Eucalyptus growth in relation to combined nitrogen and phosphorus fertiliser and soil chemistry in Tasmania

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Summary

Two experiments were established to determine the early nutrient requirements for plantations of *Eucalyptus globulus* (Nabowla site) and *E. nitens* (Westfield site) in Tasmania, Australia. Nitrogen (N) and phosphorus (P) were broadcast together, 2 and 26 months after planting, at cumulative rates of up to 1200 kg N ha^{-1} and 600 kg P ha^{-1}. Soil chemistry was characterised at each site in three profiles, and in all plots at the Westfield site. Nabowla has a relatively infertile, poorly structured soil, low in N and P, and receives about 800 mm of rainfall per annum. Growth was very poor without fertiliser, but trees responded rapidly and strongly to added NP. Stem volume increased directly with the rate of applied fertiliser, with no evidence that the response had peaked at the highest rate. Even at the highest rate of NP fertiliser, however, productivity was relatively low (mean annual increment about 15 m^3 ha^{-1} y^{-1}). Establishment of plantations on such sites is unlikely to be economically viable, with or without fertiliser, but fertile ex-pasture sites that are otherwise similar should be considered. Westfield has a relatively fertile, well-structured soil, and receives 1400–1500 mm of rainfall per annum. Response to NP fertiliser was delayed at this site, with first responses measured 33 months after planting. The response in stem volume was sigmoidal in relation to fertiliser rate, with a plateau at an application rate of 400 kg N ha^{-1} and 200 kg P ha^{-1}. This rate of fertiliser is expected to increase mean annual increment from 20 (without fertiliser) to 25 m^3 ha^{-1} y^{-1}. Splitting applications of fertiliser at the highest rate did not alter the growth response.

Although high rates of N and P fertiliser may be required to maximise growth of eucalypt plantations in Tasmania on ex-forest sites, rates required during the first few years might be lower than those reported here if the timing and placement of fertiliser is optimised. Soil chemical analyses were indicative of N and P requirements, and about a third of the variation in growth across the Westfield site was accounted for by natural variability in initial concentrations of total P and exchangeable K in surface soil.

Keywords: nitrogen; phosphorus; fertilisers; plant nutrition; growth rate; soil chemistry; *Eucalyptus globulus*; *Eucalyptus nitens*; Tasmania; Australia

Introduction

The area of hardwood plantations in Australia has increased dramatically during the past decade and a significant portion of this expansion has been in Tasmania on sites that previously supported native forest. Compared with investment in softwood plantations, establishment of commercial hardwood plantations on a significant scale is a relatively new endeavour in Australia, and a sustained research effort is necessary to provide managers with the tools to ensure an optimum return on such investments. In particular, managers require guidance on fertiliser management over a range of soil types, climates and previous land uses.

In southern Australia, species in the 'southern blue gum' group of the genus *Eucalyptus* (sub-genus Symphyomyrtus, section Maidenaria) have become important plantation crops because of their rapid early growth and valuable wood properties. The two most important of these species are *Eucalyptus globulus* Labill. (subsp. *globulus*) and the more frost-tolerant *Eucalyptus nitens* (Deane and Maiden) Maiden. *E. nitens*, however, is not native to Tasmania and research on the potential of both species, particularly an examination of the limitations due to nutrients, started only about 20 y ago (Orme *et al.* 1992; Cromer 1996).

A number of studies in Tasmania have aimed to determine the response of *E. globulus*, *E. nitens* and other eucalypts to site preparation, fertilisers and weed control. For example, several eucalypt species (including *E. globulus* and *E. nitens*) plus several species from other genera were tested in a series of experiments established at four low-altitude sites (100–140 m) in north-eastern Tasmania between 1978 and 1980 (Orme *et al.* 1992). The sites were characterised by soils with shallow, impeding layers and very low fertility. Results after 8–10 y showed that *E. globulus* was generally the best of the eucalypt species tested and there was a substantial response to fertiliser applied at two years of age, but growth at all sites was poor. The authors concluded that such areas should not be used for the establishment of eucalypt plantations, but the particular site characteristics that would eliminate a potential site from consideration were not defined.

Table 1. Some climate and soil characteristics of the Westfield and Nabowla sites

Characteristic	Westfield	Nabowla
Rainfall (mm for 1994–95)	1470	810
Esoclim estimate (mm y^{-1})	1426	1016
Altitude (m)	430	100–240
Mean monthly temperature		
(min °C)	4	7
(max °C)	15	17
Australian Soil Classification (Isbell 1996)	Kurosol	Kurosol
US Soil Taxonomy (Soil Survey Staff 1990)	Paleustult	Paleustult
Great soil group (Nicolls and Dimmock 1965)	Yellow podzolic (gradational)	Yellow podzolic (duplex)
Parent material	Mudstone	Sandstone
pH[a]	5.0	5.2
E.C. (dS m^{-1})	0.08	0.04
Loss on ignition (%)	11.9	5.1
Organic carbon (%)	6.2	1.7
Total carbon	6.8	2.3
Total N (%)	0.58	0.08
C:N ratio	11	29
Total P (%)	0.121	0.012
Bray2 P modified (μg g^{-1})	21.9	1.9
Bulk density (g cm^{-3})	0.9	1.3

[a] Chemical analyses are for the surface horizons, i.e. A2-B1 (2–5 cm depth) at Westfield and A2 (0–17 cm depth) at Nabowla

Results from an experiment with *E. globulus* on a poor, low-rainfall (750 mm y^{-1}) site near Fingal in north-eastern Tasmania (Neilsen and Wilkinson 1990) showed that trees treated with a combination of nitrogen (368 kg ha^{-1}) and phosphorus (228 kg ha^{-1}) fertiliser produced four times more wood volume than did unfertilised trees at 12 y of age. Even with this moderate application of fertiliser, a resultant stem volume of 80 m^3 ha^{-1} at age 12 y is less than half the growth rate required for such plantations to be commercially viable (Gerrand *et al.* 1993).

An experiment to compare the growth of *E. nitens* and *E. delegatensis* on a high-altitude site (870 m), which contained competing *Poa* grass, was established in 1986 (Kube 1993). A combination of treatments that included scalping (to remove grass), ripping to 50 cm, chemical weed control and fertiliser, enabled *E. nitens* to survive satisfactorily, but growth was very slow (maximum 3.7 m in height after 5 y), demonstrating that sites at such high altitudes are not appropriate for commercial plantations. By comparison, *E. delegatensis* with the same treatments had largely failed and the species is no longer used for plantation establishment in Tasmania.

A series of experiments established in 1983 compared the growth of *E. globulus* and *E. nitens* across four sites in southern Tasmania at different altitudes from 60 to 650 m (Beadle *et al.* 1996). The results highlighted the fact that good growth rates (mean annual increments exceeding 20 m^3 ha^{-1} y^{-1}) could be obtained with both species on relatively fertile sites that also received fertiliser, and where annual rainfall exceeded 1000 mm.

An experiment was established in 1989 on a yellow podzolic soil in southern Tasmania to examine the interaction between fertiliser application to *E. nitens* and the method of clearing (Turnbull *et al.* 1997). Significant responses were observed after an application of 300 kg N ha^{-1}, compared with 100 kg N ha^{-1}, but not until the third year after planting. As no fertiliser was applied at the lower level of treatment in the first year, compared with 100 kg N ha^{-1} in the higher level, it was concluded that mineralisation of native organic matter initially supplied sufficient N for seedlings in both treatments. Studies on other 'wet' forest sites in Tasmania have also indicated that the rate of N mineralisation during the first year or two after clearing provides adequate N for the requirements of eucalypt plantations on many sites (Wang *et al.* 1998; Smethurst *et al.* 2001a; Moroni *et al.* 2002).

The nutrient requirements of a plantation cannot be considered in isolation from other environmental factors. A method for assessing site productivity and land suitability for eucalypt plantations in Tasmania was developed by Laffan (1994) based on the principles of land evaluation of the Food and Agriculture Organization (1984). The method included an assessment of nutrient availability (total soil phosphorus and organic carbon) and nutrient retention (cation exchange capacity, field texture and native vegetation type). This approach provided a useful start to the evaluation of factors that affect productivity at various sites, but it was found to be both conservative and biased (Osler *et al.* 1996). A more sophisticated approach has been based on an understanding of the processes that drive photosynthesis, water relations and growth in eucalypt species (Battaglia and Sands 1997). In this context, the benefits of applying fertiliser to soils that lack adequate nutrients can be seen as accelerating the development of the canopy to maximise interception of radiation and ensure early capture of the site. In the Tasmanian environment, canopy closure in eucalypt plantations occurs at age 3–4 y provided water and nutrients are not limiting (Beadle and Mummery 1990).

Against this background, the current study contributes further understanding of the growth of eucalypts on different sites, and to applications of fertiliser. It aims to (1) determine the growth response of *E. nitens* and *E. globulus* at two ex-forest sites in response to N and P fertiliser at rates higher than those previously tested, and (2) to determine the extent to which growth was related to soil chemistry.

Table 2. Soil profile descriptions of the Westfield and Nabowla sites

Westfield	Nabowla
A1 (0–2 cm, commonly absent): Very dark gray clay-loam, fine weak crumb structure, abrupt boundary, often absent	A2 (0–17 cm, A1 absent): Light yellowish brown, weakly structured clay-loam, 50–90% coarse fragments, abrupt boundary
A2-B1 (2–5 cm): Light brownish gray clay-loam to light medium clay, weak structure, abrupt boundary (almost bleached to quite dull)	B1 (17–37 cm): Vary pale brown medium clay, 10–20% yellowish brown mottles, 2–10% coarse fragments, diffuse boundary
B21 (5–40 cm): Yellowish brown medium to medium-heavy clay, 10–20% distinct yellow mottles, 2–5 mm angular blocky structure, 0–20% coarse fragments, diffuse boundary	B2 (37–78 cm): Light yellowish brown medium clay, 10–20% very pale brown mottles, <2% coarse fragments, diffuse boundary
B22 (40–70 cm): Yellowish brown light medium to medium clay, 10–20% fine red and yellow mottles, moderate structure, diffuse boundary	BC (78–100 cm): Yellowish brown light clay, 20–50% light brownish gray mottles, 2–10% coarse fragments
B3 (70–90 cm): As above but with 50% coarse fragments of mudstone	

Materials and methods

Site descriptions and establishment

Two sites of contrasting climate and soils were chosen for the experiments, with *E. globulus* planted at a dry, lower-altitude site, and *E. nitens* at a site with higher rainfall and slightly higher altitude (Tables 1 and 2).

The experiment with *E. globulus* was established at Nabowla on land owned by Gunns (previously Boral Timber) in north-eastern Tasmania (41°07'S, 147°23'E) at a mean altitude of 170 m a.s.l., with moderate to steep slopes and a generally northerly aspect. The soil had high bulk density, poor physical properties and was relatively infertile, with low concentrations of organic carbon, total N and total P (Table 1). The original forest was of low site quality with an overstorey of *E. obliqua* L'Herit. and *E. amygdalina* Labill., and was clearfelled in 1989. The site was then ripped, mounded and planted with *E. globulus*, but the plantation failed and was cleared for the current study in 1991–92. Stumps were removed from within the trial area and the site was mounded along the contour in conjunction with deep ripping at intervals of 3.5 m. Seedlings were raised in paper pots using improved seed and planted in October 1992 at a nominal spacing of 3.5 m between and 2 m within rows (1430 stems ha^{-1}). Actual planting density was measured as 1250 stems ha^{-1} and a small number of dead seedlings were replaced in November 1992.

Mean monthly temperatures recorded by an automatic weather station for a twelve-month period in 1994–95 were 7.3ºC minimum and 16.5ºC maximum, with a total annual rainfall of 810 mm (compared with an estimated average of 1016 mm y^{-1}, Table 1).

The experiment with *E. nitens* was established at Westfield, on crown land managed by Norske Skog (previously Fletcher Challenge Forests and ANM Forest Management) in southern Tasmania (42º39'S, 146º28'E). Altitude of the site was 430 m a.s.l., with a slope of 4–12% and the aspect faced from south-west to south-east. The soil had relatively good structure and was moderately fertile with high levels of organic carbon, total N and total P (Table 1). The site was originally occupied by mature forest of *E. regnans* F.Muell. (mean dominant height >55 m), which was clearfelled and logged in 1968. The slash was burned and the site planted to *Pinus radiata* D.Don in 1969; the stand was clearfelled in 1991–92 (age 22 y). Slash from the *P. radiata* crop was windrowed; planting rows in the bays were ripped to a nominal depth of 70 cm and stumps were left *in situ*. Planting strips 1.5 m wide were cultivated and mounded simultaneously with a heavy off-set disc plough. Seedlings were raised in paper pots from seed orchard seed and planted in October 1992. Nominal spacing was 2 m within and 3.5 m between rows (1430 stems ha^{-1}), but the actual density of planting was 1270 stems ha^{-1}. A small number of dead seedlings were replaced in November 1992.

The climate of the area is cool temperate with appreciable rainfall in both summer and winter (Dick 1975). Mean monthly temperatures recorded over a twelve-month period in 1994–95 by an automatic weather station were 4ºC (minimum) and 15ºC (maximum). Total annual rainfall during the same period was 1470 mm (similar to the estimated mean of 1426 mm, Table 1).

Fertiliser treatments

The experimental design included six levels of nitrogen plus phosphorus (NP) fertiliser (Table 3) in randomised blocks, but due to constraints of space, treatment six was not included at Nabowla. At Westfield, five replicates of the six treatments (N0P0–N5P5) were established in plots containing 70 trees (7 rows × 10 trees, gross plot) with an internal measured plot of 30 trees (5 rows × 6 trees). At Nabowla, four replicates of five treatments (N0P0–N4P4) were established in the same plot configuration as for Westfield.

Fertiliser rates ranged from nil in the control (N0P0) up to a maximum of 600 kg ha^{-1} N with 300 kg ha^{-1} P, applied twice (at 2 and 26 months in T1–T5). The N5P5 treatment (Westfield only) received the same total quantity as N4P4 but applied in smaller amounts, four times per year over four years. The ratio of elemental N to P contained in the fertiliser was 2:1 for all treatments. Treatment dosages were calculated on a per-tree basis and this amount was uniformly broadcast by hand over the area occupied by each tree. Materials used were sulfate of ammonia (20.5% N) and triple superphosphate (20.0% P) supplied in granular form (West Lake Fertilisers Pty Ltd, Launceston). A circle, 30 cm in diameter, around each tree was left free of sulfate of ammonia to minimise the chance of damage to roots from high solute concentrations.

Table 3. Quantities (kg ha^{-1}) of elemental nitrogen (N) and phosphorus (P) fertiliser applied each year, plus the cumulative totals for each of the six treatments

Treatment	1992[a] N : P	1993 N : P	1994[b] N : P	1995 N : P	Cumulative total N : P
N0P0	0 : 0	0 : 0	0 : 0	0 : 0	0 : 0
N1P1	75 : 37.5	0 : 0	75 : 37.5	0 : 0	150 : 75
N2P2	150 : 75	0 : 0	150 : 75	0 : 0	300 : 150
N3P3	300 : 150	0 : 0	300 : 150	0 : 0	600 : 300
N4P4	600 : 300	0 : 0	600 : 300	0 : 0	1200 : 600
N5P5[c]	300 : 150	300 : 150	300 : 150	300 : 150	1200 : 600

[a] Applied in December 1992, 2 months after planting

[b] Applied in December 1994, 26 months after planting

[c] Applied four times per year at Westfield only, final application in February 1996

Protection

A weed control treatment of glyphosate (1.5 kg ha^{-1}) was applied over the whole area at Westfield before planting. After planting, a further weed control treatment was applied over the trees (covered individually) from knapsacks in January 1993 with a mixture of glyphosate (1.5 kg ha^{-1}) and simazine (6 kg ha^{-1}). A second post-planting spray was applied in 1994 using metsulf-methyl (12 g ha^{-1}) plus glyphosate (600 g ha^{-1}) from knapsacks within rows, and from a shrouded-boom sprayer between rows (metsulf-methyl at 30 g ha^{-1} and glyphosate at 600 g ha^{-1}). Weeds in the trial area were slashed by hand in 1995. A weed control treatment of simazine (5.4 kg ha^{-1}) was band-sprayed on cultivated strips at Nabowla before planting. After planting, weed control at Nabowla was the same as for Westfield in 1993 and the trial was mechanically slashed between the rows in 1995 and 1996. These weed control treatments kept weeds to <5% of ground cover for most of the study.

Tree measurements

After planting in October 1992, measurements were made in June or July of each year from 1993 to1997 at Nabowla and from 1993 to 1998 at Westfield (9, 20, 33, 44, 56 and 69 months). Heights (Ht) of all trees in plots were measured at from 9 to 44 months, but at 56 and 69 months the number of measured trees was reduced to five per plot (covering the range in size classes), and the height of remaining trees was estimated from a regression of diameter against height. At the time of the first measurement in 1993 (9 months) all trees were <1.3 m in height at both sites and diameter over bark was measured 15 cm above the ground (D_{15}). After trees reached >1.3 m in height, diameter over bark was measured at 1.3 m above ground (Dbh) by diameter tape. Trees less than 1.3 m in height were scored as missing for Dbh measurements. Over 40% of trees at Westfield developed multiple leaders, which increased in size along with the main stem. Where more than one leader was present below the Dbh measurement point (1.3 m), the Dbh of up to two additional leaders was measured in 1997 and 1998. Trees at Nabowla also developed multiple leaders, but the overall incidence was less than 20%.

Volume estimation

Data from a previous experiment planted in 1969 at Silver Creek in Victoria (Cromer *et al.* 1975; Cromer and Williams 1982) were used to develop an equation to estimate the volume of *E. globulus* trees. Individual-tree data including stem volume under bark were available for 119 trees aged 2, 4, 6 and 9.5 y; these were within the ranges 0.5–15.6 cm Dbh and 1.3–17.5 m height. The following equation was derived to estimate the stem volume of *E. globulus*: $V_{EG} = \exp(A + 1.667*\ln(Dbh) + 1.072*\ln(Ht))$ ($R^2 = 0.979$), where V_{EG} = volume (L, under bark), Dbh = diameter at breast height (m), Ht = tree height (m) and A is a factor for tree age where: $A = -2.523 - 0.0074*(\text{age in months}) + 0.00003*(\text{age in months})^2$. The standard error of observations was 0.218 and a factor of +1.049 was applied to correct for bias involved in taking logs on both sides of the equation, using the ratio estimator method described by Snowdon (1992).

A stand volume equation for *E. nitens* has been published by Candy (1997) and used to estimate stand volume of this species in Tasmania (Candy and Gerrand 1997):

$$V_{EN} = \exp(-0.4885 + 0.8252*\ln(MDH) + 0.9682*\ln(BA)),$$

where V_{EN} is the stand volume of *E. nitens* (m^3 ha^{-1}, under bark), MDH is the mean dominant stand height (mean of the tallest 50 trees ha^{-1}, m) and BA is stand basal area (m^2 ha^{-1}). In all, 228 plots with over 1000 measurements were included in the data set from which the equation was derived. Stand volume was also derived from an equation for individual trees in the same dataset (S. Candy, Forestry Tasmania and A. Corbould, Gunns; *pers. comm.*). This equation was derived from 148 trees ranging in size from 12.0 to 49.2 cm Dbh, and 9.4 to 32.3 m high. When the stand and single-tree equations were applied to the Westfield data, volume estimates based on the stand volume equation were slightly higher (0–5%) than those from the single-tree equation. As the single-tree volume equation provided the more conservative estimate, results presented here were derived from the unpublished single-tree equation. Trees at Westfield were too small to apply the single-tree equation for *E. nitens* until they had reached four years of age. As the equation developed for *E. globulus* covered smaller size classes, this was applied to *E. nitens* at Westfield for the first two measurements only.

Stem volume and basal area were determined on an area basis by summing the estimates of individual trees over each plot and dividing by the measured area of each plot to convert individual tree and plot data to an area basis.

Soil sampling

Prior to fertilising Westfield, 20 surface soil (0–10 cm) samples per plot were collected from the uncultivated zone between tree

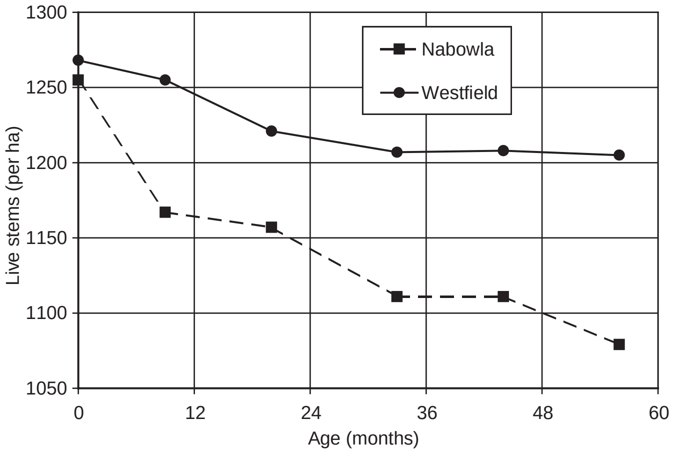

Figure 1. Number of live trees ha^{-1} remaining at Westfield and Nabowla, from time of planting to 56 months. Treatment had no significant effect on survival at any time for either site.

rows in four replicates, then bulked, air-dried and sieved. The <2 mm fraction was sub-sampled and analysed for pH, electrical conductivity (EC), total N, total P, Colwell-extractable P, $CaCl_2$-extractable P, organic C and exchangeable bases by standard laboratory methods. Soil water content was measured on a similar set of samples collected at age 6 y.

Results

Survival, growth and stem form

Fertiliser treatment had no significant effect on survival at either site, but over time a marked contrast developed between the two sites in the number of live stems (Fig. 1). Initially there was a small decrease at Westfield over the first three years, after which the number of live trees stabilised at about 1205 ha^{-1}, or 95% survival. In comparison, there was a continuous decline at Nabowla down to 1079 live stems ha^{-1} (86% survival) 56 months after planting.

By nine months after planting, both height and diameter at Nabowla had increased significantly in response to fertiliser at all rates of application ($P < 0.001$, data not presented). Even at that early age, the highest rate of application had doubled the height and almost trebled the diameter of trees compared to the control treatment. Significant differences in height and diameter due to treatment ($P < 0.001$) were measured every year thereafter, up to 56 months after planting. Differences in growth due to fertiliser treatment increased over time and, after 56 months, trees in N4P4 had about three times the height and over four times the diameter of trees in N0P0 (Ht = 3.58 m, Dbh = 2.85 cm).

In contrast to Nabowla, a significant response to fertiliser was not measured at Westfield until 33 months after planting, with an increase of about 15% in diameter (N4P4 compared with N0P0). A further 23 months elapsed (56 months after planting) before the first significant response was measured in tree height at Westfield, with an increase of only about 6% (N3P3 compared with N0P0, for which Ht = 10.5 m and Dbh = 12.4 cm). Splitting fertiliser applications into four doses per year over four years (N5P5) did not significantly increase growth compared with applications made only twice at 2 and 26 months (N4P4).

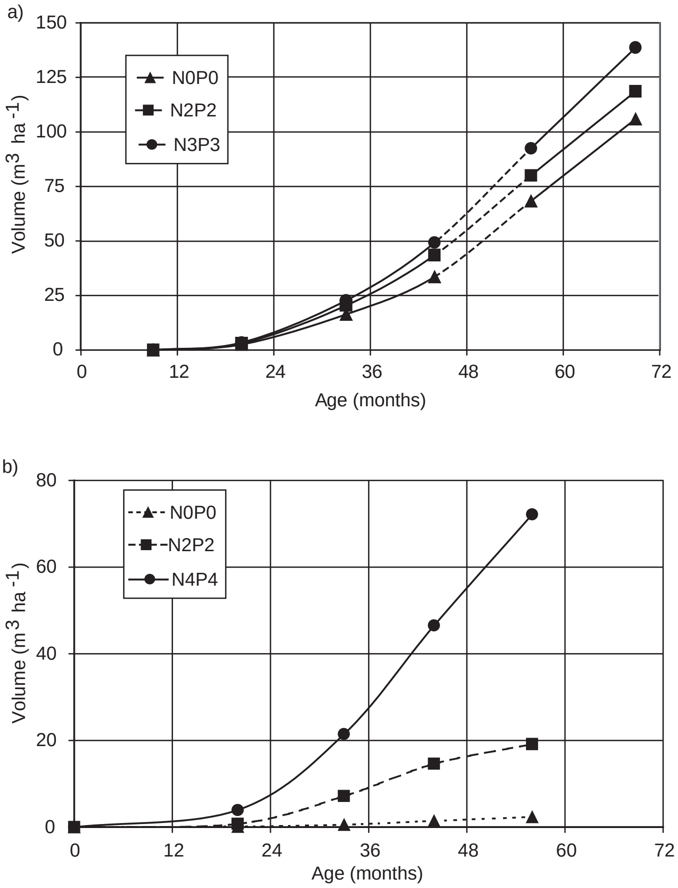

Figure 2. Accumulation in stem volume under bark for three fertiliser treatments in (a) *E. nitens* at Westfield, and (b) *E. globulus* at Nabowla. Dashed lines at Westfield indicate the change from including the largest stem only where there were multiple stems per tree (9–44 months), to all multiple stems (56–69 months). At Nabowla, data are from 9 to 56 months, and include only the largest stem per tree. Differences among treatments were significant ($P < 0.01$) at 44, 56 and 69 months at Westfield, and ($P < 0.001$) from 20 to 56 months at Nabowla.

Stem volume (under-bark) accumulated rapidly in *E. nitens* at Westfield even without fertiliser addition (68.3 m^3 ha^{-1} at 56 months), and the addition of fertiliser increased this by a further 35% (92.5 m^3 ha^{-1}in N3P3, Fig. 2a). A year later (69 months), the relative difference between control and the best fertiliser treatment had declined slightly to 31%, but the absolute difference had increased by 8 m^3 ha^{-1}. In comparison, accumulation of stem volume in *E. globulus* at Nabowla was exceedingly slow without fertiliser, reaching only 2.4 m^3 ha^{-1} after 56 months (Fig. 2b). The addition of fertiliser caused early and dramatic increases in productivity, by almost 7 times at the N2P2 rate (19.1 m^3 ha^{-1}), and almost 30 times with the heaviest rate (72.2 m^3 ha^{-1} in N4P4). Only the heaviest rate of fertiliser enabled stem volume at Nabowla to approach that of the control at Westfield. Differences among treatments at Westfield were significant ($P < 0.01$) for volume measurements made at 44 months after planting and thereafter. In comparison, differences among treatments at Nabowla were significant ($P < 0.001$) at the measurements made on and after 20 months.

At Westfield, the heaviest fertiliser treatment had a significantly higher proportion of multiple stems compared with other treatments, with no differences amongst the latter (mean 45%).

Table 4. Chemistry of soil samples, 0–10 cm, from plots at Westfield prior to fertilising (except water content, which was sampled in November 2001)

Attribute	Mean	S.D.	Minimum	Maximum
Water (%)	0.54	0.08	0.42	0.69
Total N (%)	0.34	0.08	0.18	0.48
Total P (%)	0.078	0.031	0.022	0.121
$P_{Colwell}$ (µg g^{-1})	44	23	8	103
P_{caCl2} (µM)	2.0	1.6	0.2	5.8
Ox.C (%)	7.4	2.0	4.0	11.0
pH	4.7	0.2	4.3	5.0
EC (dS m^{-1})	0.16	0.03	0.10	0.22
Exch. Ca (cmol$_+$ kg^{-1})	4.00	0.89	2.04	5.78
Exch. Mg (cmol$_+$ kg^{-1})	1.50	0.38	0.85	2.54
Exch. K (cmol$_+$ kg^{-1})	0.47	0.10	0.29	0.68
Exch. Na (cmol$_+$ kg^{-1})	0.14	0.02	0.11	0.20

Table 5. Non-linear regression between fertiliser rate, soil chemistry and growth for plots at Westfield (n = 24). The function fitted was stem volume (m^3 ha^{-1}, age 6 y, under bark) = constant + ((b–c)/(1 + (b–d)/(d–c))*exp(–0.02*N rate)) + e*total P + f*exch. K; r^2 = 0.83; s.e. estimate = 10.3.

Parameter	Related coefficients	Value
Constant		44.34
N rate (kg ha^{-1})	b	97.31
	c	58.44
	d	58.71
Total P (%)	e	281.1
Exch. K (cmol$_+$ 100 g^{-1})	f	71.57

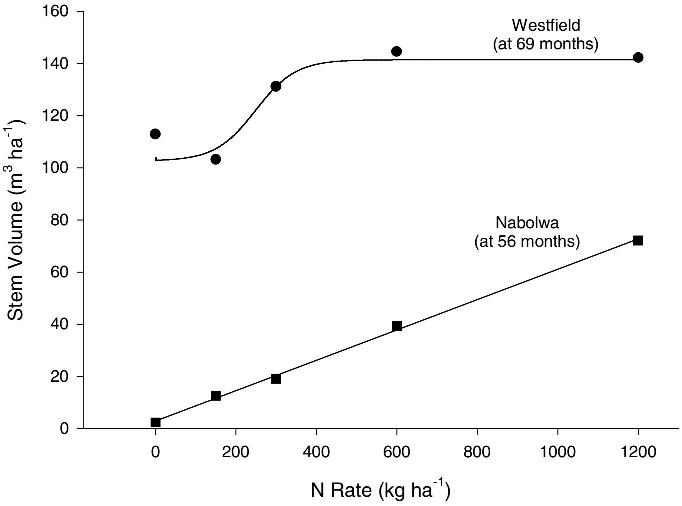

Figure 3. Response in total stem volume under-bark of *E. globulus* at Nabowla (at 56 months) and *E. nitens* at Westfield (at 69 months) in relation to rate of N fertiliser (ratio of N:P = 2:1). The relationship for Nabowla is $y = 2.932 + 0.0582x$ ($R^2 = 0.85$, $n = 20$), and that for Westfield is given in Table 5 (assuming average values of total P and exchangeable K, Table 4).

Inclusion of multiple leaders at Westfield increased stem volumes at 56 months by 18% in the N0P0 treatment and 13% in N3P3.

An analysis of increments in stem volumes — MAI and CAI, mean and current annual increment, respectively — for the untreated control and the best treatment at each site indicated that CAI at Westfield peaked at 35 and 43 m^3 ha^{-1} y^{-1} in the N0P0 and N3P3 treatments, respectively, at 5 y of age. The trajectory of the graphs indicated that CAIs would fall and cross the peak of the MAI curves at about 8 y of age, with values in the order of 22 and 27 m^3 ha^{-1} (N0P0 and N3P3, respectively). Application of fertiliser thus appears likely to have lifted MAI over the rotation by about 5 m^3 ha^{-1}. In comparison, CAI of both treatments at Nabowla peaked at less than 4 y of age at values of 1 and 27 m^3 ha^{-1} in the N0P0 and N4P4 treatments, respectively. Inclusion of multiple leaders would increase CAI of the fertilised trees somewhat but it is unlikely to change the result in the N0P0 treatment. The trajectory of the increment curves in the N4P4 treatment suggested that CAI would fall and cross the MAI curve when the trees were about 6 y of age at a value of about 17 m^3 ha^{-1}.

Growth in relation to fertiliser rate and soil chemistry

It was possible to examine the relationships between soil chemistry (Table 4), fertiliser rate and growth only at Westfield. Of the soil chemistry variables, forward and backward stepwise multiple regression indicated that soil total N, total P and exchangeable K and exchangeable Mg significantly affected growth, but, because several of these variables were correlated, selected sets of uncorrelated variables were examined separately. High proportions of variation were explained by including either N (50% alone) or P rate, either total N or total P, and either exchangeable K or exchangeable Mg, but most variation was explained by a sigmoidal function of N rate, combined with linear functions of total P and exchangeable K ($r^2 = 0.83$; Table 5). The relationship with N rate indicated a plateau in growth was reached at an N rate of about 400 kg N ha^{-1} (Fig. 3).

Since growth was so heavily dependent on nutrient supply at Westfield, which is the relatively fertile site in this study, it is not surprising that the response to fertiliser was even more dramatic at Nabowla, which soil analyses indicated had far lower N and P availability (Table 1). The linear relationship between N (or P) rate and growth at Nabowla explained 85% of the variation, and the relationship provided no indication that the response to fertiliser had reached a maximum in relation to fertiliser rate.

The response in stem volume for the best treatment at each site was plotted against stand age (Fig. 4). Response was calculated by subtracting the volume of the N0P0 treatment from the volume

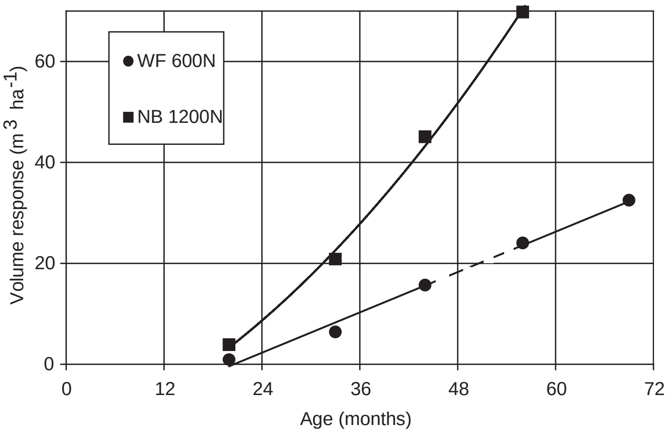

Figure 4. Response in stem volume under bark (V) to fertiliser in relation to age of stand at Westfield (Westfield, 24 points, 600 kg N ha^{-1}), where dashed line indicates change from including the largest stem only to multiple stems, and Nabowla (Nabowla, 16 points, 1200 kg N ha^{-1}), for one stem only. The equations that best described the responses were as follows: $V_{Westfield} = -12.53 + 0.653(A)$ ($R^2 = 0.43$); $V_{Nabowla} = -12.67 + 0.482(A) + 0.018(A)^2$ ($R^2 = 0.74$).

of the N3P3 treatment (600 kg N ha^{-1}) at Westfield and from the N4P4 treatment (1200 kg N ha^{-1}) at Nabowla. The relationships were derived from 25 points at Westfield and 16 points at Nabowla. The response at Westfield was linear ($R^2 = 0.44$), whereas at Nabowla it was quadratic ($R^2 = 0.74$). These responses show that the nutrients applied to these sites clearly had a lasting effect, and that the absolute response continued to increase each year.

Discussion

Soils at the two contrasting sites are within the boundaries of soils that have developed under 'dry' (Nabowla) and 'wet' (Westfield) forest in Tasmania as described by Laffan *et al.* (1998). Given the soil characteristics at the Nabowla and Westfield sites, the growth rates and responses obtained generally comply with those expected for similar sites elsewhere in Tasmania (Laffan *et al.* 1998). A somewhat unexpected result was the relatively high level of productivity obtained at Nabowla where the highest level of NP fertiliser was applied. Previous studies in north-eastern Tasmania reported very low productivity on sites similar to Nabowla, even where fertiliser was applied. For example, an MAI of about 2.4 m^3 ha^{-1} y^{-1} was reported for *E. globulus* aged 8–10 y at North Retreat, a site about 25 km west of Nabowla with similar rainfall and soil (Orme *et al.* 1992). While a small starter dose of fertiliser was applied to trees at North Retreat, they received no further additions. Two other experiments in the same series received additional fertiliser (140 kg N ha^{-1} and 120 kg P ha^{-1}) two years after planting, and, while this application increased productivity at those sites two- to three-fold, it was still very low (MAI <2 m^3 ha^{-1} y^{-1}). The application provided the same amount of N, but more P, than the N1P1 rate in the experiment at Nabowla, which produced a stem volume of 12.5 m^3 ha^{-1} at 56 months (4.7 y), or an MAI of 2.7 m^3 ha^{-1} y^{-1}. In comparison, the control had a stem volume of 2.4 m^3 ha^{-1} (MAI = 0.5 m^3 ha^{-1} y^{-1}). Given the difference in age between the reporting dates of the two experiments, productivity at the two sites without fertiliser, or with similar rates of NP, appears to be similar. In the Nabowla experiment, productivity in the N4P4 treatment was six times that achieved in N1P1, but the amounts of N and P applied were eight times greater. The level of weed control applied (if any) was not indicated for the earlier experiments (Orme et *al.* 1992), but it was likely to have been of lower intensity than that applied in the present experiments.

Results from a fertiliser experiment with *E. globulus* at Fingal, with soil and rainfall similar to those at Nabowla, showed that stem volume at 7 y increased from about 2 m^3 ha^{-1} without fertiliser to 20 m^3 ha^{-1} with a total application of 368 kg N ha^{-1} and 228 kg P ha^{-1} (Neilsen and Wilkinson 1990). This compares with an increase at Nabowla from 2.4 m^3 ha^{-1} without fertiliser to 19 m^3 ha^{-1} following a total application of 300 kg N ha^{-1} and 150 kg P ha^{-1} (N2P2) at 56 months (Fig. 2, 4.7 y). While the overall productivity at Fingal was slightly less than at Nabowla, the response to fertiliser was remarkably similar at the two sites when similar quantities of N and P are compared. The effects of N and P were separated in the experiment at Fingal, which indicated that trees responded to each nutrient individually and there was an additive effect with the two together. Results from the present work highlight the extreme nutrient deficiencies in these 'dry' duplex forest soils in north-eastern Tasmania, and demonstrate that to achieve reasonable growth of plantation eucalypts much larger amounts of N and P will be required than have been envisaged previously.

In comparison with the linear response at Nabowla, the response to fertiliser at Westfield was best explained by a sigmoidal function with a plateau in stem volume at about 400 kg N ha^{-1} (Fig. 3) and, after 69 months, a stem volume that had increased by 32 m^3 ha^{-1} (Fig. 4). These results may be compared with an experiment at Creekton in southern Tasmania that examined the effects of N fertiliser and method of clearing on the growth of *E. nitens* (Turnbull *et al.* 1997). Two levels of N (100 and 300 kg N ha^{-1}) were combined with two types of clearing (bulldozer and excavator). In common with results at Westfield, fertiliser treatment did not have a significant effect on tree growth until trees were three years of age. While the effect at Creekton was significant for only a further year, the level of replication in the trial probably limited the degree to which responses were identified as statistically significant. However, an additional 200 kg N ha^{-1} (300 compared with 100) produced a large and continuing difference in growth. There was no significant interaction between N and clearing method, but the effects appear to have been additive, and each additional 100 kg ha^{-1} of N fertiliser produced an extra 14 to 19 m^3 ha^{-1} of wood at 7 y of age.

Research in several eucalypt plantations on ex-forest sites receiving rainfall of at least 1000 mm y^{-1} indicates that N deficiency within the first 3 y can be expected if the concentration of total N in surface soil (0–10 cm) is less than 0.5% (Moroni 2001). Thereafter, N deficiency tends to occur where the concentration of NH_4 in soil solution is less than 0.05 mM and of NO_3 less than 0.1 mM, or KCl-extractable NO_3 is less than 0.1 mg kg^{-1}. The concentration of total N at Westfield (Table 1) was just above this critical value, and concentrations of soil solution NH_4 and NO_3 were less than their critical values by 2 y of age (Smethurst *et al.* 2001a). It is not surprising, therefore, that the Westfield plantation seemed to become N-deficient between 2 and 3 y of age. Very low concentrations of total N at Nabowla correctly indicated severe N deficiency at that site. Concentrations of NH_4 and NO_3 in soil solution or KCl extracts were less useful indicators of N deficiency at this site, probably because the low water content prevailing at this low-rainfall site (810 mm y^{-1}) would restrict mass-flow and diffusive transport of these ions to root surfaces. Hence, soil water content also needs consideration when interpreting NH_4 and NO_3 availability.

The concentration of Bray2-P is more reliable than total-P as an indicator of the need for P fertiliser with *E. globulus* and *E. nitens* on Ferrosol soils (highly P-fixing) and non-Ferrosol soils in southern Australia (Mendham *et al.* 2002). The concentration of Bray2-P at the Westfield site was much higher (21.9 mg kg^{-1}) than on any of the non-Ferrosols examined, for which there was a moderate response to P fertiliser at the top of the range (<4 mg kg^{-1}), and a very strong response at some of the sites with very low concentrations (<1 mg kg^{-1}). Further, concentrations of $CaCl_2$-P sampled at 6 y of age at Westfield indicated that less than 10% of plots had concentrations below a value of 0.0005 mM, which has been suggested as critical for young *E. nitens* (Table 4; Mendham *et al.* 2002). It is therefore unlikely that trees at Westfield responded strongly to the P component of the fertiliser. Total P was related to growth at Westfield independently of fertiliser rate (Table 5), but this relationship may not be causal because total P was also significantly correlated with total N and EC (data not presented). By comparison, the low concentration of Bray2-P at Nabowla (1.9 mg kg^{-1}) suggests that a large proportion of the growth response at that site was due to the P component of the fertiliser. Where P fertiliser is needed, the standard spot of NP fertiliser, applied by most companies near each seedling at the time of planting, would be expected to provide sufficient P for the life of most eucalypt plantations on soils with high P-buffering (Smethurst and Wang 1998).

The concentration of exchangeable K in surface soil was related to growth at Westfield (Table 5), suggesting that low K availability might have limited growth at this site. Studies of K nutrition are therefore warranted in temperate eucalypt plantations, and some instances of deficiency have already been recorded (Bennett *et al.* 1997: P.J. Smethurst *pers. comm.*). However, our knowledge of the diagnosis and correction of base cation deficiencies in temperate eucalypt plantations is very limited, and correlations of this type do not necessarily indicate deficiency. For example, productivity of *P. radiata* is closely related to concentrations of Ca in surface soil (Turvey and Smethurst 1994), but there is no evidence that low Ca availability is currently a severe limitation to growth of pine or eucalypt plantations in Australia.

To maximise the productivity and financial return from investments in hardwood plantations, industry requires information on optimum management regimes, including the best fertiliser treatments. A major difficulty in determining site nutrient requirements is that long-term experiments are required to fully evaluate the effects of nutrient additions over a rotation. Growth responses to fertiliser at our sites were continuing at 5 or 6 y of age (Fig. 4), indicating that it is reasonable to expect that the total response at Westfield to 600 kg N ha^{-1} will reach at least 50 m^3 ha^{-1} over a rotation of 12–15 y, and could go much higher. A response of this magnitude is equivalent to about 8 m^3 ha^{-1} of wood for each additional 100 kg ha^{-1} of N applied. A financial analysis of pulpwood crops (Gerrand *et al.* 1993) indicates that, even at a high level of royalty for pulpwood, the net present value of a site with a productivity of 15 m^3 ha^{-1} y^{-1} (i.e. Nabowla with N4P4) would be less than a 'typical' establishment cost of \$1600 ha^{-1} (1993 costs). If we further assume that the maximum treatment of 1200 kg N ha^{-1} and 600 kg P ha^{-1} would be required to obtain a merchantable MAI of 15 m^3 ha^{-1} y^{-1} at Nabowla, this would at current costs add \$2500–3000 ha^{-1} over the first 3 y. Hence, even by boosting productivity with fertiliser, it appears that sites like Nabowla are unlikely to provide an economic return on investment. Such heavy applications of NP also could have deleterious environmental effects from nutrient run-off and long-term impacts on soil properties. However, sites with similar soils that have had a period of fertility improvement in agriculture might profitably produce wood without further additions of fertiliser.

In comparison, the Westfield site had a high level of productivity, and here a lower rate of fertiliser was required to achieve maximum growth and the economic rotation will be shorter. The NPV for a site with a productivity of 20 m^3 ha^{-1} y^{-1} would exceed the cost of establishment for pulpwood royalties above \$14 m^{-3}. Other experiments have indicated that the primary response on these soils is to N, and we have assumed that a starter dose of P would be sufficient. An additional cost of \$600–750 ha^{-1} (W. Neilsen, *pers. comm.*, 1999 prices) to purchase and apply 600 kg N ha^{-1} (as urea from the air) would increase merchantable MAI from 20 to 25 m^3 ha^{-1}, and reduce rotation length from 15 to 12 y. Given that the second application of N probably caused most of the response, an application of 300 kg N ha^{-1} at 2–3 y of age may provide a similar level of response at half the cost. Thus application of urea to such sites could provide an attractive return on investment, which is in general agreement with a recent economic analysis of N fertiliser options in eucalypt plantations (Smethurst *et al.* 2001b).

Conclusions

These experiments have demonstrated that the productivity of sites with duplex, infertile soils in 'dry' forest regions of Tasmania can be substantially increased by applications of very large amounts of N and P fertiliser. The response will be directly related to the quantity of nutrients applied. However, the cost of providing the quantity of nutrients needed to obtain reasonable levels of productivity on such sites is so high that it appears to be uneconomic. High rates of N application might also cause environmental impacts from nutrient runoff and soil degradation, and could not be justified with present knowledge. Further work to identify the relative importance of N compared with P on these sites may be warranted.

Significant increases in productivity can also be obtained by applying fertiliser to sites with gradational soils on 'wet' ex-forest sites with relatively fertile soils. The increases in productivity that can be obtained will probably provide a positive return on the investment required to purchase and apply fertiliser to such sites. In general, an application of at least 300 kg N ha^{-1} at age 2–3 y is recommended.

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