Growth and nutrient relationships of juvenile *Pinus pinaster* grown on ex-farmland in Western Australia

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Summary

The action and interaction of N, P and K on the growth and nutrient relationships of young *Pinus pinaster* were examined on three sites with dissimilar soils and land use histories in Western Australia. The three sites were a fertile gravelly loam (ex-pasture), a deep fertile sand (ex-pasture) and a deep infertile sand (newly cleared banksia woodland). Mean annual rainfall over the 3 y of the experiment was 615 mm, concentrated from May to September, with mean annual evaporation of about 2150 mm. Phosphorus was the key nutrient limiting growth on the infertile sands. Tree height was significantly increased on this site by the application of 140 kg P ha^{-1}. No effect was found on the other two more fertile sites. The addition of 276 kg N ha^{-1} and/or 250 kg K ha^{-1} did not increase height growth on any site. There was a negative N × P interaction at all sites, such that the application of N in combination with P significantly reduced tree height growth and lowered P concentrations in the foliage. Foliar P concentrations below 0.07% were found to be deficient for optimum early growth of *P. pinaster* on all sites. Three years after the treatments were applied, a mean concentration of plant-available P (Olsen bic-P) as low as 0.75 mg kg^{-1} in the surface soil was sufficient for adequate early growth of *P. pinaster*, but a mean bic-P of 0.04 mg kg^{-1} was clearly inadequate. Therefore, while P is the critical element in the optimal early growth of *P. pinaster,* the amount required is very small.

Keywords: nitrogen; phosphorus; potassium; fertilisers; foliar nutrition; soil chemistry; growth rate; *Pinus pinaster*; Western Australia

Introduction

Dryland salinity is acknowledged as the most serious land degradation issue in southern Western Australia (WA), with 1.8 M ha of agricultural land already salinised and an estimated 8.8 M ha at risk of salinisation. Revegetation of up to 3 M ha of cleared agricultural land has been proposed as part of the WA Salinity Action Plan (State Salinity Council 2000). Due to its reputation as a hardy species, *Pinus pinaster* Ait. has been identified as potentially having a significant role in the revegetation of the medium-rainfall zone (400–600 mm y^{-1}) of the agricultural area in south-western WA. *Pinus pinaster* can tolerate dry conditions and is well suited to sandy sites with at least 500 mm annual rainfall. Selective breeding of this species in WA over three generations has produced major improvements in growth rate, stem straightness and (reduced) branch size. More recent breeding work has produced trees that are better adapted to sites with an annual rainfall of only 400 mm (Harwood and Bush 2002). In addition to their value in combating salinity, *P. pinaster* plantations will contribute to carbon sequestration (Shea *et al*. 1998). A large-scale planting program based on *P. pinaster* commenced in1994, and now 3500 ha are planted annually.

Western Australia already has the largest area of *P. pinaster* plantations in the Southern Hemisphere, with an established market for its products, such as structural veneer board and laminated veneer lumber for which it is particularly suited. *P. pinaster* has wood properties broadly similar to those of *P. radiata*, and this similarity allows it to complement sawn timber and medium density fibreboard already produced from a large *P. radiata* resource (Harwood and Bush 2002). To date these plantations have been restricted to the areas with >750 mm y^{-1} rainfall on the infertile coastal sand plain, but these areas are in increasing demand for urban expansion. Little is known of *P. pinaster's* critical nutrient concentrations and early-rotation growth responses to additional nutrient supplies when grown on the improved ex-pasture sites (with increased fertility and soil water storage) that are now being planted in the medium-rainfall zone of WA. If the large-scale plantations desired in WA are to be established, *P. pinaster* must be commercially viable in this environment. To that end, its early-rotation nutrient status and growth need to be understood and optimised.

Early nutrition research on *P. pinaster* in WA (Kessel and Stoate 1938; Stoate 1950; Hopkins 1960; Keay *et al.* 1968; Butcher 1982) was conducted with genetically unimproved stock growing on infertile ex-native vegetation sites on the coastal sand plain, with annual rainfall >750 mm. This series of experiments showed that phosphorus (P) was the main nutrient limiting growth of *P. pinaster* on sandy soils (Butcher 1982). On infertile (ex-native forest) sites the application of phosphorus was critical to establishment, and re-application prior to canopy closure was essential for adequate growth (Hopkins 1960). Nitrogen (N) and potassium (K) applied at planting gave no growth response in the absence of phosphorus (Stoate 1950; Butcher 1982). Later in the rotation, basal area growth increased with the application of N and NP fertiliser. These increases in basal area growth were superior to those obtained with P alone (Hopkins 1960; Keay *et al*. 1968; Butcher 1982). Very low concentrations of trace elements have been found in foliage of young *P. pinaster* growing on both ex-native forest and ex-farmland. Application of zinc (Stoate 1950; Butcher 1982), copper and manganese (Dumbrell unpublished data) increased foliar concentrations to levels that are currently considered adequate (Reuter and Robinson 1997) and corrected deficiency symptoms, but did not result in an increase in tree growth.

This project was commenced in 1996 to examine the growth and nutrient relationships of *P. pinaster* now being planted on relatively fertile ex-farmland in the medium rainfall (400–600 mm y^{-1}) zone of WA. The overall aim was to be able to optimise early growth of *P. pinaster* by identifying and correcting nutrient deficiencies. A specific aim was to determine critical concentrations of nutrients in foliage and soil. This paper describes growth response to N, P and K and the relationship between soil and foliar nutrients and growth from three replicated N × P × K factorial experiments on three different soils in the medium-rainfall zone of WA.

Methods

Three sites with a similar climate but differing soil types and previous land use were chosen for an investigation of the interaction between N, P and K on the early growth of *P. pinaster*. The three sites are in the Gingin area about 100 km north of Perth, WA (Site 1: 31.15ºS 116.15ºE, Site 2: 31.10ºS 115.45ºE, Site 3: 31.15ºS 115.40ºE). Long-term mean annual rainfall is about 600 mm with 85% falling in the months May to September, while mean annual evaporation is about 2150 mm. These figures were derived from data from nearby recording stations of the Bureau of Meteorology and of Agriculture Western Australia. The sites chosen are representative of sites available for the further expansion of *P. pinaster* on farmland in this region.

Experimental sites

The soil at Site 1 has formed from deeply weathered granites of the Yilgarn Craton. Generally these soils have gravelly surface horizons which overlie clay that often has weathering profiles to 30 m deep overlying bedrock. They are typical of the lateritic gravels of the Darling Plateau described by McArthur (1991). The soil of the experimental site is typically a dark reddish brown loam in the top 15 cm with 40% ferricrete gravel (3–4 mm), which grades to a yellowish brown loamy sand with 50% ferricrete gravel (3–4 mm) between 15 and 250 cm.

Site 2 is on the Cretaceous sediments of the Perth Basin. Here, soil parent materials are aeolian sands that have been deposited over deeply weathered sediments. The soils have a dark stained (very dark greyish brown) medium-grained sand surface horizon overlying a brownish-yellow medium-grained sand >300 cm deep. This soil is typical of the deep sandy soils of the Dandaragan Plateau (McArthur 1991).

Table 1. Fertiliser treatments applied at each site

Treatment	Elemental rates (kg ha^{-1})		
	N	P	K
Nil	0	0	0
N	276	–	–
P	–	140	–
K	–	–	250
NP	276	140	–
NK	276	–	250
PK	–	140	250
NPK	276	140	250

N applied as 600 kg ha^{-1} urea (46% N)
P applied as 800 kg ha^{-1} double super (17.5% P)
K applied as 500 kg ha^{-1} muriate of potash (49.6% K)

Prior to planting in 1996, both Sites 1 and 2 supported a legume-based (subterranean clover) pasture that had a long history of fertiliser application.

The soils of Site 3 have formed on the Quaternary sand dunes of the Swan Coastal Plain and correspond to the Karrakatta sands described by McArthur (1991). The sand profile is coarse-grained with a dark-stained surface (very dark greyish-brown, 0–10 cm), then pale brown to 40 cm over a brownish-yellow medium-grained sand to at least 300 cm deep. This site had recently been cleared of banksia woodland and had not received fertiliser, and was thus expected to be extremely nutrient deficient.

Experimental methods

The experimental design used was a fully randomised N × P × K factorial experiment with eight treatments (Table 1) replicated three times at Sites 1 and 3, and twice at Site 2. All trees were 1 y old at the time of treatment application (July 1996) and planted at about 1515 stems ha^{-1} (sph) for Site 1 and 1800 sph at Sites 2 and 3. Mean stocking rates after 1 y at the time of treatment application were 1416 sph, 1517 sph and 1714 sph respectively. The area of each treatment plot was 0.06 ha, while the area of each internal measurement plot was about 0.018 ha, which gave an average of 25, 27 and 31 trees per plot for Sites 1, 2 and 3 respectively.

Fertiliser was broadcast evenly by hand over the entire plot. Each plot also received a basal application of copper sulphate (5 kg ha^{-1}), manganese sulphate (5 kg ha^{-1}) and zinc sulphate (10 kg ha^{-1}).

Tree height was measured annually and soil samples were collected prior to treatment application and at the end of 3 y. Sampling of foliage for nutrient analysis at Site 3 commenced in May 1997, 10 mo after the experiment commenced, and continued quarterly until August 1998, then monthly for the following year. Foliage samples were collected from five randomly selected trees within the internal measurement plots and consisted of the youngest fully expanded needles from the upper third of the crown.

Two weeks prior to the final height measurement and soil sampling, Site 2 was inadvertently re-fertilised by the landowner with an unknown rate and mix of fertiliser. At this point the trees were not growing so the final tree heights were not compromised. However, the soil analysis was affected, such that no final soil nutrient data are available for this site. Final foliar samples had been collected before the re-fertilising.

Analysis of total nitrogen in both soil and foliage was by the Kjeldahl method (M^{c}Kenzie and Wallace 1954). Analysis of total potassium in soil and foliage was by flame photometer following acid digests. Foliar phosphorus was analysed colorimetrically using a spectrophotometer (Kitson and Mellon 1944) following acid digest (Piper 1942), and total soil phosphorus was determined colorimetrically by the modified Murphy and Riley (1962) method after hydrochloric acid digestion. Plant-available soil phosphorus was analysed following bicarbonate digestion of air-dry soil samples (<2 mm) using the Olsen method (Rayment and Higgins 1992). Soil organic carbon was determined using Walkley and Black's rapid titration method (Piper 1942) and pH was determined using 1:5 soil–water suspension.

Statistical analysis

A three-factor exponential rise to a maximum (Mitscherlich) equation ($y = y_0 + a(1-e^{-bx})$) (Black 1993[1]) was fitted to the relationship between the concentration of phosphorus in foliage (measured in June 1999) and annual height increment for the 1998–99 growing season. Relative height increment, defined as the height increment of individual plots as a percentage of the maximum height increment for each of the three sites, is also presented here. The relative height data remove the differences in growth between the sites that were not due to treatment effects.

Critical concentration in this study is defined as the nutrient concentration corresponding to 90% of the maximum relative height growth determined from the Mitscherlich equation (Ware *et al.* 1982).

Analysis of variance of final mean tree heights was used to assess all; site; fertiliser treatment; site by fertiliser treatment and fertiliser treatment interaction differences. SYSTAT statistical software was used for the analyses.

Results

Tree growth

Height growth over the three-year period ranged from 206 cm to 244 cm with mean annual increment (MAI) of 69–81 cm y^{-1} at Site 1, and from 290 cm to 378 cm (MAI 97–126 cm y^{-1}) at Site 2. For the +P treatments at Site 3 height growth ranged from 220 cm to 275 (MAI 73–92 cm y^{-1}) and for the −P treatments height growth ranged from 73 cm to 117 cm (MAI 24–39 cm y^{-1}) (Fig. 1).

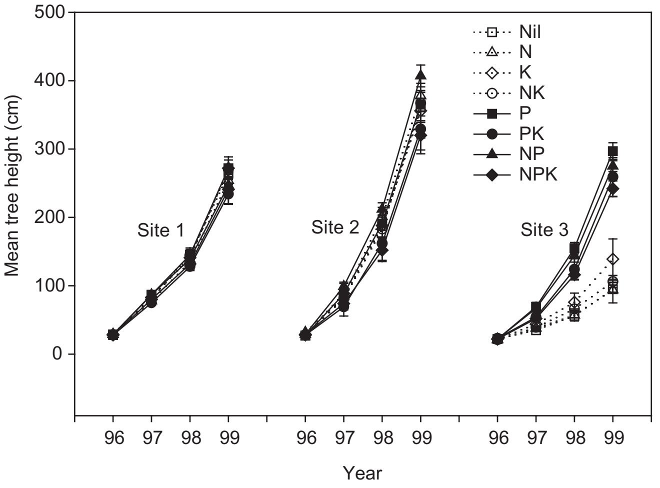

Figure 1. Mean treatment height growth at each site over three years from age 1 to 4 y

There was no significant difference in total height growth or MAI between any treatment at Sites 1 and 2 in each of the three growing seasons following treatment application. At Site 3 there was a significant difference ($P < 0.001$) in height growth in each year between trees in the four treatments that received an application of phosphorus and the four treatments that did not. However, within the Nil, N, K and NK (−P) treatments and the P, NP, PK and NPK (+P) treatments, there was no significant difference between individual treatments (Table 2).

Analysis of variance of mean height growth at August 1999 in all plots across the three sites showed that site, P, site × P and N effects were all highly significant ($P< 0.001$), while the N × P interaction ($P < 0.01$) was also significant.

While height growth at all sites differed significantly ($P < 0.001$), the difference between Sites 1 and 3 was brought about by the very poor growth in the −P treatments at Site 3 alone. Phosphorus is the major limiting nutrient for *P. pinaster* growth in WA. This is highlighted by the large and highly significant ($P < 0.001$) growth response at Site 3 between the +P and −P treatments. The addition of phosphorus increased mean height growth by 146% over the –P treatments by age 4 y on this P-deficient ex-banksia woodland site. In addition, the single large application of phosphorus was enough to increase mean height of the +P treatments (246 cm) to be similar to the mean height increment (1996–99) of all treatments on the ex-improved pasture at Site 1 (228 cm) (Table 2). This removed the significant difference between Site 1 and the +P treatments at Site 3. The large difference in height growth at Site 3 between trees in the +P and −P treatments caused the highly significant ($P < 0.001$) site × P interaction.

The application of nitrogen reduced tree heights in 75% of treatments across all three sites. Pairwise comparisons of −P treatments showed that there was no significant effect on growth from nitrogen application. However, the application of nitrogen significantly reduced tree heights in all of the +P treatments (Table 2). The consistency and magnitude of the negative response to the application of nitrogen over all sites determined the significance ($P < 0.001$) of this treatment. The effect was greatest

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[1] The Mitscherlich equation is widely discussed in Black (1993) and refers to the original work by Mitscherlich (1909).

Table 2. Mean height increments and standard errors (in brackets) for all treatments at each site

Site	Treatment	Mean height increment (cm)				MAI
		1996–97	1997–98	1998–99	1996–99	1996/99
1	Nil	57 (2)	59 (1)	118 (9)	234 (9)	78 (3)
	N	50 (3)	57 (5)	118 (4)	225 (5)	75 (2)
	K	54 (3)	58 (3)	131 (9)	243 (13)	81 (4)
	NK	53 (7)	64 (3)	126 (9)	243 (1)	81 (0)
	P	59 (5)	58 (6)	127 (7)	244 (16)	81 (5)
	PK	57 (4)	52 (3)	108 (3)	217 (5)	72 (2)
	NP	47 (4)	53 (3)	106 (9)	206 (15)	69 (5)
	NPK	52 (4)	51 (4)	109 (14)	212 (22)	71 (7)
2	Nil	56 (1)	104 (14)	174 (5)	334 (19)	111 (6)
	N	52 (0)	118 (0)	176 (0)	346 (0)	115 (0)
	K	61 (11)	99 (12)	168 (13)	328 (37)	109 (12)
	NK	53 (3)	102 (5)	184 (7)	339 (16)	113 (5)
	P	61 (4)	103 (3)	174 (0)	338 (7)	113 (2)
	PK	70 (2)	113 (3)	195 (6)	378 (11)	126 (4)
	NP	41 (12)	93 (12)	167 (11)	301 (35)	100 (12)
	NPK	44 (6)	79 (7)	167 (5)	290 (18)	97 (6)
3	Nil	13 (1)	20 (6)	40 (12)	73 (19)	24 (6)
	N	17 (2)	19 (1)	37 (1)	73 (3)	24 (1)
	K	22 (3)	32 (9)	63 (16)	117 (28)	39 (10)
	NK	18 (2)	26 (1)	41 (1)	85 (0)	28 (0)
	P	48 (5)	86 (2)	142 (8)	276 (11)	92 (4)
	PK	45 (4.8)	77 (4)	131 (2)	253 (7)	84 (2)
	NP	31 (3)	70 (11)	135 (13)	236 (27)	79 (9)
	NPK	30 (2)	64 (4)	126 (6)	220 (11)	73 (4)

MAI = mean annual increment

and most consistent in conjunction with the application of phosphorus, which is highlighted by the significant ($P < 0.01$) negative interaction between N and P.

Foliar nutrient relationships

As well as the large growth differences, foliar P concentrations at Site 3 were markedly increased by the application of phosphorus. Foliar phosphorus concentrations were highest between the months of May and September, when the soil profiles are wettest.

The N × P interaction shown for height growth was evident in the foliar P concentrations, such that, in the absence of applied P where all P concentrations were low, there was little or no effect of N on foliar P concentrations. In treatments with applied P, however, the application of N resulted in a marked and prolonged depression in foliar P concentrations over two and a half years (Fig. 2).

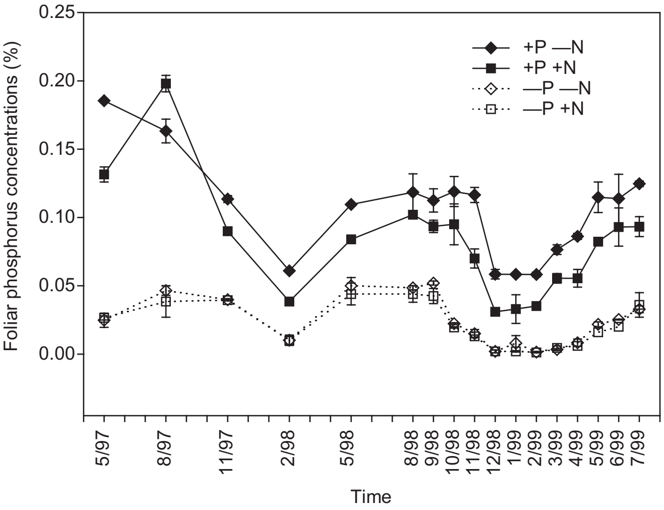

Figure 2. Mean foliar phosphorus concentrations (%) over 26 months at Site 3. The youngest fully expanded needles from the upper third of the crown of five randomly selected trees per plot were used for analysis.

There were no significant differences in mean concentrations of foliar N (not shown) between treatments that received nitrogen and those that did not. Foliar samples collected in late winter each year (1997, 1998 and 1999) showed mean concentrations in the +N treatments declining from 2.12% to 2.01% and finally to 1.54%. Concentrations in the −N treatments also declined from 1.80% to 1.76% and finally to 1.31%. Mean foliar K concentrations were consistently higher over the two-and-a-half-year sampling period in the treatments that received potassium compared to those that did not. Although the difference was consistent it was not significant and did not affect tree growth. Concentrations of foliar K were steady over the duration of the trial, with a mean of 0.41% in the +K treatments and 0.30% in the −K treatments. The application of potassium had no significant effect on concentrations of foliar phosphorus.

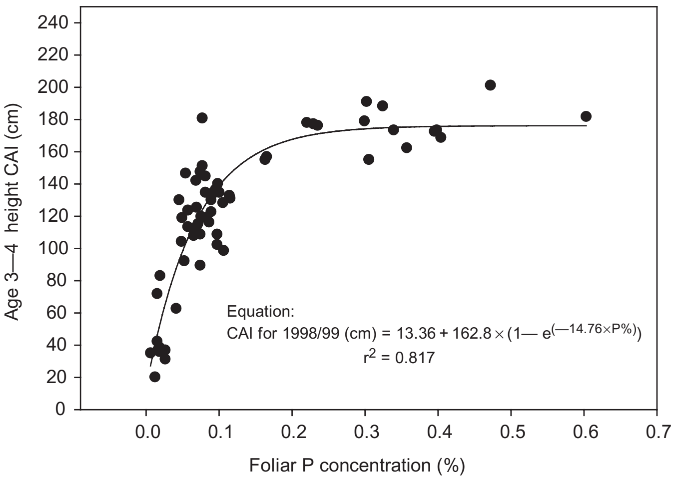

Figure 3. Relationship between absolute height increment (cm) for 1998/99 (age 3–4 y) and foliar phosphorus concentrations (%) as measured at June 1999 (age 4 y). CAI = current annual increment.

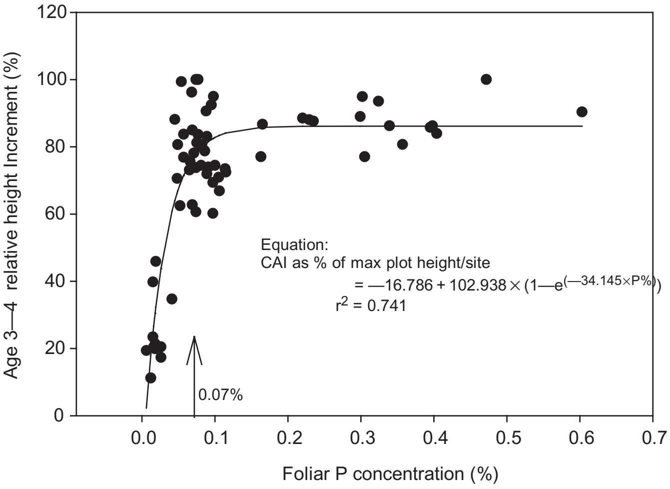

Figure 4. Relationship between relative height increment (as a percentage of maximum plot height per site) for 1998/99 (age 3–4 y) and foliar phosphorus concentrations (%) as measured at June 1999 (age 4 y)

All three sites were measured and foliage was sampled in June 1999. Height growth had ceased for the 1998–99 growing season and concentrations of foliar nutrients were a fair representation of peak concentrations of the past two years (Fig. 2). Figure 3 shows mean height increments for 1998–99 against mean concentrations of foliar P per plot at all sites at June 1999. The regression curve was calculated using the Mitscherlich equation and shows the height response to varying concentration of foliar P in 4-y-old *P. pinaster*.

Figure 4 uses the same data but the height growth increments are expressed relative to the maximum for each site. The Mitscherlich equation was also used to fit the response curve to the data. The relative growth response removes the effects of site from the data from each site by relating growth response to the maximum achieved at each site. These data indicate that the critical concentration of foliar P for adequate growth of young *P. pinaster* was 0.07%.

Soil nutrient status

The soil nutrient data (Table 3) are for the surface soil (0–10 cm). Addition of phosphorus at Site 1 did not significantly alter total soil P, but it did raise bicarbonate extractable P (bic-P) from a mean of 1.63 mg kg^{-1} to a mean of 7.35 mg kg^{-1}. At the same time, mean bic-P in the –P plots decreased from 2.04 mg kg^{-1} to 0.75 mg kg^{-1} over 3 y. At Site 3, which was extremely phosphorus deficient, the application of 140 kg P ha^{-1} increased mean total P from 0.5 mg kg^{-1} to 9.8 mg kg^{-1} and mean bic-P from <0.01 mg kg^{-1} to 2.37 mg kg^{-1}. Mean total P (0.5 mg kg^{-1}) and bic-P (<0.04 mg kg^{-1}) in the −P treatments did not change over the 3-y period. Total soil N and organic carbon decreased slightly in all plots (except total N in the −P plots at Site 1, which decreased substantially) over the three years 1996–1999. Total K decreased at Site 1 while it increased at Site 3. The increase at Site 3 was greatest in association with applied P. Mean pH did not significantly change over the 3 y (Table 3).

The addition of nitrogen appeared to have reduced bic-P in the +P treatments at both Sites 1 and 3 (data not shown). At Site 3 in 1999, mean bic-P in the +P−N treatment was 2.85 mg kg^{-1} while in the +P+N treatments it was 0.84 mg kg^{-1}. This reduction was significant at $P < 0.06$ (df = 9). At Site 1 in 1999, mean bic-p in the +P−N treatment was 9.15 mg kg^{-1}, while in the +P+N treatments it was 5.55 mg kg^{-1}. There was no significant difference between these concentrations.

Discussion

Results from this study confirm findings by Hopkins (1960) and Butcher (1982) that phosphorus is the key nutrient limiting growth of *P. pinaster*. Plant-available phosphorus, as measured by bicarbonate extraction (bic-P) in this study, was a good indicator of the supply of phosphorus to *P. pinaster*. This was evident from the growth response at each site (Fig. 1) and the corresponding concentrations of total and bicarbonate-extractable soil phosphorus (Table 3).

The great P-fixing capacity of the soil at Site 1 is evident in comparison with that of the soil at the other ex-pasture site (Site 2). Prior to fertiliser application, mean total P at Site 1 was four and a half times higher (~220 mg kg^{-1}) than at Site 2 (~50 mg kg^{-1}), yet mean plant-available P (~1.8 mg kg^{-1}) was less than that of Site 2 (~2.4 mg kg^{-1}). The poor nutrient status of the soils at Site 3 prior to fertilising was evidenced by total P concentrations of only 0.5 mg kg^{-1}, with undetectable levels of bic-P (<0.01 mg kg^{-1}). Three years after the application of phosphorus, mean total P on the ex-pasture site (Site 1) was unchanged in both the +P and −P treatments, while bic-P values increased to a mean of 7.35 mg kg^{-1} in the +P treatments and decreased to a mean of 0.75 mg kg^{-1} in the –P treatments. At Site 3, mean total P increased to 9.8 mg kg^{-1} and bic-P to a mean of 2.37 mg kg^{-1} in the +P treatments, while in the −P treatments both mean total P and bic-P did not change significantly. For Site 1, the mean bic-P concentration in the −P plots was as low as 0.75 mg kg^{-1} in 1999, yet the trees still exhibited good growth at age 4 y. In fact the −P treatments exhibited better growth than the +P plots at the same site which still had a mean bic-P concentration of 7.35 mg kg^{-1} in 1999. These results suggest that *P. pinaster* has a very low threshold requirement of plant-available phosphorus (bic-P) for adequate growth. The mean bic-P value in plots at Site 3 that

Table 3. Surface soil analysis and plantation stand density for the three sites prior to and three years after treatment

Site, treatment, year	Total N (%)	Total P (mg kg^{-1})	bic-P (mg kg^{-1})	Total K (mg kg^{-1})	Organic C (%)	pH	Mean stocking (sph)
1 +P 1996	0.16	214.0	1.63	298.9	2.5	5.6	1406
	(0.01)	(11.2)	(0.28)	(16.4)	(0.1)	(0.1)	(29)
1999	0.16	205.6	7.35	232.4	1.9	5.7	1378
	(0.01)	(13.4)	(1.98)	(15.8)	(0.1)	(0.1)	(30)
1 −P 1996	0.18	223.7	2.04	294.9	2.6	5.5	1426
	(0.01)	(13.4)	(0.27)	(15.8)	(0.1)	(0.1)	(30)
1999	0.13	215.3	0.75	227.4	2.0	5.6	1399
	(0.01)	(11.2)	(0.26)	(16.4)	(0.1)	(0.1)	(32)
2 +P 1996	0.04	51.0 (8.7)	2.88	0.9	0.6	5.0	1416
	(0.00)	NA	(0.34)	(0.3)	(0.1)	(0.0)	(90)
1999	NA		NA	NA	NA	NA	1306
							(101)
2 −P 1996	0.03	48.5 (5.5)	2.02	0.5	0.6	4.9	1603
	(0.00)	NA	(0.30)	(0.1)	(0.1)	(0.0)	(41)
1999	NA		NA	NA	NA	NA	1603
							(41)
3 +P 1996	0.02	0.5	<0.01*	11.1	0.6	4.8	1743
	(0.00)	(0.4)	(0.00)	(1.9)	(0.1)	(0.0)	(56)
1999	0.02	9.8	2.37	21.6	0.4	4.6	1714
	(0.00)	(0.4)	(0.66)	(1.9)	(0.1)	(0.1)	(49)
3 −P 1996	0.2	0.5	<0.01*	11.3	0.6	4.8	1684
	(0.00)	(0.4)	(0.00)	(1.8)	(0.0)	0.0	(32)
1999	0.02	0.4	0.04	13.7	0.5	4.4	1662
	(0.00)	(0.2)	(0.13)	(1.8)	(0.0)	(0.0)	(32)

+P indicates the mean of plots that had phosphorus applied.
−P indicates the mean of plots that had no phosphorus applied.
Standard errors are in brackets. Standard errors of zero are due to rounding of values.
* Less than detectable values.

exhibited poor growth was 0.04 mg kg^{-1} and thus it seems that the threshold concentration of plant-available phosphorus required by juvenile *P. pinaster* lies somewhere between 0.04 mg kg^{-1} and 0.75 mg kg^{-1}.

With the exception of the −P treatments at Site 3, mean annual height increments measured in this study were as good as or better than those previously recorded on the coastal sand plain in WA. In experiments described by Butcher (1982), height growth at age 4 y (on infertile sands similar to those at Site 3) were similar to those recorded at Site 2 and the +P plots at Site 3. These were achieved with application of as little as 55 g of superphosphate per tree at planting, which equates to about 10 kg P ha^{-1}. At Site 3 in an adjoining experiment examining tree growth in response to various rates of phosphorus, there has been no difference in height growth to age 4 y between treatments that applied 35 kg P ha^{-1} and 175 kg P ha^{-1}, yet there was the same large response between 0 kg P ha^{-1} and 35 kg P ha^{-1} (Dumbrell unpublished data). Height growth in the 35 kg P ha^{-1} treatment is similar to that in the 140 kg P ha^{-1} treatment in this study. The growth responses to much lower rates of applied phosphorus are now being studied. The data from this trial suggest that while phosphorus is critical to the early growth of *P. pinaster*, the amount required is very small.

In relation to optimal early growth of *P. pinaster* in this study, a critical deficiency for foliar phosphorus may be defined as a concentration of 0.07%. This figure corresponds to 90% of the maximum relative height growth from the Mitscherlich equation in Figure 4. If the absolute height growth data are used (Fig. 3), the critical concentration of foliar phosphorus would be 0.16%. The relative data are preferred as they remove differences between sites and provide a good spread of data points around the region of 90% of maximum growth. If using data for actual height growth, some doubt still exists as to the shape of the curve due to a lack of data points in the 0.1–0.2% foliar P range. The shape of the curve and the point of 90% of maximum growth ultimately define the critical concentration. The use of the point of 90% of maximum yield (growth) to define critical foliar nutrient concentrations was first described by Ware (1982) and has been commonly used since (Ohki 1984; El-Gharably and Bussler 1985). No other reports relating critical concentrations of foliar phosphorus to growth of juvenile *P. pinaster* have been published, and further work is required to refine this relationship. Reuter and Robinson (1997) state that concentrations of <0.05% are deficient, 0.06%–0.08% are marginal and 0.1%–0.2% are adequate for mature *P. pinaster*. These figures were derived from only two published studies and two sets of unpublished data from Australia and France. Early fertiliser experiments by Keay *et al.* (1968) showed very low concentrations of foliar P, 0.04–0.05% in 1-y-old needles, were associated with poor growth in *P. pinaster* (in plots with no added P) on a lateritic gravel soil in WA. Loustau *et al.* (1999) also reported low concentrations of foliar P of 0.04% in *P. pinaster* grown in a nutrient solution without P. Such low concentrations adversely affected photosynthesis and consequently growth. In our study, 100% of relative growth was achieved with foliar P concentrations above 0.1%, a result consistent with Reuter and Robinson's (1997) value for mature *P. pinaster.*

Our study also confirms results by Hopkins (1960) and Butcher (1982) that the addition of both nitrogen and potassium does not enhance the growth of young *P. pinaster* even on infertile sites. Applied phosphorus increased bic-P at all sites, even on the soils with high phosphorus-fixing capacity at Site 1. The application of nitrogen to the −P plots at all sites did not influence growth, yet when nitrogen was applied to the +P plots, height growth was consistently reduced. Nohrstedt *et al.* (2000) found that the amount of AL-extractable phosphorus (Egner's ammonium lactate extraction) in the surface soil was negatively correlated with the rate of nitrogen application. The reduced growth in the +N+P plots compared to the −N+P plots was reflected in the concentrations of foliar phosphorus, which were consistently lower in the +N+P plots. There was virtually no difference in the concentration of foliar phosphorus between the +N−P and the −N−P plots. Therefore where plant-available phosphorus was increased with the application of P at 140 kg ha^{-1}, the application of nitrogen reduced mean height growth, and appears to have lowered concentrations of soil bic-P. Therefore the reduction in concentration of foliar P could possibly be related to either a reduced uptake of phosphorus due to lower bic-P or dilution due to an increase in foliar biomass, which was not measured, or a combination of both. These data are contradictory to those presented in Glendinning (2000), which demonstrated that the application of ammonium nitrogen enhanced the uptake of phosphorus by plant roots.

For the duration of the trial, concentrations of foliar nitrogen and potassium at all sites remained greater than 0.6% and 0.25% respectively. These are the current stated lower limits of adequate concentration for mature *P. pinaster* (Reuter and Robinson 1997), even with extremely low total concentrations of nitrogen and potassium in the soil. The application of nitrogen and potassium, although increasing foliar concentrations of each nutrient, did not enhance growth.

Conclusions

An adequate level of plant-available phosphorus is crucial to the growth of young *P. pinaster.* Concentrations of bic-P (Olsen) as low as 0.75 mg kg^{-1} appear suitable in surface soil, and the threshold value necessary for the adequate growth of juvenile *P. pinaster* lies between 0.04 mg kg^{-1} and 0.75 mg kg^{-1}.

Very low concentrations of both total nitrogen (0.021%) and total potassium (0.50%) in soil were adequate for early growth of juvenile *P. pinaster*. Additions of both nutrients did not enhance tree growth either with or without applied phosphorus.

For juvenile *P. pinaster*, concentrations of foliar phosphorus <0.07% are deficient and will result in sub-optimal growth; concentrations >0.07% will result in optimal early growth.

There is a negative interaction between N and P such that the application of N in combination with P reduces the concentration of foliar P and reduces height growth significantly.

Plantations established on ex-pasture sites are unlikely to need fertiliser application in the first 5 y. Soil and foliar analyses should be carried out in winter to provide the best indication of phosphorus status.

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