Nitrogen and phosphorus increase growth of thinned late-rotation *Pinus radiata* on coastal sands in Western Australia

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Summary

The capacity of *Pinus radiata*, growing on the infertile sandy soils of the Swan Coastal Plain, Western Australia, to respond to the application of fertiliser following second thinning was evaluated by applying a combined nitrogen (N) and phosphorus (P) fertiliser at rates of up to 175 kg N ha^{-1} and 76 kg P ha^{-1}. At the highest rate the basal area increment in the 6 y after application increased by about 50%. The response, however, was transitory — at even the highest rate the annual volume increment increased for only 4 y after application. There appeared to be little competition between trees in this widely spaced plantation, as the treatment did not change the distribution of basal area increment within the stand.

A further series of experiments on the same site evaluated the response to N following a third thinning (at around 30 y of age) and whether N was more effectively applied in spring than in autumn, or in a split application. There was a response to N and it was similar for spring and autumn applications, and there was no advantage in a split application. The 50% increase in volume increment from N in the timing-of-fertiliser-application trial, which evaluated the response to N alone, indicated that a large component of the response to mixed fertiliser on these soils was due to N.

Keywords: phosphorus fertilizers; nitrogen fertilizers; thinning; growth effects; response duration, application date; split dressings; *Pinus radiata*; Australia

Introduction

Increased stem growth following application of fertiliser to relatively old *Pinus radiata* stands occurs most commonly when the stands have been thinned or pruned prior to treatment. For example, Hunter *et al.* (1985a) found that, on pumice soils in New Zealand, basal area increment increased following an application of nitrogen (N) where the canopy had room to expand as a result of prior thinning or pruning. Post-thinning fertiliser responses have now been demonstrated for an extensive range of sites (Woollons and Will 1975; Mead and Gadgil 1978; Crane 1981; Snowdon and Waring 1990; Turner *et al.* 1996; Carlyle 1998).

A strong positive interaction between thinning and fertiliser application on the volume increment of individual trees was demonstrated for *P. pinaster* Ait., 20 y old, on the deep sands of the Swan Coastal Plain in Western Australia (WA) (Butcher 1977). This interaction was related to the supply of water. In dry years, heavily stocked stands showed little response to fertiliser, because soil moisture rather than nutrient supply limited growth. Lightly stocked stands responded to fertiliser in both wet and dry years as sufficient soil moisture was available to maintain growth even in dry years.

In southern WA the growth of *P. radiata* plantations established on ex-native forest sites was improved by application at planting of phosphorus (P) (McGrath 1978) or N and P (Chevis 1983). Prior to canopy closure, stem diameter increased following the application of N and P (Moore 1981). However, it was not known if the growth of older *P. radiata* on such sites could be increased by further fertiliser application.

This paper reports the response of stands 21 and 23 y old, growing on an infertile soil, when N and P were applied following second thinning. It also reports the response to N of stands 30 y old on the same site following a third thinning. The latter experiments also sought to determine whether N is more effectively applied in spring than autumn, and the advantage of splitting the application of N into two, 2 y apart.

Materials and methods

The experiments are located in the Myalup plantation (latitude 33°04'S, longitude 115°45'E) on the Swan Coastal Plain 130 km south of Perth, WA. The climate is Mediterranean, with cool moist winters and hot dry summers. The mean annual rainfall at Myalup, 2 km south-east of the plots, is about 900 mm, 80% of which falls in the period May to September.

The soils are relatively deep (about 15 m to the water table) yellow-brown siliceous sands (Karrakatta Sands) that are part of the Spearwood Dune System (McArthur and Bettenay 1960; McArthur 1991). The sands overlie deposits of secondary calcite (Tamala Limestone) which have been exposed on the western margin of the dunes by wind action. Within the trial area there were no calcite outcrops.

Selected soil parameters for the experimental sites are given in Table 1. Soil pH was determined in a 1:5 soil:0.1M $CaCl_2$ suspension. Organic carbon was measured by the technique of Walkley and Black (1934); N was measured by a micro-Kjeldahl method (McKenzie and Wallace 1954); and P was extracted in

Table 1. Chemical properties of surface soil at the experimental sites prior to fertiliser application

Site	Depth (cm)	pH	Organic carbon (%)	Nitrogen (%)	Phosphorus HCl extract (mg kg^{-1})	Phosphorus HCO_3 extract (mg kg^{-1})
1	0–10	5.1	0.71	0.03	24	0.5
	10–20	5.6	0.54	0.03	18	0.3
2	0–10	4.7	0.73	0.03	13	0.6
	10–20	4.8	0.53	0.03	10	0.4

both 6N HCl and 0.5M $NaHCO_3$ solutions and determined colorimetrically (Murphy and Riley 1962).

The experiment was duplicated in two separate compartments of the plantation. Both compartments had been planted at 1300 stems ha^{-1}: Site 1 (Compartment 53) in 1957 and Site 2 (Compartment 65) in 1955. At planting, the seedlings were given superphosphate at 100 g tree^{-1}. In 1969 Site 1 received an additional 500 kg ha^{-1} of superphosphate (45 kg P ha^{-1}). Both sites were thinned to about 400 stems ha^{-1} in 1969. A second thinning in late 1977 reduced the stocking to about 220 stems ha^{-1}. When the first experiment was established in May 1978 (i.e. following second thinning) the basal area was 13.6 m^2 ha^{-1} at Site 1 and 14.1 m^2 ha^{-1} at Site 2; mean height at both sites was 21 m.

Application of fertiliser following second thinning

At both sites a compound fertiliser (Agras No. 1) containing 17.5% N, 7.6% P, 16% S (sulphur) and 0.06% Zn (zinc) was applied at six rates (0, 200, 400, 600, 800 and 1000 kg ha^{-1}). The treatments were replicated in four randomised blocks at each site. Assignment of plots to blocks was based on the initial basal area of the plots rather than their spatial location within sites. The area of treatment plots was 0.25 ha, and of measurement plots about 0.12 ha; there was a treated buffer with minimum width of 7.5 m on all sides of the latter.

Diameter at breast height (1.3 m) over bark (DBHOB) and height were measured prior to the application of fertiliser in May 1978 (5/78) and again in January 1984 (1/84). Basal area increments (m^2 ha^{-1}) for this period were used to represent the response to fertiliser over this period. The effect of the fertiliser on the distribution of basal area increment within the stand was examined by dividing the population into the largest and smallest 10th and 20th percentiles based on basal area. The contributions of these components of the population to the initial basal area and basal area increment of the stands were then compared by an analysis of variance. Differences among individual mean values were assessed using least significant differences (LSD). Height data are not presented, as there was no response in height growth to any treatment.

The time course of the response at Site 1 was determined by a stem analysis of the two trees per plot closest to the mean diameter at the beginning (5/78) and end (1/84) of the experiment. Volumes were calculated to a height of 16 m using Smalian's formula for sectional log volumes (Carron 1968). Each data point was made up of eight measurements; the coefficient of variation (CV) for these data varied from 4% to 15% (mean CV 8%).

Application of fertiliser following third thinning

In 1987, 9 y after the initial experiments were established and following a third thinning, two further experiments were established on the same experimental sites. These experiments examined the response to the application of fertiliser at this late stage of the rotation, and whether there was an advantage in applying N in spring compared with autumn, and whether an application of fertiliser split into two and applied at intervals of 2 y was more effective in increasing tree growth than a single application of the same total quantity of nutrient. The stands had been thinned to a residual stocking of 100 stems ha^{-1} with a residual basal area of 10–16 m^2 ha^{-1}.

The effectiveness of applications in autumn and spring was assessed by applying ammonium nitrate at rates equivalent to 0, 100, 200 and 400 kg ha^{-1} of N in April and September, respectively. All plots in the timing experiment received a basal application of 200 kg P ha^{-1}, 7.6 kg Zn ha^{-1} and 3.6 kg Cu ha^{-1} (copper). The effectiveness of splitting applications of fertiliser was tested by applying P and N in a single application in April 1987 or two half-rate applications in April 1987 and April 1989. The total N and P applied (in kg ha^{-1}) was 0P 0N, 50P 100N, 100P 200N and 200P 400N.

Both trials were factorial combinations of four rates of fertiliser by two application treatments (season of application and single versus split application) with three replicate blocks. While the original plots from the first series of experiments were maintained for the second series of experiments, the assignment of the plots to blocks for the latter was based on the residual basal area following the thinning in 1987. Both trials were terminated in 1991 when fire destroyed the plantation. The responses to fertiliser were estimated from a stem analysis of a subsample of trees from each plot. The data from both trials were analysed using covariance analysis with the initial mean tree volume as the covariate. Differences between the treatment means were tested using Tukey's multiple pairwise comparisons.

Results

Response to fertiliser following second thinning

Increasing rates of application of N and P following second thinning in stands aged 21 and 23 y resulted in a linear increase in basal area increment during the following 6 y (Fig. 1). The maximum application (175 kg N ha^{-1} and 76 kg P ha^{-1}) increased basal area increment in this period by about 50% or 3.5 m^2 t^{-1} Agras.

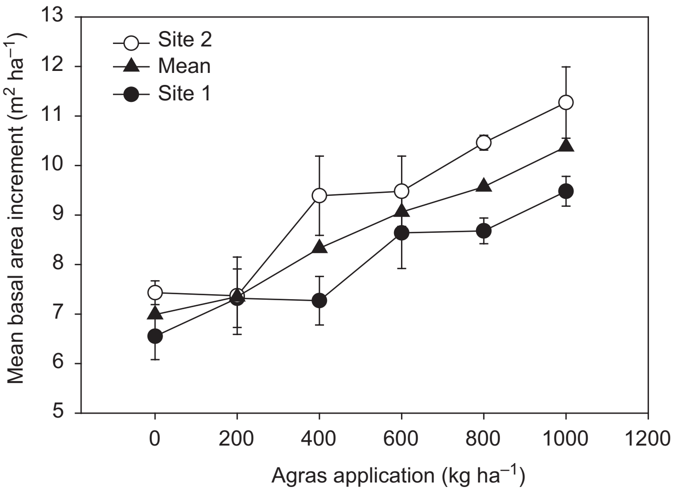

Figure 1. The effect of Agras No. 1 (17.5% N and 7.6% P) on basal area increment of *Pinus radiata* in the 6 y after application to a second-thinned stand (May 1978 to January 1984). Standard errors are shown as vertical bars on the data for each site (bars are 2 SE).

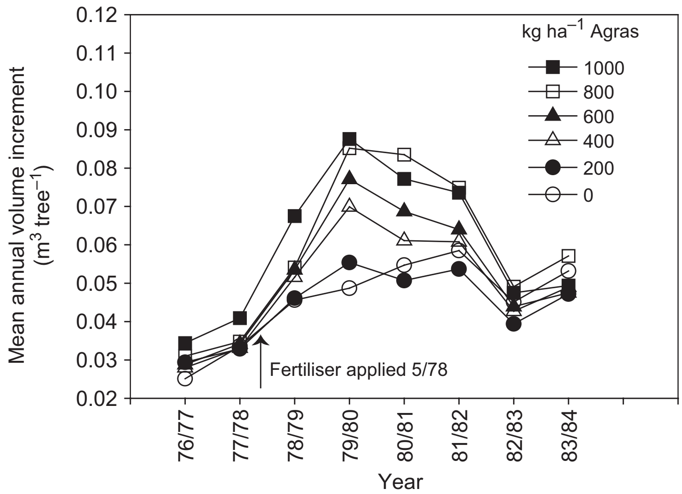

Figure 2. The effect of Agras No. 1 (17.5% N and 7.6% P) on annual volume increment of *Pinus radiata* for 6 y after application. The coefficient of variation for the individual data points varied between 4% and 15% (mean CV = 8%).

The annual volume increments for the period 1976–1977 to 1983–1984 show that the response to the application of nitrogen and phosphorus was transitory (Fig. 2). Relative to the control treatment there was a small increase in volume increment in the first year following the application of fertiliser. At the highest rate of fertiliser, the volume increment in the second year after treatment was 75% greater than that of the control, and at the intermediate rates (70N 30P and 105N 46P) about 50% greater than that of the control. The annual volume increments for the lowest application rate (35N 15P) did not differ significantly from the control during this period (Fig. 2). Following the large increase in the second year, the annual volume increments began to decline for all the fertilised treatments (Fig. 2). The annual volume increments of all treatments remained above that of the control for only 4 y (Fig. 2).

To determine how the increase in growth caused by fertiliser was distributed within the stand, the contribution of the largest and smallest 10% and 20% of trees to stand basal area at the beginning of the experiment (at 5/78), and the contribution of these trees to subsequent increment in basal area, were examined. The application of fertiliser had no effect on the distribution of basal area increment within the tree population (Table 2). In both the control and the highest fertiliser treatment, the largest 10% of trees accounted for about 16% of both the total initial basal area (at 5/78) and the basal area increment between 5/78 and 1/84. The smallest 10% of trees contributed 5–6% of the initial basal area and 4% of the basal area increment (Table 2). The data for the largest and smallest 20% of the population shows similar trends

Table 2. Contribution of the largest and smallest 10% and 20% of *Pinus radiata* trees to the total initial basal area in May 1978, and basal area increment between May 1978 and January 1984 in response to different rates of fertiliser application

Rate of application of Agras (kg ha⁻¹)	Ten percent of population				Twenty percent of population			
	Fraction of basal area contributed at 5/78 (%)		Fraction of basal area increment contributed between 5/78 and 1/84 (%)		Fraction of basal area contributed at 5/78 (%)		Fraction of basal area increment contributed between 5/78 and 1/84 (%)	
	Largest trees	Smallest trees	Largest trees	Smallest trees	Largest trees	Smallest trees	Largest trees	Smallest trees
0	15.8	5.9	16.5	4.5	28.3	12.8	30.0	10.8
200	16.0	5.7	14.6	4.1	29.7	13.0	29.7	10.4
400	17.2	5.2	19.7	4.4	30.0	12.6	34.1	9.8
600	15.3	6.0	15.9	4.5	28.5	13.6	30.4	11.0
800	16.5	5.5	17.5	3.9	29.6	12.6	32.0	10.0
1000	15.4	5.6	16.0	3.6	29.0	12.8	30.1	9.8
Mean	16.0	5.6	16.7	4.2	29.2	12.9	31.0	10.3
LSD ($P < 0.05$)[a]	2.4	1.0			2.7	1.3		

[a] LSDs for comparison of individual mean values between the initial basal area distribution at 5/78 and the distribution of basal area increment between 5/78 and 1/84.

Table 3. The effect of fertiliser application in autumn and spring following a third thinning on the volume growth of *Pinus radiata* during the 4 y following treatment

Nutrient applied (kg ha^{-1})		Volume increment (m^3 tree^{-1})		
Nitrogen	Phosphorus	Autumn application	Spring application	Mean
0	200	0.38	0.35	0.36 a
100	200	0.44	0.44	0.44 ab
200	200	0.52	0.45	0.48 b
400	200	0.53	0.54	0.54 b

Significance: no significant differences in timing of application; fertiliser rate significant at $P < 0.01$. Means of fertiliser treatments that are significantly different are followed by a different letter.

Table 4. The effect of single and split fertiliser applications in a third-thinned stand on the volume growth of *Pinus radiata* in the 4 y following the initial treatment

Nutrient applied (kg ha^{-1})		Volume increment (m^3 tree^{-1})		
Nitrogen	Phosphorus	Single application	Split * application	Mean
0	0	0.27	0.33	0.30 a
100	50	0.31	0.35	0.33 ab
200	100	0.45	0.45	0.45 bc
400	200	0.47	0.47	0.47 c

*Application at a 2-y interval (0 and 2 y) to provide the same total nutrient application in two separate applications as the single application

Significance: no significant differences in frequency of application; fertiliser rate significant at $P < 0.01$. Means of fertiliser treatments that are significantly different are followed by a different letter.

(Table 2). The consistent small difference between the initial proportion of basal area and basal area increment for the smallest 10% and 20% of trees is significant ($P < 0.01$). The difference is small, however, and suggests that there was little competition between the trees in this widely spaced stand.

Response to N following third thinning

In the 4 y following the third thinning, mean volume increment in the control treatment was 0.036 m^3 tree^{-1}. Over the same period, following application of 400 kg ha^{-1} of N, mean volume increment was 0.54 m^3 tree^{-1}, 50% above that of the control (Table 3). The responses to N applied in autumn and spring were similar.

There was no advantage in splitting an application of fertiliser into two, and the response to N and P was similar to that in the timing-of-application experiment: an increase of 50% in volume increment following application of 400 kg N ha^{-1} and 200 kg P ha^{-1} (Table 4). On the basis of the first series of trials on this site, the effect of the fertiliser could be expected to last for 4–5 y after application (Fig. 2). As a large part of the response occurred in the first 2 y following application (Fig. 2), the second series — despite its early termination — was still an effective test of the response to split fertiliser application.

Discussion

The 50% increase in basal area increment following second thinning (at age 21 and 23 y) and also following the third thinning (at age 30 y) clearly demonstrated that, on these soils, thinned *P. radiata* responds to fertiliser applied late in the rotation. Although the response in the first trial was measured as basal area increment, it is possible to compare this response with work where the response was measured as volume increments. Where there is no response in height, as occurred in these experiments, basal area responses will be of a similar magnitude to volume responses (Snowdon 2002). The percentage increase in basal area increment was greater (50%) than the maximum 37% increase in stem volume increment reported for *P. radiata* in south-eastern Australia by Crane (1981). This is despite the fact that the rates of P and N used by Crane were 70% and 80% greater, respectively, than the highest rate used in this experiment. The difference in response may have been due to the soils in this experiment being less fertile than those used by Crane (1981), as shown by the very low bicarbonate-extractable P and Kjeldahl N concentrations in this soil (Table 1). Consequently the trees in this study may have been more deficient in nitrogen and phosphorus and thus able to respond more to fertiliser.

Another factor that may have contributed to the greater response to fertiliser in this study was the low basal area (13.6–14.1 m^2 ha^{-1}) compared with that in Crane's (1981) study (21.2–31.6 m^2 ha^{-1}). As Butcher (1977) demonstrated in *P. pinaster* plantations on similar soils, the response to fertiliser depended on the availability of soil moisture. It is possible that a greater demand for water in the denser stands used by Crane may have limited the response to fertiliser.

The linear increase in basal area increment with increasing rate of fertiliser application (Fig. 1) indicated that there was no decline in effectiveness of fertiliser with increasing rates; thus it was just as efficient to apply a large application (up to 175N 76P) as a small application. As there was no response plateau it was not possible to determine the maximum response to N and P from the first series of trials.

The response to N and P following the second thinning was transitory, with the annual volume increment of even the highest rate of fertiliser application being greater than that of the control treatment for only four growing seasons. The duration of this response was similar to that when 11-y-old thinned *P. radiata* on a coastal sand in New Zealand was treated with N and P (Hunter and Hoy 1983). In that study the largest increase relative to the control (160%) occurred in the first year after application and declined thereafter. This contrasts with the response pattern in this experiment, where there was a small increase in volume increment in the first year and a larger (up to 75%) increase in the second year. A similar 1-y lag in response to nitrogen application has been reported for 32-y-old *P. nigra* var. *maritima* (Miller and Cooper 1973) and for 45-y-old *P. banksiana* Lamb (Groot *et al.* 1984).

In contrast to the short-term response observed here, there are reports of fertiliser responses by conifers of greater duration. A response by *Pseudotsuga menziesii* in the Pacific North West of USA to a single N application lasted 15 y (Miller and Tarrant 1983), and for unthinned *P. radiata* in south-eastern Australia a single application of P lasted 13 y (Flinn *et al.* 1979). Auchmoody (1985) has suggested that fertiliser responses by trees consist of an initial increase in growth directly attributable to the increase in nutrient status, and a subsequent passive response caused by the larger fertilised trees having larger increments. This passive response may be a considerable component of sustained fertiliser responses. There was no evidence from these trials that there was a sustained increase in annual volume increment following the application of fertiliser. Snowdon and Waring (1984) described this type of response as a Type 1 response, defined as resulting in a short-term increase in growth but with no sustained improvement in annual growth rates. Such responses result in shorter rotations but no overall improvement in site productivity.

The reported duration of increases in foliar nutrient concentrations in *P. radiata* following fertiliser application differs markedly for N and P. Increased concentrations of foliar N following fertiliser application are of short duration (Hunter and Hoy 1983; Knight *et al.* 1983). On severely P-deficient sites, increases in concentrations of foliar P following fertiliser application last much longer: 5 y (Knight *et al.* 1983), 11 and 13 y (Flinn *et al.* 1979) and 15 y (Hunter *et al.* 1985b). The short duration of increased concentrations of foliar N compared with foliar P may explain the short duration of the responses to N fertiliser. Following the application of labelled ammonium sulphate to *P. radiata* growing on a podzolized sandy soil, uptake of ^{15}N ceased 1 y after application, suggesting that fertiliser N was available for only a short period after application (Nambiar and Bowen 1986). As N and P were applied together in our experiment it is not possible to determine the relative extent to which the two elements are required. The short-lived response to fertiliser on this infertile soil suggests, however, that sub-optimal N supply was a major constraint to tree growth. Responses by thinned *P. radiata* growing on a lateritic gravel soil to N and P separately and in combination have demonstrated that phosphorus deficiency must be overcome before responses to nitrogen occur. On this site both nutrients were necessary to optimise tree growth (McGrath *et. al.* 2003).

Fertiliser application did not affect the distribution of the growth increment between trees, indicating that this treatment did not increase the competition between trees in these thinned stands. This may be due to the effective recharge of the soil water in these low-density stands during winter, thus maintaining an adequate supply of water throughout the seasonal summer drought. Thinned *P. pinaster* has also been found to respond to fertiliser application, even in dry years, as soil water deficit did not limit growth (Butcher 1977). In contrast, the application of fertiliser to an unthinned *P. radiata* stand at age 5 y that remained unthinned (initial stocking 1000 stems ha^{-1}) led to increased mortality by age 23 y (Hunter *et al.* 1985a): the increased mortality appeared to affect all size classes, and reduced the initial increase in growth due to fertiliser application. The treatment appeared to have increased competition between trees. Similarly, in a 30-y-old stand of *Pseudotsuga menziesii* (initial stocking 3500 stems ha^{-1}) fertiliser intensified competition from dominant trees and increased the mortality of suppressed trees (Gessel and Shareeff 1957). In dense stands of *P. nigra* (2110 stems ha^{-1}) (Miller and Cooper 1973) and *P. banksiana* (3430 stems ha^{-1}) (Groot *et al.* 1984) , the smaller trees responded less to fertiliser application than the intermediate and larger trees in the stands. Thus it appears that in dense stands fertiliser increases competition between trees and can change the distribution of growth between the trees.

The similar response to the application of fertiliser in spring and autumn contrasts with the larger response to spring treatment shown for young *P. radiata* by McGrath and McArthur (1990). The differential response in that study was attributed to the greater loss of N through leaching when trees were treated in autumn. The deep and extensive root systems in the older trees in this study may have reduced the loss of N by leaching.

There was no difference between single and split fertiliser applications of N and P on tree growth in the 4 y after the initial application. The premature termination of the second series of trials may have prevented the full expression of a response to the second of the split applications of fertiliser. However, as both the first and second trials showed linear responses (doubling the rate doubled the response to fertiliser), it is likely that there was no advantage in splitting the application of fertiliser.

The response to fertiliser following third thinning at age 30 y demonstrates that responses to fertiliser application after thinning can be achieved throughout the rotation. This makes the application of fertiliser towards the end of the rotation an attractive option from both a wood production and an economic perspective — a conclusion also reached by Turner *et al.* (1996).

The transitory response to fertiliser and the repeated response at an interval of 9 y indicate that the growth of *P. radiata* on infertile soils could be improved by more frequent fertiliser application, particularly of N, as most of the response in the second series of trials was from N. Applications at more frequent intervals, possibly every 3–4 y, may be necessary to optimise growth on these deep sandy soils. The very short duration of the increase in N uptake following fertiliser application on deep sandy soils in South Australia (Carlyle 1998) also indicated that repeated applications of N would be necessary to optimize tree growth on these sites. While deep drainage has been demonstrated in low-density pine stands on similar soils on the Swan Coastal Plain (Butcher 1977; J. McGrath unpublished 2002), the capacity of *P. radiata* to absorb water from at least 15 m in sandy soils (J. McGrath unpublished 2002) suggests that leaching losses on these soils may be small.

These trials have demonstrated that the productivity of *P. radiata* plantations on the coastal plain can be improved considerably by the application of N and P fertiliser following thinning, and that these responses can be achieved during the latter part of the rotation when fertiliser applications are most economic. The short-term responses to N indicate that N applications at intervals of 3–4 y could be used to optimise growth.

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