based on data from the five sites in this study where N fluxes were measured, soil total P was a better predictor of NNM ($r^2 = 0.9$) than total N ($r^2 = 0.7$) (Moroni, personal communication), but the usefulness of these relationships is limited because they were dominated by the two high-P sites (Potters and Basils), the low total number of sites, and the unclear causal link between total P and NNM. Alternatively, combining Tasmanian data with measurements from many other Australian sites enabled predictions of NNM from relatively simple measurements (Paul et al., 2002). However, in both approaches, the confidence intervals of prediction of the relationships (about 60 kg N ha^{-1}) were relatively large compared to the potential rate of N uptake (100 kg N ha^{-1} by age 2 years; Fig. 1) and other sinks for N in forest ecosystems (Moroni, 2001). Although such relationships should be useful for generalising N supply and demand in Australian forest plantations, uncertainties associated with their predictions compel caution when using them as diagnostic tools in a site-specific, N-budgeting approach.

4.1.2. Onset of N deficiency

Experience in South Africa led to an interest in organic C, rather than soil N or P, as a predictor of N deficiency in *E. grandis* plantations such that concentrations of organic C < 50 mg g^{-1} indicated an intermediate to high likelihood of a response to N fertiliser (Noble and Herbert, 1990). This observation was broadly consistent with our results for *E. nitens* (Fig. 3), and the optimum rate of N to apply was inversely proportional to the concentration of C. In a review of the nutritional management of eucalypt plantations in several regions of the world (Attiwill and Adams, 1996), soil organic C was the only soil analysis suggested as an indicator of N deficiency (Barros and Novais, 1996), which reflects the difficulty

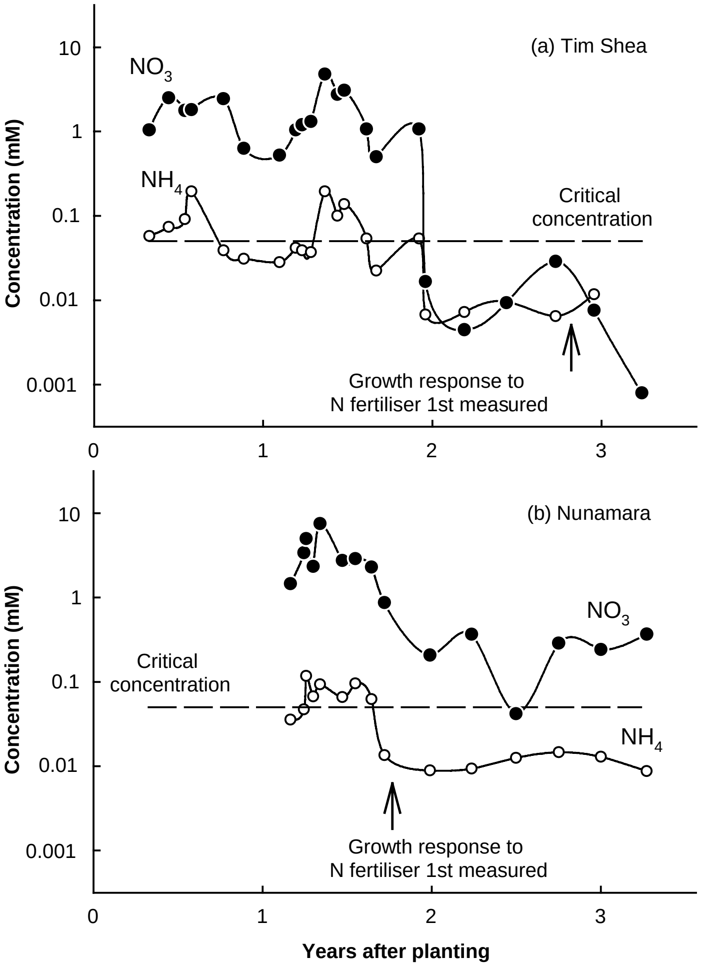

Fig. 4. Concentrations of NH_4 and NO_3 in soil solution of unfertilized treatments at two sites (top Tim Shea, bottom Nunamara) in relation to the theoretical critical concentration (0.05 mM regardless of N form, Sands and Smethurst, 1995) and the age when a growth response to N fertilisation was first measured.

in using soil analyses for N management. Our result that total N was a better indicator of N deficiency than organic C indicates that total N should not be dismissed as a potentially useful indicator in future studies of this type. Total P should also be considered in such studies, because it was correlated with rates of NNM (Moroni, personal communication) and was also of use as a predictor of N deficiency (Figs. 2 and 3). However, the casual links between total P and N deficiency need further elucidation.

Several factors may be important in explaining the discrepancies between the timing of the onset of N deficiency and concentrations in soil solution of NH_4 and NO_3 (Fig. 4). Firstly, the critical concentration suggested is more appropriately compared to that which can be maintained at a typical root surface, rather that in the bulk soil solution as reported here. Secondly, soil water content will play a major role in determining those concentrations, because it directly affects mass flow and diffusion processes that deliver nutrients to root surfaces. It is noteworthy that this error would have been greatest at the drier site, i.e. Nunamara, where the discrepancy in predicting a response was greatest. Thirdly, eucalypts are known to prefer

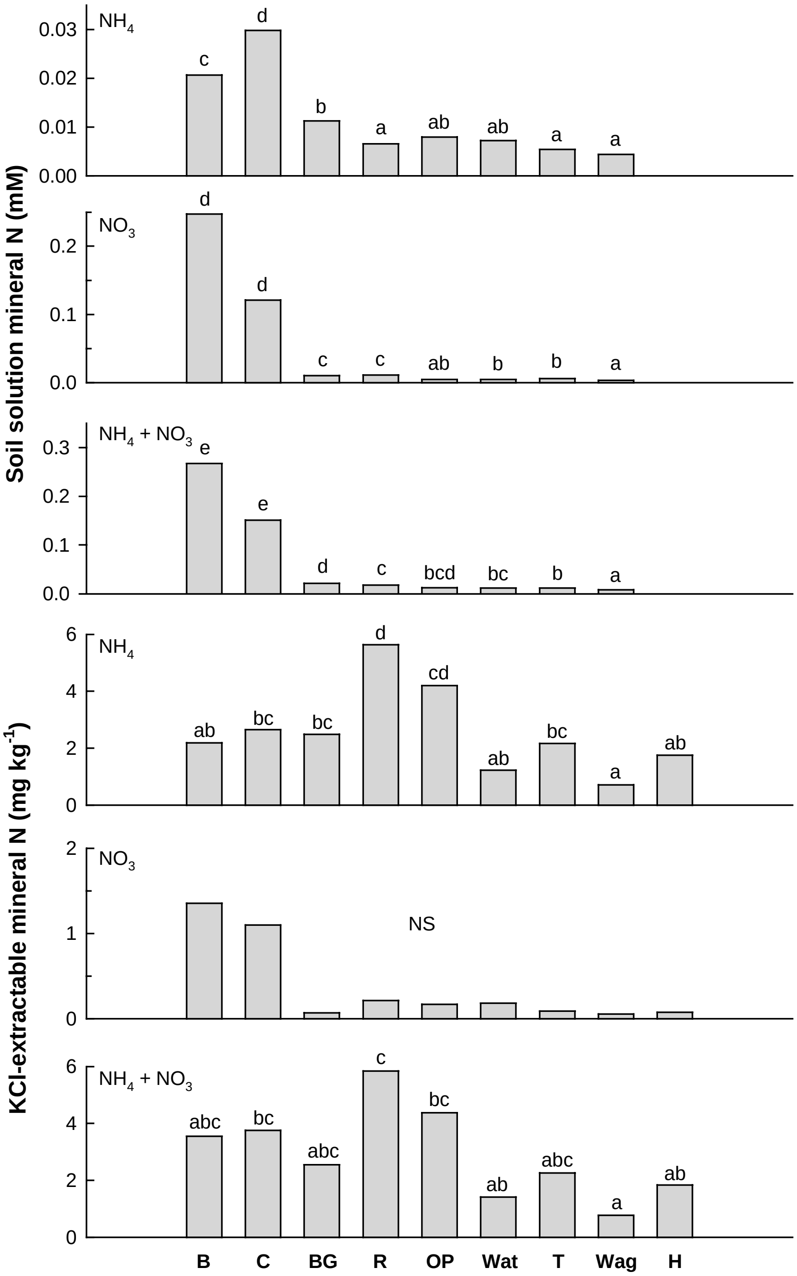

Fig. 5. Concentrations of NH_4 and NO_3 in soil solution and KCl extracts at nine sites, including two sites where trees did not respond to N fertiliser (B: Basalt, and C: Chromys) and seven sites where trees did respond to N fertiliser (BG: Blue Gum, R: Rabbits, OP: Old Park, Wat: Wattle, T: Talbots, Wag: Wages, and H: Hurds). Soil solution data were not available for Hurds. Bars with common letters within a graph are not significantly different ($P = 0.05$), based on an LSD for transformed data. NS indicates no significant site effect.

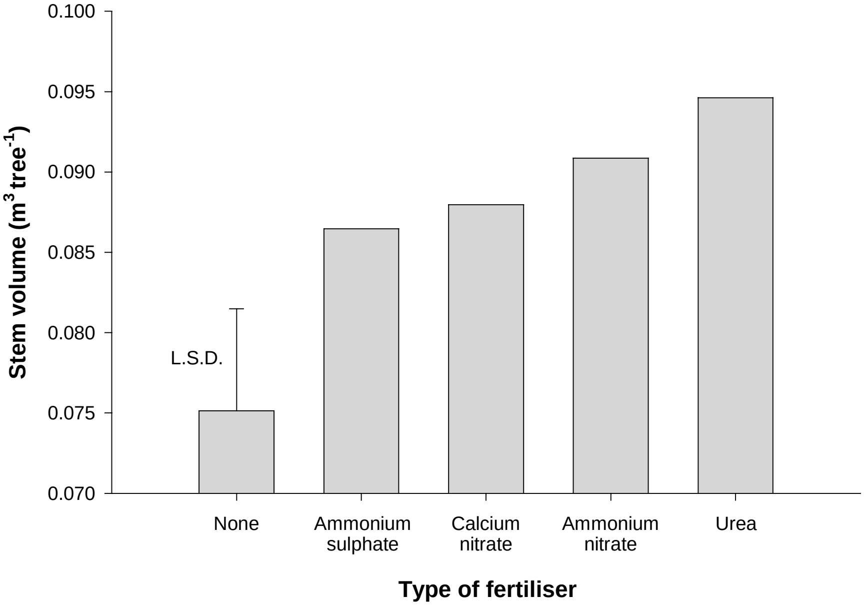

Fig. 6. Average stem volume per tree at 7 years of age at Allensbush 4 years after receiving no fertiliser or alternative forms of N fertiliser at a rate of 200 kg N ha^{-1}. LSD: least significant difference ($P = 0.05$).

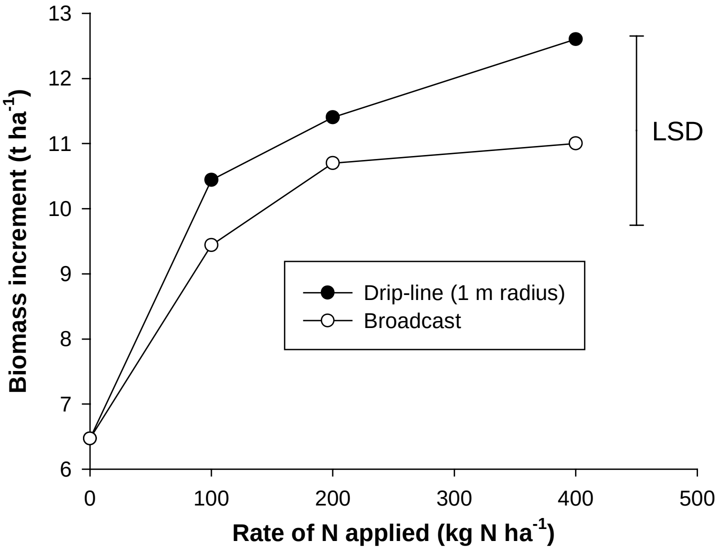

Fig. 7. Biomass increment at Allenbush between 3 and 5 years of age in relation to the rate of N fertilisation and placement. LSD: least significant difference ($P = 0.05$) based on a two-way ANOVA of replicates and groups of rate by placement combinations. Regression analysis also indicated a significant trend with rate, but no difference between placement methods.

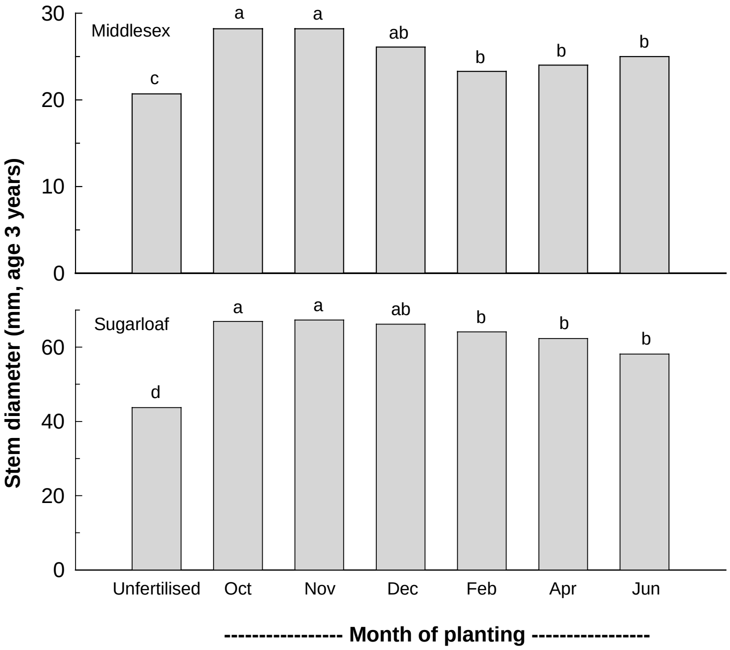

Fig. 8. Stem diameter of unfertilised, 3-year-old *E. nitens* at two sites in relation to those fertilised with diammonium phosphate immediately after planting (October) or on five alternative occasions during the subsequent 10 months. Bars with common letters within a graph are not significantly different ($P = 0.05$).

ammonium, but they can also utilise NO_3 (Shedley et al., 1993; Barros and Novais, 1996; Garnett et al., 2001). These complexities will need to be resolved if the precise timing of N deficiency is to be better predicted from concentrations of NH_4 and NO_3.

4.1.3. Current N status

Results indicate that surface soil (0–10 cm) total N, total P, organic C, soil solution NH_4 and NO_3, and to a lesser extent soil solution and KCl-extractable NO_3, warrant use and further testing as indicators of N

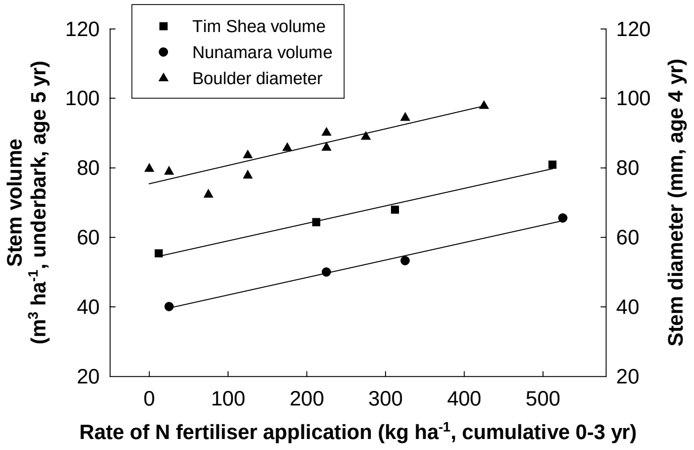

Fig. 9. Stem volume at age 5 years or diameter at age 4 years of three *E. nitens* plantations in relation to the cumulative rate of N fertiliser between planting and 3 years of age.

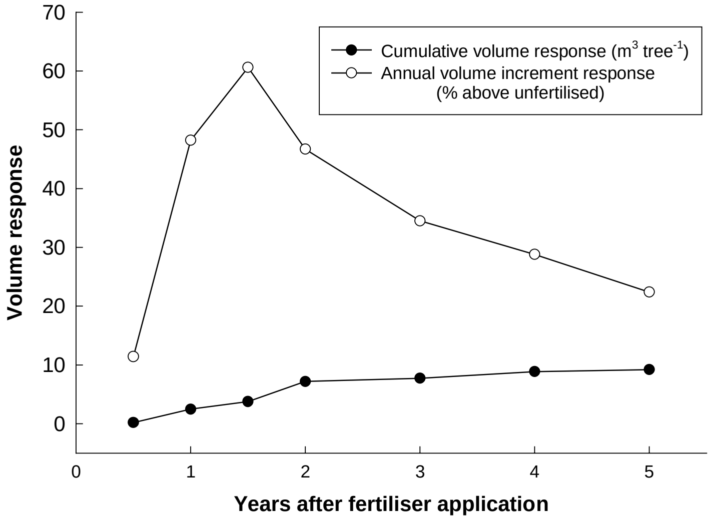

Fig. 10. Absolute and percentage response of fertilised trees at Old Park in relation to years after fertilisation.

deficient *E. nitens* plantations in Tasmania. Based on the relationships in Figs. 3–5, we suggest critical levels for these analyses of 6 mg g^{-1} total N, 3 mg g^{-1} total P, 80 mg g^{-1} C, 0.05 mM soil solution NH_4, 0.1 mM soil solution NO_3 and 1 mg kg^{-1} KCl-extractable NO_3, with lower concentrations indicating that N deficiency is likely. These critical concentrations for soil solution NH_4 and NO_3 are an improvement on, but generally consistent with, the earlier tentative critical values suggested by Sands and Smethurst (1995), which was a theoretical prediction and not specific for N form. Users should have reasonable confidence in applying these critical concentrations to weed-free, *E. nitens* plantations established on ex-forest sites in Tasmania, and although these criteria will be of some use in other circumstances, we caution against extrapolating these critical concentrations too precisely without confirmatory data.

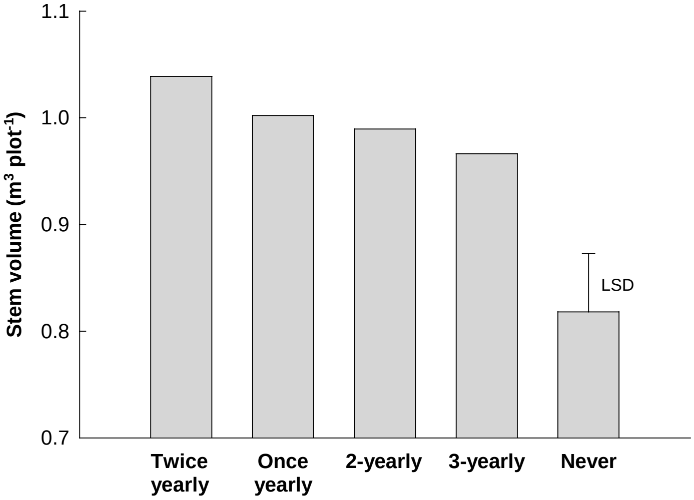

Fig. 11. Effect of frequency of fertiliser application (at a rate of 200 kg ha^{-1} per application) on stem volume at Allensbush at 7 years of age, i.e. 3 years after fertiliser treatments commenced. LSD: least significant difference ($P = 0.05$). Plot size was about 0.08 ha.

Foliar analysis or visual symptoms have been suggested as potentially useful in diagnosing nutrient deficiencies in eucalypt plantations (Knight and Nicholas, 1996; Dell et al., 2001). Diameter growth rate of 26 *E. nitens* plantations was related to foliar N:P ratio by an envelope curve that suggested the highest potential growth rates could be achieved only if this ratio was 15–16 (Judd, 1996). This result was consistent with that found for several other eucalypt species in fertiliser experiments, i.e. lower ratios indicated N deficiency and higher ratios P deficiency (Cromer et al., 1981). Foliar analyses at our sites, however, did not support the generalised use of foliar N or N:P ratios as indicators of N deficiency in *E. nitens* (data not presented) without further development and more rigorous justification of critical concentrations or ratios. Likewise, visual symptoms of N deficiency were not apparent at the leaf level at our sites; the only consistent visual symptom was an early loss of lower leaves leading to low values of leaf area index (LAI) (Smethurst et al., 2003). Assessment of LAI by the visual method of Cherry et al. (2002) is currently being included in some routine inventory programs.

4.2. *Fertiliser management options*

4.2.1. *Form of N*

Eucalyptus nitens, *E. globulus* and *E. alba* preferred NH_4 to NO_3 in hydroponic studies (Shedley et al., 1993; Barros and Novais, 1996; Garnett et al., 2001), but under field conditions we found these two forms of N approximately equally effective in enhancing the growth of *E. nitens* (Fig. 6). This result suggests some flexibility in choosing the form of N fertiliser, but urea or other NH_4-based fertilisers should still be preferred to NO_3 sources, because urea (i) is the cheapest form of N; (ii) it has the least propensity to produce NO_3 and associated leaching losses; and (iii) there is a low risk of volatilisation in the cool, moist Tasmanian climate. Our data suggest there might also be an advantage in using urea over ammonium sulphate, but this result needs confirmation and the mechanism responsible needs to be defined.

4.2.2. *Placement*

Whilst broadcasting fertiliser from the air is commonly the cheapest method of applying N, fertiliser efficacy could be low if root systems do not extend fully between the trees. For this reason, localised placement of a relatively low rate of fertiliser is widely used during the first few months after planting in most eucalypt plantations (e.g. Schönau and Herbert, 1989; Cromer, 1996; Knight and Nicholas, 1996). Though broadcast applications have been encouraged to maximise fertiliser-root contact and minimise N leaching, the stage at which one should switch from localised to broadcast applications is not clear and the importance of localised placement has not been tested in older plantations. An alternative hypothesis is that the rate of N uptake per unit root is maximised at the high concentrations (Garnett et al., 2001) promoted by localised placement, and the relative importance of N immobilisation by biotic and abiotic processes is reduced at high concentrations. We found no significant benefit in restricting fertiliser placement at a low-productivity, 6-year-old site (Allensbush 1; Fig. 7) where the canopies had not closed (LAI 1–2, Smethurst et al., 2003). Hence, even in this low-productivity plantation, localised application did not improve fertiliser efficacy.

4.2.3. *Rate and timing of application*

It is common to apply a small amount of fertiliser containing N and P close to the plant soon after planting, but there are few data on the importance of the timing of this application. At two sites, we found that the response to fertiliser was maximised if fertiliser was applied within 3 months of planting, which was similar to results for *E. saligna* at two sites in New Zealand (Knight and Nicholas, 1996). Growth at these sites was probably temperature-driven and maximal during mid summer. In warmer, drier climates where growth can be suppressed during summer due to low water availability, growth response of eucalypts and pines is reduced if fertiliser application is delayed for more than 1 month (Woods, 1976; Herbert, 1996). These results underscore the need, even during the first year of growth, to synchronise nutrient supply from fertilisers with nutrient demand by the plant.

On another Tasmanian site where N deficiency developed after 2 years of age and higher rates of N were examined, the response to N rate was sigmoidal (Cromer et al., 2002). At Allensbush, we also found a sigmoidal (unpublished data) or asymptotic response (Fig. 7). However, at none of these sites did results suggest a significant advantage in applying more than 200 kg N ha^{-1} in any single application.

4.2.4. Duration of response

Soil N availability was increased for only 1–2 years by a single application of N fertiliser (Smethurst et al., 2001a), but growth responses continued for a longer period. This observation suggests that, through retranslocation, additional N uptake due to fertilisation remains partially effective at maintaining high LAI (Smethurst et al., 2003) or photosynthetic efficiency for several annual cycles of crown development. Repeated applications of fertiliser, which also increase the total amount of N applied, appeared to promote a more sustained growth response to N fertiliser (Fig. 11). Hence, maximisation of growth on ex-forest sites will require a spot application of diammonium phosphate at planting and more than one application of 100–200 kg N ha^{-1} during the following 6 years.

4.3. Economics of N fertilisation and current trends in usage

The economic benefits of N fertilisation depend on several factors, i.e. the degree of N deficiency and hence additional wood yield, the cost of and age at fertilisation, the value of wood products and harvest ages, and a number of organisation-specific factors, such as estate-wide considerations of total wood availability, cost of capital, and government taxation or subsidisation. Without considering organisation-specific factors, analyses suggest that, under current Tasmanian conditions, N fertilisation for pulpwood production will be profitable on-sites where the rotation-length yield response will be relatively high, i.e. >13 m^3 per 100 kg N applied, and the practice would become profitable on less responsive sites if there were just small, favourable movements in several economic criteria, e.g. value of wood, cost of fertiliser, and opportunity costs (Smethurst et al., 2001b). Only one of the 14 sites in Fig. 3 had a yield response in excess of 13 m^3 per 100 kg N applied, which suggests few ex-forest, pulpwood-only sites could be economically N fertilised without favourable organisation-specific considerations.

Eucalypt plantations in Tasmania, are currently established on two classes of land. Those established on land converted from native forest or a plantation of *P. radiata*, i.e. ex-forest sites, are generally N and P deficient (Attiwill and Leeper, 1987; Bennett et al., 1996; Cromer, 1996; see also Fig. 3). In contrast, plantations established on land converted from pasture are generally not deficient in N or P for the first rotation of eucalypts, but deficiencies of N are likely to develop in future rotations (O'Connell and Rance, 1999). Usage of N fertiliser on ex-forest sites is increasing; some growers who produce solid wood as well as pulpwood plan to apply cumulative amounts of 500–700 kg N ha^{-1} during each rotation, but the current total area in this regime in Tasmania is <5000 ha. Currently, little effort is made to discriminate operationally between high and low response sites, which implies that the overall benefits of N fertilisation are expected to be widely applicable. In contrast to ex-forest sites, many ex-pasture sites have quite high N availability and a low likelihood of an economic response to N fertiliser during the first rotation. On this class of sites, lower cumulative rates of N fertilisation are used than on the ex-forest sites.

4.4. Environmental considerations

High rates of nitrification, and leaching below 10 cm depth, occurred at our study sites, all except one of which received more than 1000 mm per year rainfall. Concentrations of NO_3 in subsoils were high at the ex-pasture site (Potters; 2.8 mM at 75 cm depth; Moroni, 2001) as noted in studies of some agricultural soils in the region (Sparrow and Chapman, 2003), and after clearfelling *E. regnans* forest (Weston and Attiwill, 1996). Potential NO_3 entry to groundwater represents an environmental risk that warrants assessment, but the risk from unfertilised forests is likely to be very low. Conversely, over-use of N fertilisation in forestry has the potential to adversely affect the environment both off- and on-site. Off-site effects have been studied because of the potential for N concentrations to exceed water quality standards (Binkley et al., 1999). The research base included a wide range of ecosystems and rates, forms, and timings of N fertilisation, and concluded that there was a very low likelihood of a significant detrimental effect of N fertilisation if the fertiliser was applied in an NH_4 form (e.g. as urea or ammonium sulphate), especially if it was not directly applied to surface water, and if rates did not exceed 200 kg N ha^{-1}. Current practices generally fall within these constraints. Research is needed to determine the environmental risks associated with higher single and cumulative rates, even though the risk seems low for the next few decades.

Although the impact of frequent and high cumulative rates of N fertilisation in forestry have not been widely studied experimentally, a comparison with systems that have high inputs of N in Europe and North America suggest caution is warranted. Forests in some parts of Europe have received 54 kg N ha^{-1} per year from the atmosphere for several decades, i.e. about 1000 kg N ha^{-1} every 20 years (Wright and van Breeman, 1995). This rate of N input is similar to high N regimes currently being implemented in some eucalypt plantation systems. Systems with high N inputs will eventually start to leak NO_3 (Aber, 2002; Matson et al., 2002). Although we cannot accurately predict when this will occur, there is probably a low risk of N saturation occurring in most Tasmanian eucalypt plantations during the next few decades.

The main on-site concerns with high rates of N fertilisation are that soils will acidify with a concurrent increase in Al concentrations in soil solution, and deficiencies of base cations (K, Mg, and Ca). These deficiencies develop because (i) the rate of removal of base cations in biomass is increased (Judd, 1996); and (ii) base cation availability is reduced due to increased acidity and Al concentrations and NO_3 leaching that is accompanied by the movement of base cations lower down the profile or off-site. The latter is also exemplified by European and North American experience, where long-term, anthropogenic inputs of N and S have enhanced the leaching of base cations and led to deficiency symptoms of these nutrients in some forests (Wright and van Breeman, 1995; Magill et al., 1997). High N inputs also caused decreased base cation availability in Tasmanian surface soils (Mitchell and Smethurst, 2004). Although some research has been directed at this topic for other forest ecosystems, we still have a poor basis for predicting the onset of these deficiencies, their accurate diagnosis, and the impact on tree growth.

4.5. Summary

We draw the following conclusions from our research into N fertilisation of *E. nitens* plantations.

- Low N availability commonly limits the growth of *E. nitens* plantations on ex-forest sites in Tasmania, Australia.
- Potential deficiencies of N between planting and 10 years of age were indicated by N budgeting or the concentrations of soil NH_4, NO_3, total N and total P.
- Plantations on low-N sites experienced N-deficiency during the first few years of growth, but others experienced it later or not at all.
- Multiple applications of N will be needed to maximise growth on most ex-forest sites.
- Urea was the preferred form of N.
- The current profitability of N-fertilising pulpwood-only rotations to maximise growth is not obvious.
- Applications of N fertilisers as currently planned are unlikely to be a threat to water quality, but research is needed to determine the environmental risks associated with long-term and higher intensity uses.

Acknowledgements

We thank Norske Skog and Gunns for assistance in setting up and maintaining the experimental sites.

References

Aber, J.D., 2002. Nitrogen saturation in temperate forest ecosystems: current theory, remaining questions and recent advances. In: Horst, W.J., et al. (Eds.), Progress in Plant Nutrition: Plenary Lectures of the XIV International Plant Nutrition Colloquium. Kluwer Academic Publishers, Dordrecht, pp. 179–188.

Attiwill, P.M., Adams, M.A. (Eds.), 1996. Nutrition of Eucalypts. CSIRO, Collingwood, Australia, 440 pp.

Attiwill, P.M., Leeper, G.W., 1987. Forest Soils and Nutrient Cycles. Melbourne University Press, Carlton, Vic., Australia, 202 pp.

Barros, N.F., Novais, R.F., 1996. Eucalypt nutrition and fertiliser regimes in Brazil. In: Attiwill, P.M., Adams, M.A. (Eds.), Nutrition of Eucalypts. CSIRO, Australia, pp. 335–355.

Bennett, L.T., Weston, C.J., Judd, T.S., Attiwill, P.M., Whiteman, P.H., 1996. The effects of fertilisers on early growth and foliar nutrient concentrations of three plantation eucalypts on high quality sites in Gippsland, southeastern Australia. For. Ecol. Manage. 89, 213–226.

Binkley, D., Burnham, H., Allen, H.L., 1999. Water quality impacts of forest fertilisation with nitrogen and phosphorus. For. Ecol. Manage. 121, 191–213.

Cherry, M.L., MacFarlane, C., Smethurst, P., Beadle, C., 2002. Visual Guide to Leaf Area Index of Eucalypt Plantations.

Cooperative Research Centre for Sustainable Production Forestry, Hobart, Australia, 22 pp.

Cromer, R.N., Cameron, D., Cameron, J.N., Flinn, D.W., Neilsen, W.A., Raupach, M., Snowdon, P., Waring, H.D., 1981. Response of eucalypt species to fertiliser applied soon after planting at several sites. Aust. For. 44, 3–13.

Cromer, R.N., 1996. Silviculture of eucalypt plantations in Australia. In: Attiwill, P.M., Adams, M.A. (Eds.), Nutrition of Eucalypts. CSIRO, Australia, pp. 259–273.

Cromer, R.N., Cameron, D.M., Rance, S.J., Ryan, P.A., Brown, M., 1993. Response to nutrients in *Eucalyptus grandis*. 2. Nitrogen accumulation. For. Ecol. Manage. 62, 231–243.

Cromer, R.N., Turnbull, C.R.A., LaSala, A.V., Smethurst, P.J., Mitchell, A.D., 2002. *Eucalyptus* growth in relation to combined nitrogen and phosphorus fertiliser and soil chemistry in Tasmania. Aust. For. 65, 87–95.

Dell, B., Malajckzuk, N., Xu, D., Grove, T.S., 2001. Nutrient Disorders in Plantation Eucalypts, second ed. ACIAR Monograph No. 74, Canberra, 188 pp.

Garnett, T.P., Shabala, S.N., Smethurst, P.J., Newman, I.A., 2001. Simultaneous measurement of ammonium, nitrate and proton fluxes along the length of eucalypt roots. Plant Soil 236, 55–62.

Herbert, M.A., 1996. Fertilisers and eucalypt plantations in South Africa. In: Attiwill, P.M., Adams, M.A. (Eds.), Nutrition of Eucalypts. CSIRO, Australia, pp. 303–326.

Isbell, R., 1996. The Australian Soil Classification. CSIRO, Collingwood, Australia.

Judd, T.S., 1996. Simulated nutrient losses due to timber harvesting in highly productive eucalypt forests and plantations. In: Attiwill, P.M., Adams, M.A. (Eds.), Nutrition of Eucalypts. CSIRO, Australia, pp. 249–258.

Knight, P.J., Nicholas, I.D., 1996. Eucalypt nutrition: New Zealand experience. In: Attiwill, P.M., Adams, M.A. (Eds.), Nutrition of Eucalypts. CSIRO, Australia, pp. 275–302.

Magill, A.H., Aber, J.D., Hendricks, J.J., Bowden, R.D., Melillo, J.M., Steudler, P., 1997. Biogeochemical responses of forest ecosystems to simulated chronic nitrogen deposition. Ecol. Appl. 7, 402–415.

Matson, P., Lohse, K.A., Hall, S.J., 2002. The globalization of nitrogen deposition: consequences for terrestrial ecosystems. Ambio 31, 113–119.

Mitchell, A.D., Smethurst, P.J., 2004. Surface soil changes in base cation concentrations in fertilised hardwood and softwood plantations in Australia. For. Ecol. Manage. 191, 253–265.

Misra, R.K., Turnbull, C.R.A., Cromer, R.N., Gibbons, A.K., LaSala, A.V., 1998a. Below and above ground growth of *Eucalyptus nitens* in a young plantation. I. Biomass. For. Ecol. Manage. 106, 283–293.

Misra, R.K., Turnbull, C.R.A., Cromer, R.N., Gibbons, A.K., LaSala, A.V., Ballard, L.M., 1998b. Below and above ground growth of *Eucalyptus nitens* in a young plantation. II. Nitrogen and phosphorus. For. Ecol. Manage. 106, 295–306.

Moroni, M.T., 2001. Predicting N deficiency in *E. nitens* plantations. Ph.D. thesis, University of Tasmania, Hobart, Australia.

Moroni, M.T., Smethurst, P.J., Holz, G.K., 2002. Nitrogen fluxes in surface soils of young *Eucalyptus nitens* plantations in Tasmania. Aust. J. Soil Res. 40, 543–553.

Mummery, D., Battaglia, M., 2001. Applying PROMOD spatially across Tasmania with sensitivity analysis to screen for prospective *Eucalyptus globulus* plantation sites. For. Ecol. Manage. 140, 51–63.

Nambiar, E.K.S., 1995. Relationships between water, nutrients and productivity in Australian forests: application to wood production and quality. Plant Soil 168–169, 427–435.

Noble, A.D., Herbert, M.A., 1990. Influence of soil organic matter content on the responsiveness of *Eucalyptus grandis* to nitrogen fertiliser. S. Afr. For. J. 156, 23–27.

O'Connell, A.M., Rance, S.J., 1999. Predicting nitrogen supply in plantation eucalypt forests. Soil Biol. Biochem. 31, 1943–1951.

Paul, K.I., Polglase, P.J., O'Connell, A.M., Carlyle, J.C., Smethurst, P.J., Khanna, P.K., 2002. Soil nitrogen availability predictor (SNAP): a simple model for predicting mineralisation of nitrogen in forest soils. Aust. J. Soil Res. 40, 1011–1026.

Periera, J.S., Tomé, M., Madeira, M., Oliveira, A.C., Tomé, J., Almeida, H., 1996. Eucalypt plantations in Portugal. In: Attiwill, P.M., Adams, M.A. (Eds.), Nutrition of Eucalypts. CSIRO, Melbourne, pp. 371–387.

Sands, P.J., Smethurst, P.J., 1995. Modelling nitrogen uptake in Ingestad units using Michaelis–Menten kinetics. Aust. J. Plant Physiol. 22, 823–831.

Schönau, A.P.G., Herbert, M.A., 1989. Fertilizing eucalypts at plantation establishment. For. Ecol. Manage. 29, 221–244.

Shedley, E., Dell, B., Grove, T.S., 1993. Effects of inorganic nitrogen forms on growth of *Eucalyptus globulus* seedlings. In: Barrow, N.J. (Ed.), Plant Nutrition—From Genetic Engineering to Field Practice. Kluwer Academic Publishers, Dordrecht, pp. 595–598.

Smethurst, P.J., 2000. Soil solution and other soil analyses as indicators of nutrient supply: a review. For. Ecol. Manage. 138, 397–411.

Smethurst, P.J., Baillie, C., Cherry, M., Holz, G., 2003. Fertiliser effects on LAI and growth of four *Eucalyptus nitens* plantations. For. Ecol. Manage. 176, 531–542.

Smethurst, P.J., Herbert, A.M., Ballard, L.M., 2001a. Fertilisation effects on soil solution chemistry in three eucalypt plantations. Soil Sci. Soc. Am. J. 65, 795–804.

Smethurst, P.J., Jennings, S., Matysek, A., 2001b. Economics of nitrogen fertilisation of eucalypts for pulpwood. Aust. For. 64, 96–101.

Soil Survey Staff, 1990. Key to Soil Taxonomy, fourth ed. SSMS Technical Monograph No. 19, Blacksburg, Virginia.

Sparrow, L.A., Chapman, K.S.R., 2003. Effects of nitrogen fertiliser on potato (*Solanum tuberosum* L., cv. Russet Burbank) in Tasmania. II. Petiole and soil analysis. Aust. J. Exp. Agric. 43 (6), 631–641.

Wang, X.J., Smethurst, P.J., Herbert, A.M., 1996. Relationships between three measures of organic matter or carbon in soil of eucalypt plantations in Tasmania. Aust. J. Soil Res. 34, 545–553.

Wang, X.J., Smethurst, P.J., Holz, G.K., 1998. Nitrogen fluxes in surface soils of 1–2-year-old eucalypt plantations in Tasmania. Aust. J. Soil Res. 36, 17–29.

Weston, C.J., Attiwill, P.M., 1996. Clearfelling and burning effects on nitrogen mineralisation and leaching in soils of old-age *Eucalyptus regnans* forests. For. Ecol. Manage. 89, 13–24.

White, D.A., Beadle, C.L., Worledge, D., 1996. Leaf water relations of *Eucalyptus globulus* sp. *globulus* and *E. nitens*: seasonal, drought and species effects. Tree Physiol. 16, 469–476.

Woods, R.V., 1976. Early silviculture for upgrading productivity on marginal *Pinus radiata* sites in the south-eastern region of South Australia, Bulletin 24. Woods and Forests Department, South Australia.

Wright, R.F., van Breeman, N., 1995. The NITREX project: an introduction. For. Ecol. Manage. 71, 1–5.