

# Magnitude and duration of growth and wood quality responses to phosphorus and nitrogen in thinned *Pinus radiata* in southern Western Australia

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Revised manuscript received 20 December 2002

## Summary

The responses to phosphorus (P) and nitrogen (N) following thinning were investigated in a first-rotation *Pinus radiata* D. Don plantation on an ex-native forest site in southern Western Australia. A factorial P × N trial with up to 360 kg P ha<sup>-1</sup> and 540 kg N ha<sup>-1</sup> was used to monitor tree growth for 10 y after application of fertiliser.

The primary deficiency was P, as there was no response to N in the absence of P. Without the application of N the magnitude of the response to P was limited, and the optimum P application was lower than when N was applied. The optimum response was achieved by combined applications of P and N. In the first 4 y after application there was an 86% increase in basal area increment at the optimum rate of P and N. The response to N lasted a maximum of 4 y at the highest rate of N application. The response to P continued for 10 y, although the response at the lower rates of P declined towards the end of this period. This decline in growth and the decline in concentration of both bicarbonate- and HCl-extractable P in the soil indicated that, on this lateritic soil, P availability declined over time.

Fertiliser application resulted in an extra 100 m<sup>3</sup> ha<sup>-1</sup> of wood over the 10 y of the study, and increased the periodic annual increment from 16 to 26 m<sup>3</sup> ha<sup>-1</sup>. Nitrogen application reduced wood density for the duration of the growth response to N, but the wood density remained above the minimum density necessary for structural-grade wood. Fertiliser had no detrimental effect on stem form, as the proportion of the volume classified as sawlog and small sawlog was unchanged. The movement of logs from a smaller and hence lower-value category (small sawlog) to a larger, higher-value category (sawlog) due to an increase in log diameter, enhanced the value of the response to fertiliser above the increase in total volume.

**Keywords:** phosphorus fertilizers; nitrogen fertilizers; thinning; growth effects; response duration; wood density; residues; *Pinus radiata*; Australia

## Introduction

The significant influence of both nutrient and water supply on the productivity and wood quality of plantations across southern Australia is well recognised (Nambiar 1995). The critical importance of water supply in determining overall plantation growth in the Mediterranean climate of southern Western Australia (WA) was demonstrated for *Pinus pinaster* by Butcher (1977). The limitation

to growth imposed by water deficit contributed to the development of silvicultural systems for this region that were based on early intense thinning (Butcher and Havel 1976; Kerruish and Shepherd 1982). Responses by *P. pinaster* to fertiliser application were limited by the availability of water and were generally confined to thinned stands (Butcher and Havel 1976; Butcher 1977).

Increased growth following the application of fertiliser to thinned *Pinus radiata* D. Don plantations has been demonstrated on a range of sites in Australia and New Zealand (Woollons and Will 1975; Mead and Gadgil 1978; Crane 1981; Snowdon and Waring 1990; Turner *et al.* 1996; Carlyle 1998). The natural fertility of the leached lateritic soils and deep aeolian sands, on which most *P. radiata* plantations in WA are located, is very poor (Hatch 1955; Hingston *et al.* 1981; McArthur 1991). Thus the potential for responses to fertiliser by plantations on cleared native forest sites was likely to be high, as demonstrated by an increase of 50% in basal area increment following application of N and P in thinned plantations on the coastal sand plain (McGrath *et al.* 2003). The relative responses to N and P alone could not be determined, because the initial experiment used a compound fertiliser containing N, P and sulphur (S). In subsequent experiments responses to N alone were demonstrated, but the role of N and P individually and in combination was not investigated. The post-thinning fertiliser responses shown on the coastal plain soils in WA for both *P. pinaster* (Butcher 1977) and *P. radiata* (McGrath *et al.* 2003) were short-lived, with the response in *P. radiata* being most probably due to N. In contrast, long-term responses to application of P have been shown for *P. radiata* (Flinn *et al.* 1979; Turner 1982), demonstrating that under some circumstances fertiliser can result in sustained responses.

This study sought to determine the relative importance of applications of N and P in increasing the growth of thinned *P. radiata* on a first-rotation ex-native forest site that had received only the standard application of superphosphate at the time of establishment. The high rainfall and the relatively low density of the thinned plantation at this site indicated that water deficit was unlikely to be a severe limitation. The study also examined the longevity of the fertiliser effects of N and P, and the effect of fertiliser on wood density and on the yield of wood products.

## Materials and methods

The trial was located 16 km east of Harvey in southern WA (116°03' E, 33°06' S). The gravelly lateritic soil at the trial site was typical of

the soils of the western margin of the Darling Plateau on which the native jarrah (*Eucalyptus marginata*) forest is located. These soils have a sandy surface horizon, a ferricrete gravel horizon up to 100 cm deep, and then mottled and pallid clay horizons that can be up to 30 m deep (McArthur 1991). The soil is relatively infertile with 2.4% organic carbon, 0.10% N, a C:N ratio of 24:1, 112 mg g<sup>-1</sup> HCl-extractable P, 1.4 mg g<sup>-1</sup> HCO<sub>3</sub>-extractable P and a pH of 5.2 in the surface 10 cm. The annual rainfall is about 1100 mm, seasonally distributed, with 80% falling in the wettest five months from May to September.

The trial was established in May 1985 when five rates of P and five rates of N were applied in a complete factorial combination to a 17-y-old plantation that had been commercially thinned from below in the previous spring. Phosphorus was applied as superphosphate (9.1% P) at 0, 500, 1000, 2000 and 4000 kg ha<sup>-1</sup>, giving rates of 0, 45, 90, 180 and 360 kg P ha<sup>-1</sup>. Nitrogen was applied as ammonium nitrate (34% N) at 0, 200, 400, 800 and 1600 kg ha<sup>-1</sup>, giving rates of 0, 68, 135, 270 and 540 kg N ha<sup>-1</sup>. The treatments were broadcast by hand in a single application. There were two replicate blocks based on the basal area of the plots at establishment. The treatment plots were nominally 0.16 ha in area, with an internal measurement plot of 0.04 ha.

Following thinning the mean stocking was 380 stems ha<sup>-1</sup>, with individual plots ranging from 304 to 526 stems ha<sup>-1</sup>. The mean stand parameters at the commencement of the trial were: diameter (DBHOB) 23.9 cm, height 23.2 m and basal area 17.5 m<sup>2</sup> ha<sup>-1</sup>. Diameter was subsequently measured annually and height was measured at the beginning of the study and 6 and 10 y thereafter. Volume was estimated from an equation derived by stem analysis (Carron 1968) for the trial site from a sample of 24 trees selected from a range of treatments at the end of the study. Underbark volumes were calculated from underbark diameters (DBHUB) and height using  $d^2h$  as the equation form. DBHUB was estimated using the regression equation:  $DBHUB = 1.2186 + 0.8305 DBHOB$  ( $r^2 = 0.99$ ). As the tree form changed between the beginning (17 y) and end of the trial (27 y), different coefficients were used to estimate volume at the different measurement times. Despite the considerable increase in growth following application of fertiliser, there was no significant effect of this treatment on tree form. Thus a single volume equation at each age was used to estimate volume.

Wood density was determined for annual growth rings by the maximum moisture content method (Smith 1954). This method is preferred when dealing with small irregularly-shaped samples such as sections of increment cores. It eliminates errors involved in volume determination by immersion, as described in Australian Standard AS1080.3 (Standards Association of Australia 1981). Wood density values reported here are for samples with soluble material unextracted. To obtain the samples, trees within each treatment were ranked into three equal groups using overbark diameter at breast height. One tree was selected from each of the small, medium and large diameter groups in each replicate plot, giving a total of six trees in each treatment. This sampling intensity represented 19% of the population. Leaning, damaged or malformed trees were not sampled, to minimise the possibility of compression wood occurring in the sample. A single increment core (from bark to pith) was taken at breast height (1.3 m) on the north side of each tree using a 12 mm increment borer. After removal, the cores were placed in a plastic bag and moistened with de-ionised water before the bag was sealed. If the samples

could not be processed on the same day, they were stored in a refrigerator at 4°C overnight. No sample was left more than 24 h between sampling and processing.

Three composite surface soil samples (0–10 cm) consisting of 10 small cores each were taken from each plot prior to and 1, 3, 5 and 9 y after application of fertiliser. Organic carbon was determined by the technique of Walkley and Black (1934), and N by a micro-Kjeldahl method (McKenzie and Wallace 1954). Phosphorus was extracted with both 6N HCl and 0.5N NaHCO<sub>3</sub> and determined colorimetrically (Murphy and Riley 1962), and pH was measured following equilibration of a 1:5 soil : 0.1M CaCl<sub>2</sub> solution. As the soil organic carbon, N and pH remained constant throughout the assessment period, only the values prior to treatment are provided. Application of N had no effect on the concentrations of soil P, and thus the concentrations for each rate of P shown in Figures 7 and 8 are the means of the samples from 10 plots (30 sub-samples).

A covariance analysis using initial basal area as a co-variate was used to examine the growth data. As the effect of blocking was not significant when basal area was used as a co-variate, blocking was removed from the model. The data presented in Figures 3, 4 and 5 are least squares adjusted means from the covariance analysis. The data in Figures 1 and 2 are unadjusted means of two replicates with standard errors shown as vertical bars. The growth data in Figures 8 and 9 are also unadjusted mean data. Standard errors are shown for the soil P and wood density data (Figs 6, 7 and 10).

Three-factor exponential rise-to-a-maximum relationships of the form  $f = y_0 + a(1 - \exp^{-bx})$  were fitted to the relationships between applied P and basal area increments using a least squares regression analysis (Figs 3 and 4). Linear regressions were fitted to the responsive part of the relationship between concentrations of soil P and annual increments (Figs 8 and 9). The outlier above the plateau was not included in the linear regressions.

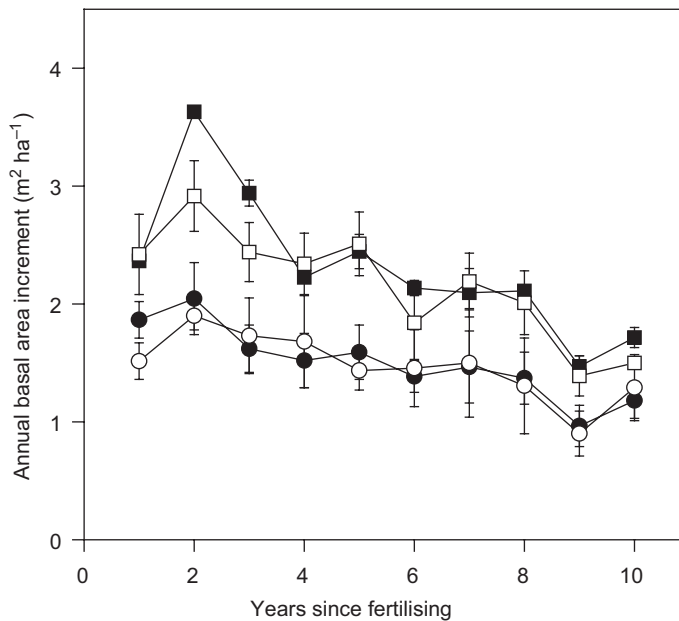
## Results

### Responses to applications of P and N

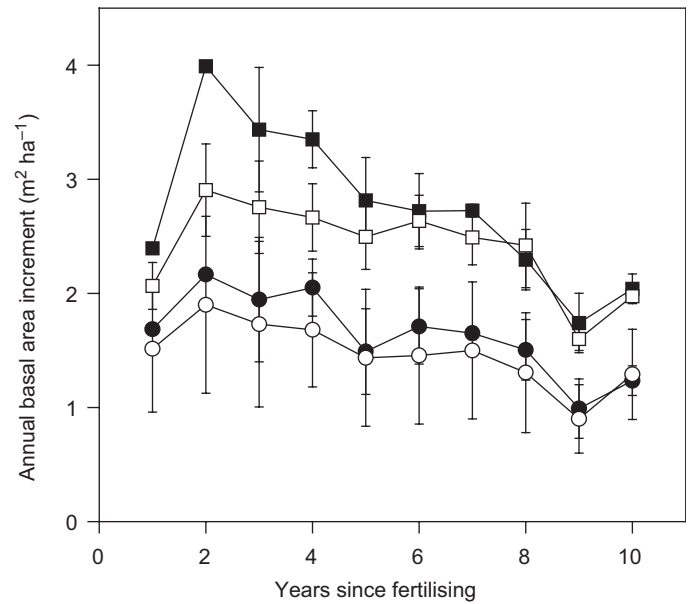
The application of P increased the annual basal area increment in the first year after application, whereas an additional response to N was delayed until the second year after treatment (Figs 1 and 2). The application of N in the absence of P did not increase basal area increment at either low (Fig. 1) or high (Fig. 2) rates of N.

The increase in basal area increment as a result of application of P was sustained throughout the whole 10 y of the study at both the lower (Fig. 1) and higher (Fig. 2) rates of application of P. In contrast, the response to N was short lived — the annual increment of the P90 N135 treatment was greater than that of the P90 N0 treatment only in the second and third years after application (Fig. 1). The response to N was maintained for 3 y when the rate of application of N was increased to 540 kg ha<sup>-1</sup> (Fig. 2). By the fifth growing season there was no effect of N at either low or high rates of N (Figs 1 and 2).

Four years after application of fertiliser, the basal area increment had been significantly increased by the separate application of P ( $P < 0.001$ ). There was a significant interaction between N and P ( $P < 0.05$ ). The interaction between N and P resulted from the absence of a response to N without the application of P, and the



**Figure 1.** Effect of low rates of nitrogen and phosphorus, applied separately and in combination, on the annual basal area increment for 10 y after fertilising (P0 N0 = O; P0 N135 = ●; P90 N0 = □; P90 N135 = ■)



**Figure 2.** Effect of high rates of nitrogen and phosphorus, applied separately and in combination, on the annual basal area increment for 10 y after fertilising (P0 N0 = O; P0 N540 = ●; P360 N0 = □; P360 N540 = ■)

contrasting positive response to N application when P was applied (Figs 1 and 2).

While there was a positive response to P at all rates of N, the magnitude of the P response was influenced by the N application only during the first 4 y of the study (Fig. 3). Without N, the four-year basal area increment was increased by 46% from 6.5 to 9.5 m<sup>2</sup> ha<sup>-1</sup>. For the two highest rates of N (270 and 540 kg ha<sup>-1</sup>) this increased to 12.1 m<sup>2</sup> ha<sup>-1</sup>, an 86% increase in basal area increment (Fig. 3). The shape of the response curve to P thus changed with increasing N. Without N, 80% of the maximum response to P was achieved at the first level of application (45 kg ha<sup>-1</sup> of P), whereas 90 kg ha<sup>-1</sup> of P was required to achieve near maximum growth at the two highest rates of N (270, 540 kg ha<sup>-1</sup>) (Fig. 3).

During the subsequent 6 y of the study there was no additional response to N (Figs 1 and 2). In the three-year period, 4–7 y after fertiliser application, the relative response to P was similar to the response to P without N in the first 4 y. In the three-year period 7–10 y the response to P at the lower rates of application (45 and 90 kg ha<sup>-1</sup>) declined relative to that at the adequate (plateau) rates of P application. For the periods 0–4 and 4–7 y, the lowest rate of P application (45 kg ha<sup>-1</sup>) achieved almost the same basal area increment as the rates of P on the plateau of the response curve. However, the decline in effectiveness of fertiliser P in the period 7–10 y meant that a rate of 180 kg P ha<sup>-1</sup> was necessary to achieve near optimal growth.

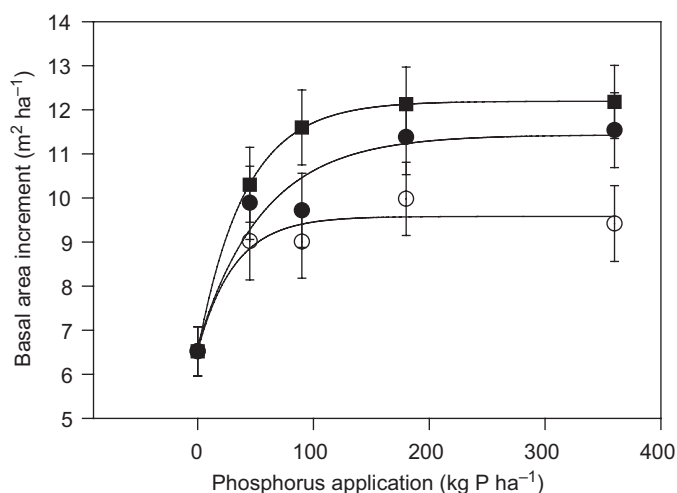
In the absence of a response to N, the response to P at the two highest rates of application (180 and 360 kg ha<sup>-1</sup>), relative to the untreated control, remained almost constant at about 50% over the course of the experiment (Fig. 4). Thus the decrease in the basal area increment at the maximum rates of application of P over the course of the experiment (Fig. 4) was likely to be due to the change in the distribution of growth in the stems rather than a

decrease in the response to P. The relatively constant volume increment across the 10-y period also indicated that the response to P was maintained at the higher rates of application (Fig. 5).

The volume response estimated at 6 y indicated no response to N in the absence of P, and this trend was maintained through to 10 y. Six years after treatment there was a significant ( $P < 0.05$ ), though relatively small, increase in volume growth as a result of applying N in combination with P (Fig. 5). By 10 y the effect of N on volume growth was no longer significant (Fig. 5). The volume response to P was significant at 6 and 10 y after application ( $P < 0.001$ ). This was in line with the sustained effect of P application on annual basal area increment (Figs 1 and 2), and resulted in an increasing difference between the untreated control and treatments with applied P over the 10-y study period (Fig. 5). With the higher rates of application of N and P, an extra 100 m<sup>3</sup> ha<sup>-1</sup> of wood was produced over the 10-y period and the periodic annual increment (PAI) increased from 16.0 to 26.0 m<sup>3</sup> ha<sup>-1</sup>.

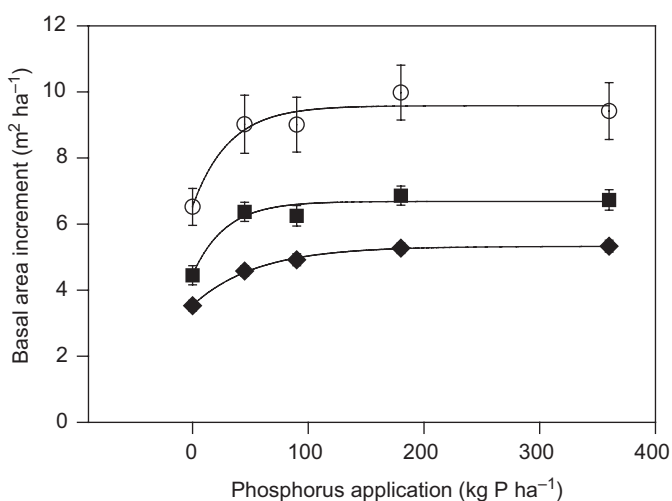
### Effect of fertiliser on soil properties

Fertiliser did not change soil pH, organic carbon or N concentrations, all of which remained at the concentrations found at the beginning of the study. Prior to treatment, HCO<sub>3</sub>-extractable P was 1.4±0.1 µg g<sup>-1</sup> and HCl-extractable P was 112±5 µg g<sup>-1</sup>. The application of phosphorus increased the concentrations of both HCO<sub>3</sub>- and HCl-extractable P in the year after treatment (Figs 6 and 7). Following the initial increase in HCO<sub>3</sub>-extractable P there was a steady decline in all treatments. At the lowest rate of application of P (45 kg ha<sup>-1</sup>) the HCO<sub>3</sub>-extractable P had returned to the pre-treatment concentrations by the fifth year after treatment. With an application of 90 kg P ha<sup>-1</sup>, the HCO<sub>3</sub>-extractable P had declined to almost the pre-treatment concentration 9 y after application. At the two highest rates of application of P (P180 and P360), HCO<sub>3</sub>-extractable P remained well above the pre-treatment



**Figure 3.** Response of basal area increment ( $\text{m}^2 \text{ha}^{-1}$ ) in the first 4 y after application of phosphorus (0, 45, 90, 180, 360  $\text{kg P ha}^{-1}$ ) and different rates of nitrogen ( $\text{kg ha}^{-1}$ ) (N0 = O; N135 = ●; N270 and N540 combined = ■). The fitted response curves were:

N0:	$BA = 6.54 + 3.04(1 - \exp^{-0.032P})$	$r^2(\text{adj}) 0.89$
N135:	$BA = 6.65 + 4.78(1 - \exp^{-0.018P})$	$r^2(\text{adj}) 0.88$
N270, N540:	$BA = 6.52 + 5.68(1 - \exp^{-0.025P})$	$r^2(\text{adj}) 0.99$

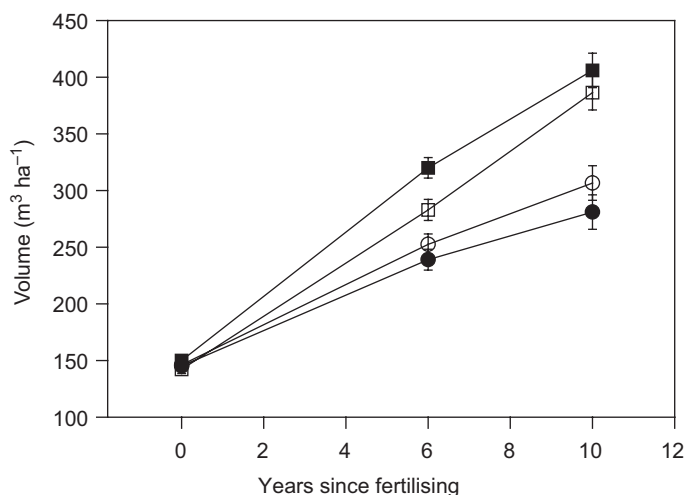


**Figure 4.** Response of basal area increment ( $\text{m}^2 \text{ha}^{-1}$ ) to application of phosphorus in the first four years (O), and in the three-year periods 4–7 y (■) and 7–10 y (◆) after application of fertiliser. The response to phosphorus in the 4–7 and 7–10 y periods is the mean for all the applications of nitrogen at each application of phosphorus. The fitted response curves for the respective periods were:

0–4 y:	$BA = 6.54 + 3.04(1 - \exp^{-0.032P})$	$r^2(\text{adj}) = 0.89$
4–7 y:	$BA = 4.46 + 2.22(1 - \exp^{-0.036P})$	$r^2(\text{adj}) = 0.91$
7–10 y:	$BA = 3.54 + 1.78(1 - \exp^{-0.018P})$	$r^2(\text{adj}) = 0.99$

concentrations throughout the study, despite declining steadily after the initial increase (Fig. 6).

After the initial increase in HCl-extractable P following treatment, concentrations declined for the remaining 8 y of the trial, with the greatest losses occurring in the first 4 y following the increase



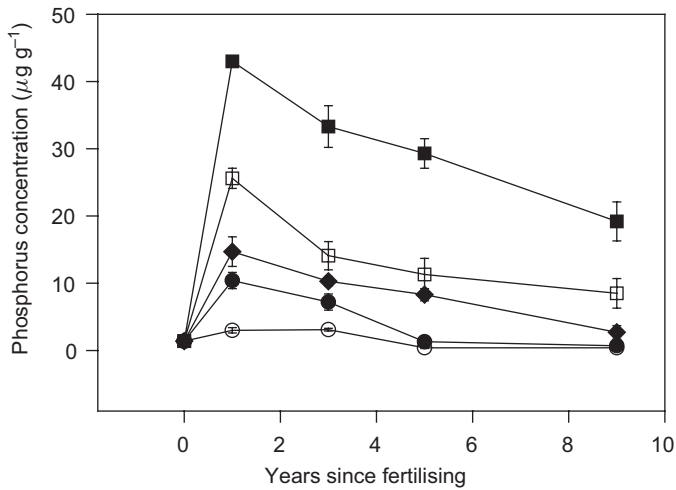
**Figure 5.** Response in volume ( $\text{m}^3 \text{ha}^{-1}$ ) over the ten years after application of phosphorus and nitrogen separately and in combination (P0 N0 = O; P0 N540 = ●; P360 N0 = □; P360 N540 = ■)

(Fig. 7). At the lower rates of application of P, within 9 y the HCl-extractable P concentrations had declined to almost the concentrations found in the untreated control (Fig. 7).

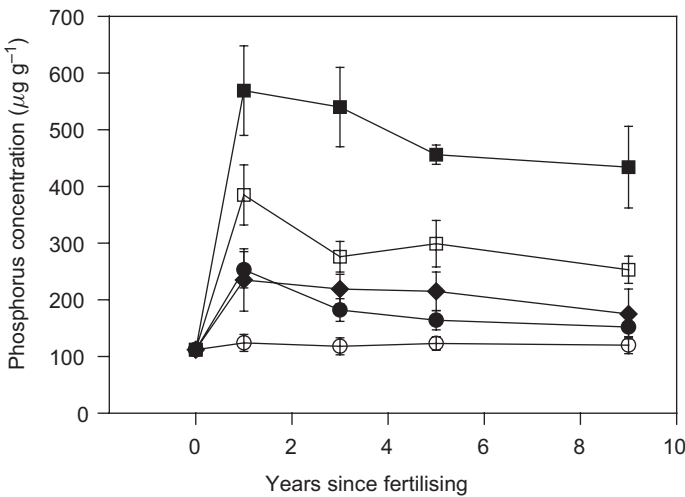
Annual basal area increment was related to the availability of P. Annual increment expressed as a fraction of the maximum increment for each year was related to the concentration of both  $\text{HCO}_3^-$  and HCl-extractable P in the soil (Figs 8 and 9). Both these relationships showed a responsive phase where higher concentrations of soil P were associated with higher annual increments, and a non-responsive phase where further increases in concentration of soil P did not result in any further increase in growth. This suggested that the decline in growth at the lower rates of application of P, towards the end of the monitoring period (Fig. 4), was likely to be a result of a decline in P availability over time (Figs 6 and 7). The point at which there was no further increase in growth was  $17 \mu\text{g g}^{-1} \text{HCO}_3^- \text{P}$  (Fig. 8) and  $330 \mu\text{g g}^{-1} \text{HCl-P}$  (Fig. 9).

#### Effect of fertiliser application on wood properties

Basic density of the wood at breast height increased until the stand was thinned at age 17 y, and then appeared to decline slightly. The most obvious impact of fertiliser was the decline in wood density to  $420 \text{ kg m}^{-3}$  in the P360 N540 treatment in the second to fourth year after treatment (Fig. 10). The basic density of wood of the control (P0 N0) treatment appeared to be higher, in the period after fertiliser application, than the basic wood density of all other treatments. During the period prior to application, this treatment consistently had the highest basic density of all the treatments. This suggests that the effect of the P360 N0 and P0 N540 treatments in reducing wood density may not have been as great as it appeared (Fig. 10). The mean basic density, measured prior to thinning and application of fertiliser at  $570 \text{ kg m}^{-3}$ , was relatively high for *P. radiata*. With the exception of the wood produced by the P360 N540 treatment 2–4 y after application, the basic density remained near or above  $500 \text{ kg m}^{-3}$  for the 10 y after treatment. Despite the sustained higher growth rates with high rates of application of P, the reduction in the basic density of wood was relatively small.



**Figure 6.** Effect of the application of phosphorus (P0 = ○; P45 = ●; P90 = ◆; P180 = □; P360 = ■) on the concentration of bicarbonate-extractable (HCO<sub>3</sub>) phosphorus in the surface soil (0–10 cm) for 9 y after application of fertiliser



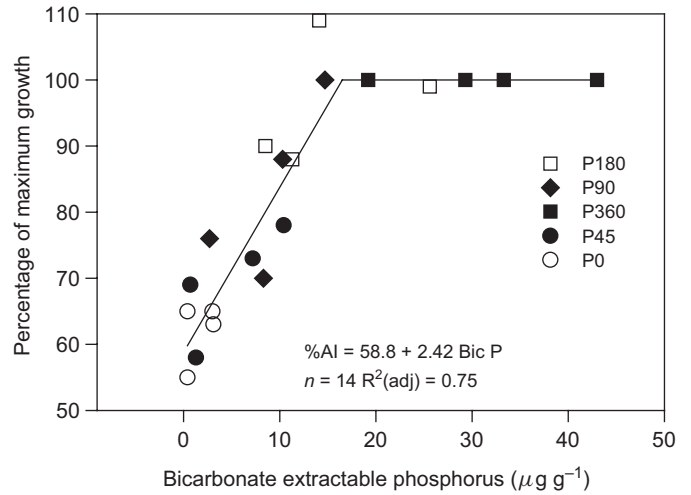
**Figure 7.** Effect of the application of phosphorus (P0 = ○; P45 = ●; P90 = ◆; P180 = □; P360 = ■) on the concentration of acid-extractable (6N HCl) phosphorus in the surface soil (0–10 cm) for 9 y after application of fertiliser

**The effect of fertiliser application on sawlog products**

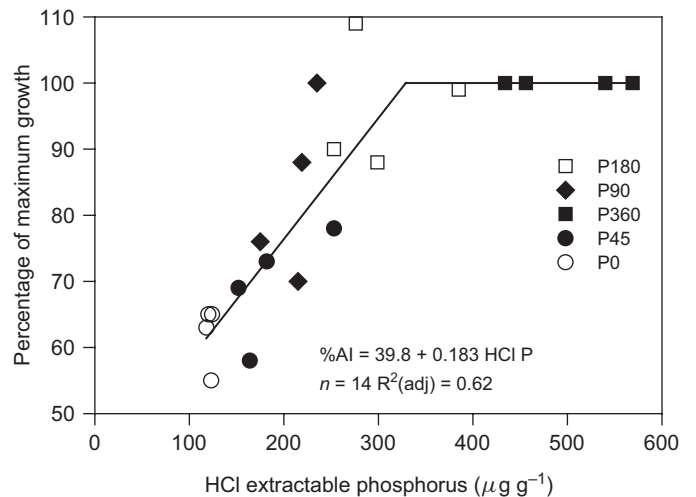
The application of P increased the proportion of the volume which was classified as sawlog material by about 8%, and reduced the proportion of volume which was classified as small sawlog material by a similar amount. Thus the combined total of sawlog and small sawlog remained relatively constant at about 70% of the total volume (Table 1). The proportion of the crop that was classified as industrial wood (chipwood) and waste remained relatively constant across the treatments at 14% and 15.3% respectively.

**Discussion**

Maximum growth on this site was achieved with the application of P and N in combination. In the first 4 y after treatment, basal area increment was increased by up to 86%. Of this response,

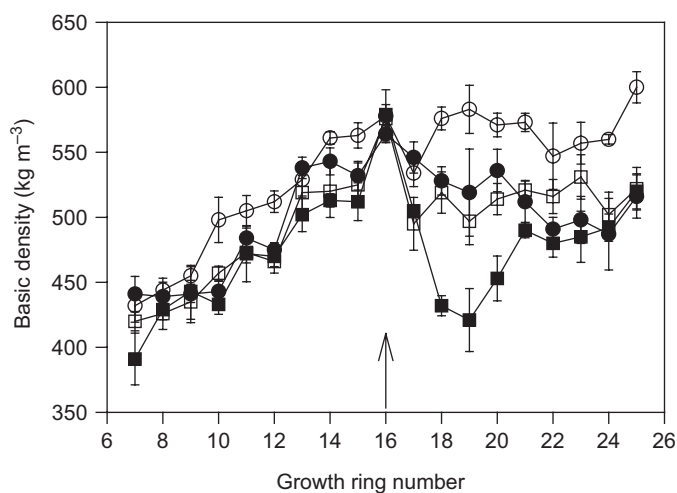


**Figure 8.** Relationship between the concentration of bicarbonate-extractable P (HCO<sub>3</sub> P) in the surface soil and annual basal area increment expressed as a percentage of the maximum increment each year. Relationships are based on sampling and measurements 1, 3, 5 and 9 y after application of fertiliser (P0 = ○; P45 = ●; P90 = ◆; P180 = □; P360 = ■).



**Figure 9.** Relationship between the concentration of HCl-extractable P (HCl P) in the surface soil and annual basal area increment expressed as a percentage of the maximum increment each year. Relationships are based on sampling and measurements 1, 3, 5 and 9 y after application of fertiliser (P0 = ○; P45 = ●; P90 = ◆; P180 = □; P360 = ■).

phosphorus application contributed 46% and N application 40%. In the subsequent 6 y during which there was no residual effect of N, P alone increased increment by 48%. The combined effect of the application of P and N was to increase volume production over the 10-y period by 69% or 100 m<sup>3</sup> ha<sup>-1</sup>, thus increasing the PAI from 16 to 26 m<sup>3</sup> ha<sup>-1</sup>. While a growth rate of 26 m<sup>3</sup> ha<sup>-1</sup> y<sup>-1</sup> appears reasonable for a stand of about 380 stems ha<sup>-1</sup>, it was well below the potential of the site, as the single N application was effective in increasing growth for a maximum of only 4 y. If the N supply had been maintained at adequate levels throughout the study, the growth rate of this thinned stand might have been further increased because water deficit was unlikely to have been a major constraint to growth in this 1100 mm rainfall zone.



**Figure 10.** Effect of nitrogen and phosphorus separately and in combination on wood basic density ( $\text{kg m}^{-3}$ ) in the 9 y after application (P0 N0 =  $\circ$ ; P0 N540 =  $\bullet$ ; P360 N0 =  $\square$ ; P360 N540 =  $\blacksquare$ ). The arrow on the x axis indicates the time of application.

The absence of a response to N without P is similar to that shown for thinned *P. radiata* of similar age in NSW (Snowdon and Waring 1990). Although the response to P was limited by the supply of N, there was still a substantial response to P in the absence of applied N. This was despite the low concentration of soil N, 0.103%, and the high C:N ratio of 24:1, suggesting that the soil was deficient in N. The high C:N ratio found here was similar to that in native jarrah forest soils (Hatch 1955; Hingston *et al.* 1981). The very low concentration of  $\text{HCO}_3$ -extractable P in the unfertilised treatments of  $1.4 \mu\text{g g}^{-1}$ , and the substantial P response, demonstrated that P was the primary limiting nutrient on this site.

The relative effectiveness of applied P appeared to decline over the 10-y study period. The growth response at the lower rates of P application, and the availability of applied P measured by concentrations of both  $\text{HCO}_3$ - and HCl-extractable P, both declined after an initial increase after treatment. The assessment of the relative effectiveness of applied P was based on the growth of the treatments without applied N as the response to N lasted only 4 y. This made it impossible to compare the P response over time in the presence of an adequate supply of N. While the growth response to P in the absence of applied N was about 50%, the response to N and P in the first 4 y after treatment was 86%. This may have resulted in an optimistic assessment of the effectiveness of P over time, as the P application necessary to produce maximum growth was lower in the absence of applied N. If the N supply had been maintained at or near optimal levels, the demand for P to sustain growth may have been higher than in the absence of applied N. Although the availability of P declined over time, the response at the higher application rates was sustained over the course of the 10-y period. This is consistent with studies that have demonstrated sustained P responses for *P. radiata* within a single rotation (Flinn *et al.* 1979; Turner 1982), and between rotations (Ballard 1978; Gentle *et al.* 1986). *Pinus radiata* thus appears to have the capacity to absorb applied P long after application on a range of soils.

While the capacity of both  $\text{HCO}_3$  and HCl to extract P from the lateritic gravel soil declined over time, the trend in concentrations

**Table 1.** Influence of phosphorus (P) application on the distribution of log products at age 27 y (10 y after treatment). Data are percentages of the total volume for each treatment; figures in parentheses are standard errors

P applied ( $\text{kg ha}^{-1}$ )	Distribution of volume by product category (%)			
	Sawlog	Small sawlog	Industrial wood (chip)	Waste
0	52.0 (5.0)	17.1 (2.7)	14.1 (0.9)	16.8 (2.4)
45	62.2 (2.8)	10.6 (2.3)	12.0 (1.5)	14.3 (0.9)
90	59.0 (1.1)	12.0 (0.9)	14.4 (1.6)	14.6 (0.4)
180	62.9 (1.4)	9.2 (1.5)	13.6 (1.7)	14.3 (0.5)
360	57.5 (1.4)	11.1 (0.6)	14.9 (1.4)	16.5 (1.2)

of extractable P differed with the two extractants — the concentration of  $\text{HCO}_3$ -extracted P declined faster than that of HCl-extracted P. The reduction in  $\text{HCO}_3$ -P over time was presumably due to the conversion of the soluble applied P to forms that were not extractable by  $\text{HCO}_3$  (Barrow and Shaw 1976). The decline in  $\text{HCO}_3$ -P found here was similar to that shown on a previously unfertilised lateritic soil by Bolland and Bowden (1982). The reasonably strong linear relationship between  $\text{HCO}_3$ -P and annual basal area increment indicated that  $\text{HCO}_3$ -P might provide a useful indication of P availability for *P. radiata* on the lateritic gravel soils of the Darling Plateau region of WA. On this soil a concentration of  $\text{HCO}_3$ -P of  $15\text{--}20 \mu\text{g g}^{-1}$  indicated that the supply of P was adequate for *P. radiata*.

Numerous studies on the availability of P to agricultural crops and pastures have demonstrated a decline in the effectiveness of fertiliser P over time (Arndt and McIntyre 1963; Russell 1977; Barrow and Carter 1978). Although such a decline occurred in this study the decrease was relatively modest, with growth being maintained over a 10-y period at the higher application rates. A number of mechanisms could contribute to the sustained response to P by *P. radiata*. The retention of foliage on *P. radiata* for an average of 2.5 y under Western Australian conditions (Warren and Adams 2000), and the capacity of *P. radiata* to retranslocate nutrients both from active needles during the annual growth cycle (Fife and Nambiar 1982, 1984), and from needles prior to senescence (Baker 1983), would reduce the demand for nutrients. These mechanisms would reduce the reliance of current growth on the current nutrient supply from the soil.

In contrast to the sustained P response, the effect of N was short-lived with even the highest rate of application ( $540 \text{ kg N ha}^{-1}$ ) increasing growth for only 4 y after treatment. Short-term growth responses to applications of N have been reported for a range of conifers (Miller and Cooper 1973; Camire and Bernier 1981; Hunter and Hoy 1983; Mead *et al.* 1984). The short duration of the response to N in this study was similar to the response to N and P by *P. radiata* on the coastal sand plain in WA (McGrath *et al.* 2003). The short-term nature of these responses indicates that periodic applications of N are necessary for a sustained response to this element. The same conclusion was reached by Miller and Cooper (1973) and Woollons and Will (1975).

Two Australian studies have indicated that the efficiency of N uptake was improved by application in spring rather than autumn.

In young *P. radiata* in WA, both the absorption of N and the growth response to N were improved by delaying the application from autumn to spring (McGrath and McArthur 1990). In South Australia, most of the increase in N absorption following application in spring occurred in the first 20 weeks after treatment, with a second though smaller peak in N absorption occurring in the second year after application (Carlyle 1995). A model that predicted N uptake and leaching indicated greater N uptake and lower leaching loss in *P. radiata* plantations from spring (September) applications than from early winter (June) applications (Carlyle 1995). In contrast, there was no difference in the growth response to N applied in either autumn or spring to a 30-y-old *P. radiata* plantation on the Swan Coastal Plain of WA (McGrath *et al.* 2003). Thus it is unclear if the modest response to N found in this study could have been increased or prolonged by applying the fertiliser in spring rather than in autumn. More work is required to determine if there is a difference in the efficiency of N uptake when applied in different seasons in the seasonally dry environment found in southern Australia.

Despite the large and sustained increase in growth as a result of the application of P, the wood basic density did not appear to decline. This was consistent with the findings of Gentle *et al.* (1968) who showed little effect of P fertiliser on wood density. The high growth rates achieved when N was applied in combination with P were associated with a temporary reduction in wood density for the same period during which growth was increased by the application of N. Although application of P provided the greatest increase in growth, application of N reduced wood density to a greater extent than did the application of P.

The basic wood density in this study was considerably higher than that for *P. radiata* in a high quality stand near Tumut, NSW (Woollons *et al.* 1995), and higher than the values generally found for *P. radiata* in Australia (Cown 1992). The lowest density reached in the P360 N540 treatment — about  $420 \text{ kg m}^{-3}$  — was similar to the basic density of unfertilised stands at Tumut where only a small (5%) decrease in wood density was found by Woollons *et al.* (1995). Substantial reductions in wood density have been reported in New Zealand following the application of fertiliser to sites that were very nutrient deficient (Cown 1977). If the supply of N had been maintained at or near adequate levels, as in the study by Woollons *et al.* (1995), then the lower wood density found in the period after the application of fertiliser may have been maintained for a longer period. When the N status of young *P. radiata* was maintained at a high level by annual applications of N, basic density remained low (I. Dumbrell *unpublished* 2002). The relatively high basic densities that were found in this study indicate that fertiliser and thinning had not reduced wood density to levels that caused problems for structural wood. A minimum basic density of  $400 \text{ kg m}^{-3}$  has been set for clearwood to ensure satisfactory in-grade performance of framing members (Standards Association of Australia 1988). Even after significant reductions in wood density following application of fertiliser, the mean basic density remained above this value in this study.

The increase in the proportion of the total volume that was classified as sawlog in the treatments receiving fertiliser, relative to the untreated control, was due to an increase in log diameter rather than any change in the form of the logs. The combined proportion of sawlog and small sawlog remained constant, as did

the proportion of industrial wood (chips) and waste, indicating that stem form was largely determined by the growing conditions prior to the thinning at age 17 y. Thus fertiliser had no impact on the classification of logs on the basis of log quality. The movement of logs from a smaller and hence lower-value category (small sawlog) to a larger higher-value category (sawlog) enhanced the value of the response to fertiliser above the increase in volume.

## Conclusions

While the response to P fertiliser declined over time, the strong response to relatively modest applications of 45 and  $90 \text{ kg P ha}^{-1}$  ( $0.5$  and  $1.0 \text{ t superphosphate ha}^{-1}$ ) on a soil with a high capacity to immobilise P demonstrated that the application of P on such sites was likely to be very rewarding economically. While the response to N fertiliser was substantial in the short term, the limited long-term response to this element suggests that repeated applications of N during the rotation would be necessary to optimise the response to N. As there are more than 20 000 ha of plantation on similar sites in WA, it is clear that substantial economic gains can be made with mid-rotation fertiliser applications. Optimising the rate and timing of applications of N is an issue that needs to be resolved.

At the application rates used in this study, no long-term detrimental effect of fertiliser on wood density was found. The larger diameter of the fertilised trees increased the proportion of volume classified as sawlog rather than as lower-value products. This increase in log diameter following application of fertiliser and thinning increased the value of the growth response to a greater extent than is indicated by the increase in volume alone.

## Acknowledgements

We thank John Bopp, Grant Hansen, Bob Hingston, Peter Jenkins, John Kruger, Keith Mungham and Terry Reilly for assistance with the establishment, maintenance and measurement of the trial. Jane Clayton, Shelley McArthur and Lin Wong analysed the soil samples. Richard Harper provided helpful comments on an earlier draft.

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