SUSTAINED GROWTH RESPONSES TO SUPERPHOSPHATE APPLIED TO ESTABLISHED STANDS OF *PINUS RADIATA*

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ABSTRACT

Growth responses to superphosphate broadcast applied at 630 and 1260 kg ha^{-1} to 9- to 18-year-old unthinned stands of **Pinus radiata** at three sites in the Scarsdale plantation (Victoria) have been measured for up to 13 years after treatment. A substantial basal area response was found for both rates of superphosphate and there is evidence that on at least two of the sites the responses will continue through to rotation age with a commensurate increase in site productivity. Sectional measurements showed that form factor of the co-dominant and partly suppressed trees was not significantly influenced by fertiliser addition.

Basal area growth curves together with favourable soil P retention characteristics and differential soil and foliar P levels between treatments indicated that the higher application rate of superphosphate will provide substantially higher yields at rotation age than the lower rate. Responses to the higher rate represented an increase in standing volume of at last 100 m^3 ha^{-1} at all sites over the 11-13 year period after treatment and reduced the time taken to obtain the equivalent basal area growth on unfertilised sites by over four years.

Foliar and soil analyses showed that the sites were not only P deficient but also low in Ca and high in Al. Correction of mild Ca deficiency and alleviation of the adverse effects of Al on the P nutrition of **P. radiata** by the application of superphosphate probably contributed to the substantial responses obtained.

INTRODUCTION

There are several reports in the literature of substantial early growth responses of *Pinus radiata* D. Don to phosphatic fertilisers applied at or near planting on a wide range of sites in Australia and New Zealand (e.g. Waring, 1972; Ballard, 1978). There are also reports of marked growth responses to P applied to established stands of *P. radiata* growing on severely P deficient sites (e.g., Gentle *et al.,* 1965; Mead and Gadgil, 1978). Few studies however have quantified the long-term production gains from phosphatic fertilisers applied early in the rotation. Though it is now widely recognised that fertilisers should be applied immediately after planting for maximum production (Waring, 1973), forest managers need to know the magnitude of production gains at rotation age due to fertiliser application at or sometime after planting so that the return from investment in fertilising can be evaluated.

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In Victoria *P. radiata* plantations have commonly been established on sites which are P deficient but otherwise suitable for growth of the species. The Forests Commission Victoria initiated several studies in the early 1960s to determine whether growth of young, slow-growing stands could be improved by fertiliser application. This paper reports results from two of these studies where growth response of established stands to broadcast superphosphate has been measured regularly over an extended period.

METHODS

The studies reported here were undertaken in the Scarsdale Plantation located 115 km west of Melbourne. The area has a predominantly winter rainfall with an annual mean of 703 mm. The lowest monthly fall is 35 mm in February and the maximum 78 mm in September. The yellow podzolic soils (Stace *et al.,* 1972) are derived from Ordovician sediments and quartz is abundant in the upper horizons. Topography is undulating and soils tend to be shallow on the ridges and relatively deep in the gullies and on the lower slopes. Growth of *P. radiata* stands at Scarsdale has generally been unsatisfactory with the exception of gully sites. Trees exhibit thin crowns with short. mildly-chlorotic needles and severe leader die-back is common on ridge sites.

Experiments were established at three sites between 1963 and 1965 in unthinned and previously unfertilised stands planted between 1947 and 1954 (Table 1) to study the response of *P. radiata* to superphosphate. At each site granulated superphosphate was broadcast applied at 0, 630 and 1260 kg ha^{-1} to 291 m^2 square plots arranged in a randomised block design with three replications. Sites were planted at a nominal 2.4 m × 2.4 m spacing, but early mortality reduced stocking by up to 15% at all sites at the time of fertiliser application.

TABLE 1—Details of experiments showing planting years and years when plots were fertilised and measured

Site	Year planted	Year fertilised	Years measured
1	1954	1963	1963, 1967, 1971, 1974, 1976
2	1947	1965	1965, 1967, 1969, 1971, 1974, 1976
3	1952	1965	1965, 1967, 1969, 1971, 1974, 1976

Measurements have been restricted to trees on an internal square sub-plot of 149 m^2. Over-bark diameters to the nearest mm at internodal points approximately 1.3 m above ground (breast height) have been measured at regular intervals (Table 1) using steel tapes. At sites 2 and 3 diameter has been measured throughout the study at a fixed point marked by a shallow saw cut in the bark on each tree but at site 1 a reference point has only been used since 1974. Heights of the three largest diameter trees on each sub-plot have been measured to the nearest 0.3 m using a Sunto clinometer.

In 1977 following the most recent re-measurement, all sub-plots and their surrounds were thinned to a residual basal area of 23 m^{2}ha^{-1} by felling the smallest diameter trees, except where larger trees were of poor form (e.g., forks, butt sweep and damaged leader) and where this would have created large gaps. A large and an intermediate sized tree of representative form were selected from the thinnings of each sub-plot and sectional measurements made to determine form factor using a method similar to that described by Whyte (1971). The total length (height) of each tree was measured together with over-bark diameters at stump level, breast height and thereafter at mid-internodal points for measured taper steps corresponding to every second internode or 2-m intervals where internodes were indistinct. At each point of diameter measurement, two bark thickness measurements to the nearest mm were made at right angles to each other using a bark gauge with a blunt edge. The total under-bark volume of each tree was then computed and its form factor calculated. Crowns of thinned trees were re-distributed over plots from which they originated to avoid possible contamination between plots with nutrients contained in the needles and fine branches which could influence subsequent growth.

An attempt was made to estimate plot volumes for each measurement year using both a regional and a more general 2-dimensional tree volume function so that volume response on a unit area basis to superphosphate could be examined over the experimental period. It was found that both functions seriously underestimated the volume of small trees (e.g., less than 10 cm diameter at breast height) and provided a poor estimate of plot volume for the earlier measurement years, and that a local tree volume function would be necessary to obtain a more reliable estimate of volume response with time to fertiliser. However, the regional tree volume function:

$$v = 0.0000216\ d^2h + 0.01011\ d - 0.1253$$

was used to calculate total under-bark volume of each tree (v) in 1976 from diameter at breast height (d) and total height (h). A regression of d on h was calculated for each plot using measured heights of standing trees in 1976 (3 per plot) and all felled trees from thinning in 1977 to estimate heights of remaining trees. Gross plot basal area, calculated on the same set of trees each measurement year, was used instead of volume to examine fertiliser response with time. To account for initial differences in plot basal areas, statistical examinations were restricted to basal area increment over the period of the study (11-13 years according to the site).

In 1970 soil samples were collected from the 0-15 cm horizon at each site. Five sub-samples were taken at random from each sub-plot, combined on an equal volume basis, air dried, passed through a 2 mm sieve and analysed for total P (Sommers and Nelson, 1972), Bray No. 2 extractable P (Bray and Kurtz, 1945) and water extractable P using a 1 : 10 soil : water ratio on a Chemlab autoanalyser according to the method of John (1970).

In May 1970 and 1976 current mature needles were collected from the second whorl beneath the leading shoot of five co-dominant trees on each plot. In the laboratory the needles were briefly washed in distilled water, dried at 80°C and combined on an equal dry weight basis to provide one composite sample per plot for chemical analysis. N, P and K were determined on H_2SO_4/H_2O_2 digests. All P determinations were carried out simultaneously and in duplicate on an autoanalyser using a colorimetric method described by John (1970). K was determined by flame photometry and N colorimetrically using an autoanalyser (Eastin, 1978) except for the 1970 samples where a steam distillation procedure was used (Clarke and Jayman, 1966). Ca, Mg, Mn, Zn and Fe were determined on $HNO_3/HC10_4$ digests by atomic absorption spectroscopy. For Ca and Mg, $SrCl_2$ was added to prevent interference from P, Fe and Al. Cu was determined on the same digests by atomic absorption spectroscopy after complex formation with sodium diethyldithiocarbamate and extraction into methyl isobutyl ketone (Clarke and Jayman, 1966). A colorimetric method (Shull and Guthan, 1967) was used to determine Al. B was also determined colorimetrically (Hatcher and Wilcox, 1950) after dry ashing at 550°C for 16 hours.

RESULTS AND DISCUSSION

There was a large and sustained basal area response to superphosphate at all sites, and at sites 1 and 2 the response was much greater for the higher application rate (Fig. 1). Although there were differences in mean plot basal areas within a site at the time of fertiliser application due largely to variations in stocking, Fig. 1 shows that the response curves for both superphosphate rates have continued to diverge from the control line throughout the measurement period. This is evidence of an increase in site index (productivity at a given age) as a result of fertilising and is consistent with the view of Waring (1973) that correction of nutrient deficiencies allows a permanent improvement in site productivity. The results strongly suggest that growth differences between fertilised and unfertilised plots will continue to expand through to rotation age (nominally 35 years at Scarsdale) since divergence of the basal area curves appears to be increasing (Fig. 1). So far, superphosphate applied at 1200 kg ha^{-1} in 1963 or 1965 has reduced the time taken to obtain the equivalent basal area on unfertilised sites in 1976 by at least four years.

Analysis of variance showed that basal area increment between the time of fertiliser application (1963-65) and 1976 was significantly increased by fertiliser treatment at site 1 ($p < 0.05$) and site 2 ($p < 0.001$) but not at site 3. At site 1, t--tests showed that 1260 kg ha^{-1} superphosphate was associated with significantly ($p < 0.05$) higher basal area increment compared with 630 kg ha^{-1} superphosphate and control, whilst at site 2 basal area increment was significantly increased by both 630 kg ha^{-1} ($p < 0.05$) and 1260 kg ha^{-1} ($p < 0.001$) superphosphate with the higher rate also being significantly ($p < 0.05$) better than the lower rate. Thus the responses shown in Fig. 1 are significant for sites 1 and 2 after allowance for initial differences in plot basal areas. At site 3, the shape of the basal area curves indicates that differences in basal area increment between treatments will further increase with time.

Gentle *et al.* (1965) reported a two-fold increase in total basal area 15 years after the broadcast application of superphosphate at 1004 kg ha^{-1} to *P. radiata* stands aged eight years in New South Wales, and even greater basal area responses have been measured following a heavy rate of phosphatic fertiliser (225 kg ha^{-1} P) applied to established and severely P deficient stands at Riverhead State Forest in New Zealand (Mead and Gadgil, 1978). In the present study the basal area response to superphosphate is substantially less than that found in the above studies, but mean plot volumes in 1976 still show increases in excess of 100 m^3ha^{-1} at all sites for the highest rate (Table 2). This is equivalent to increasing site index (Lewis *et al.*, 1976) which varies from VI to VII according to the site, by at least one class in the Scarsdale plantation in less than 13 years. Moreover the superphosphate was applied after the stands had reached crown closure when, according to Waring (1972), a marked response would not be expected. An early fertiliser application is likely to significantly increase the magnitude of a response by encouraging rapid exploitation of the site by root systems. Unpublished

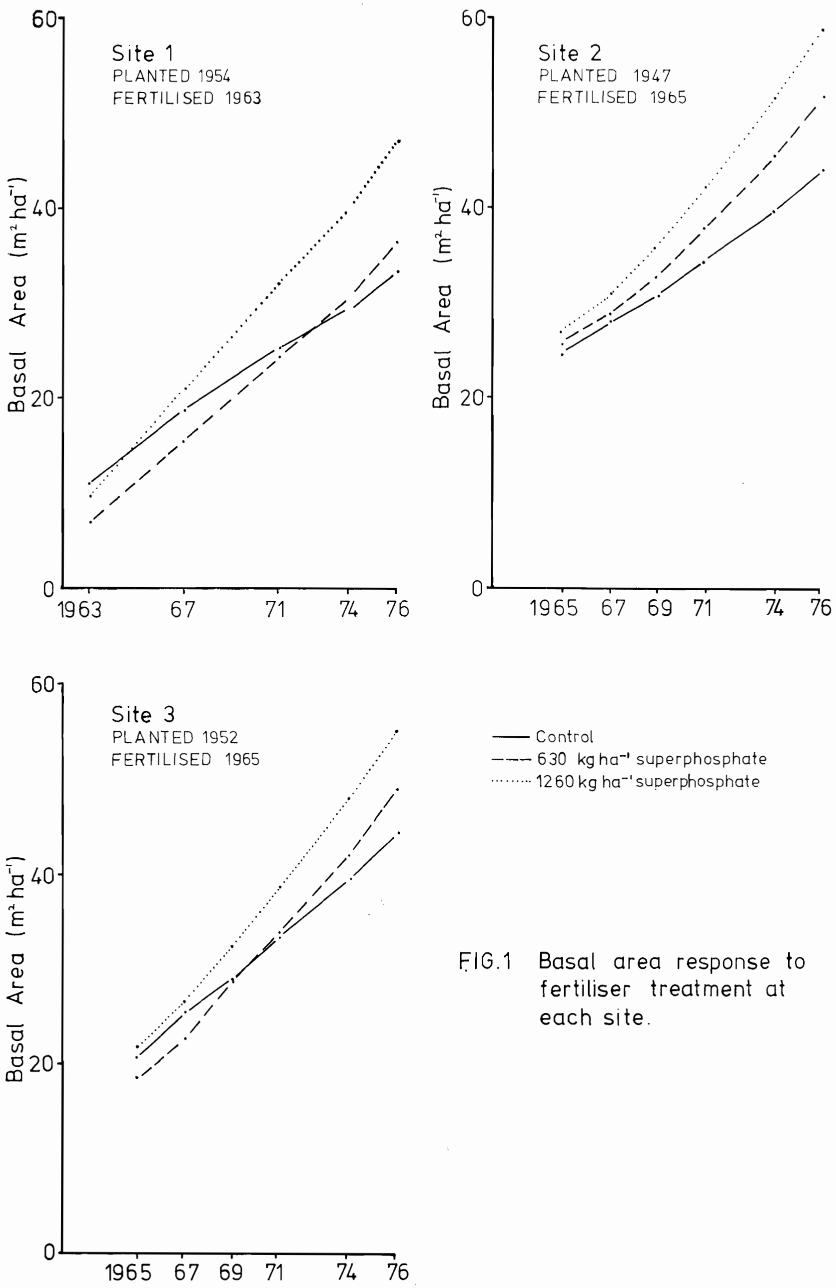

FIG.1 Basal area response to fertiliser treatment at each site.

data by the authors show that *P. radiata* responds markedly to a localised or spot application of superphosphate at establishment in this locality, and that there is no advantage in applying rates above 150 g per tree. However foliar P levels fall below 0.10% within five years of such applications irrespective of application rate and in view of the present results it seems that broadcast superphosphate is required at an early age to maintain rapid growth rates. Similar results have been observed in New Zealand (Ballard, 1978). To delay the requirement for a second fertiliser application early in the rotation following a spot application at establishment, alternative modes of fertiliser placement at planting are currently being evaluated.

TABLE 2—Mean plot volumes in 1976 calculated using a regional tree volume function

Superphosphate rate (kg ha^{-1})	Mean volume in 1976 (m^3 ha^{-1}) Site 1	Site 2	Site 3
0	172	362	384
630	277	454	400
1260	333	488	489

Waring (1973) considers that an established stand will respond better to fertiliser applied in combination with thinning, and work with *P. radiata* in New Zealand indicates that N must be applied at the time of thinning to obtain a marked response to this element (Woollons and Will, 1975). This suggests that the responses to superphosphate reported here are the minimum that can be expected on these sites, and that larger responses may have occurred if the fertiliser had contained N and had been applied to thinned or younger stands. In addition some unfertilised trees could have benefited through encroachment of roots onto fertilised plots and this would have under-estimated the response. In this study, there was no evidence of a height response which may have given fertilised trees a competitive advantage and perhaps affected the comparisons made in this paper.

Whyte and Mead (1976) found that basal area may seriously under-estimate fertiliser response because it takes no account of possible changes in tree form due to fertiliser responses further up the stem. Barker (1978) has reported substantial increases in tree form factor in *P. radiata* following thinning and the application of N. The opportunity to examine the effects of superphosphate on form factor was taken when the plots of this study were thinned in 1977, and results are given in Table 3. Analysis of variance showed no significant differences in form factor between superphosphate treatments and control for either large or intermediate sized trees sampled from the thinnings. The intermediate sized trees were partly suppressed trees which could have been insensitive to fertiliser, but the large trees had well-developed crowns and were representative of co-dominant trees in the stand. Failure to detect significant changes in form factor, particularly for the large trees, following the application of superphosphate may have been partly due to the high stocking levels which could discourage responses to fertiliser in the upper portions of the stems. The results indicate that for this study the use of basal area, which involves no estimation. to characterise response with time is valid.

The marked response to superphosphate at Scarsdale could be expected from the relatively poor P status of the soils (Table 4) which are fairly low in Bray No. 2 P compared with P responsive soils in New Zealand (Ballard, 1978). At each site, basal area increment over the experimental period increased with increasing Bray No. 2 P. Previous studies at Scarsdale have shown that the soils have a P sorption maximum of

TABLE 3—Mean form factor calculated from sectional measurements made on a large and intermediate sized tree from each sub-plot selected from the 1977 thinnings. Each value is a mean for three trees

Site	Superphosphate rate (kg ha^{-1})	Mean form factor within each tree size class Large	Intermediate
1	0	0.336	0.339
	630	0.348	0.307
	1260	0.339	0.343
2	0	0.366	0.355
	630	0.356	0.400
	1260	0.438	0.409
3	0	0.327	0.318
	630	0.330	0.349
	1260	0.340	0.321

around 400 ppm as determined by the method described by Humphreys (1964) and so have little tendency to adsorb applied phosphate and render it unavailable to the crop compared with some soils currently being planted in Victoria where values exceed 2000 ppm. This is supported by the relatively high levels of water extractable P and Bray No. 2 P on fertilised sites several years after treatment (Table 4). A sustained response to superphosphate is likely under these conditions.

TABLE 4—Mean values of total P, water extractable P and Bray No. 2 extractable P for soil samples collected in 1970 from the surface horizon (0-15 cm) on each sub-plot

Site	Superphosphate rate (kg ha^{-1})	Mean value (ppm) Total P	Water P	Bray No. 2 P
1	0	92	0.2	3.1
	630	87	0.5	5.9
	1260	109	0.7	12.1
2	0	90	1.4	4.1
	630	102	1.7	18.4
	1260	125	3.3	34.5
3	0	61	0.6	3.6
	630	93	1.6	11.5
	1260	106	3.2	21.9

The foliar nutrient results also show the sites to be markedly P deficient (Table 5). For both sampling years, foliar P concentrations in unfertilised trees were at or below levels widely recognised as being deficient (e.g., less than 0.10%) whilst levels in fertilised trees were generally much higher, with up to 0.22% P being measured. Will

(1978) considers levels above 0.14% high enough for satisfactory growth. In 1970 the highest superphosphate rate was associated with the largest increase in foliar P, particularly at sites 2 and 3, but by 1976 levels had declined to near deficiency at site 1 which according to the soil data is the most impoverished site. These results suggest that responses will continue at sites 2 and 3 but could diminish at site 1, and that further divergence in response between the two application rates is likely. Maintenance of high foliar P concentrations over a period of 13 years in trees fertilised with 1260 kg ha^{-1} superphosphate also confirms that the soils have favourable P retention characteristics.

The concentrations of K, Mg, Cu, Mn, Zn, Fe and B in the foliage of unfertilised trees on all sites in 1970 were above levels associated with satisfactory growth of *P. radiata.* Although foliar N concentration appears to be an insensitive measure of the N status of *P. radiata* the levels in 1976 for all treatments and sites are low enough to suggest that larger responses would have been obtained by applying an NP fertiliser providing the stands were thinned (Woollons and Will, 1975) and sulphur was not limiting (Lambert and Turner, 1977). The high Ca content of superphosphate is reflected in substantially higher foliar Ca levels in fertilised trees. Ca is known to be extremely immobile in *P. radiata* which has a relatively high requirement for the element compared with other conifers (Flinn, 1975). This, combined with low foliar Ca levels in unfertilised trees (e.g., 0.12%), suggests that part of the response was due to the correction of mild Ca deficiency. Dead topping is common in parts of the Scarsdale plantation and this has been attributed to Ca deficiency on the basis of exchangeable soil Ca levels which range from only 0.65 to 1.98 meq per 100 g in the surface horizon (Flinn, 1975). Humphreys (1964) considers that superphosphate should be supplemented by additional Ca (e.g. gypsum) for *P. radiata* establishment on soils which require P and have less than 1 meq per 100 g Ca.

Al is one of the major exchangeable cations in the Scarsdale soils as evidenced by high foliar Al levels which ranged from 610 to 1240 ppm according to the site and fertiliser treatment (Table 5), and exchangeable Al levels in the surface soils of 1.11 to 3.47 meq per 100 g (Flinn, 1975). Foliar levels less than 500 ppm are considered desirable. Humphreys (1964) has emphasised the possible adverse role that Al may play on soils low in P and Ca, and considers that P uptake and utilisation is likely to be reduced through accumulation of Al in the rhizosphere and within the tree, and further retarded if Ca availability is low causing poor root development. Solution culture studies have shown that Al uptake and distribution in *P. radiata* seedlings is related to both P and Al supply and that the P requirement is increased with increasing Al availability (Humphreys and Truman, 1964; 1972), and in the present study there is evidence of substantial increases in foliar Al levels with increasing P availability. It is likely that the low ratio of exchangeable Ca to Al in the Scarsdale soils has contributed to the occurrence of P deficiency, and that the marked response to superphosphate was not solely due to increased P availability but also to alleviation of the adverse effects of a high Al supply and to an increased Ca supply which stimulated root growth and improved the opportunity for utilisation of applied and indigenous P.

It is concluded that the application of superphosphate to established, unthinned stands at Scarsdale results in a marked and sustained growth response and a permanent increase in site index. Yields are likely to be markedly higher at rotation age at the

TABLE 5—Mean elemental concentrations in needles of co-dominant trees from each site and treatment at varying periods after fertiliser application

Site	Year sampled	Superphosphate rate (kg ha^{-1})	Mean elemental concentration N	P	K	Ca	Mg	Al	Cu	Mn	Zn	Fe	B
			% O.D.W.					ppm					
1	1970	0	1.69	0.096	1.05	0.166	0.189	725	8.8	95	34	144	56
	1976	0	1.30	0.068	0.73	0.121							
	1970	630	1.63	0.152	1.01	0.203	0.226	930	7.8	125	38	147	53
	1976	630	1.14	0.095	0.62	0.151							
	1970	1260	1.44	0.163	0.82	0.179	0.280	1120	6.9	102	38	176	60
	1976	1260	1.04	0.113	0.53	0.203							
2	1970	0	1.71	0.100	0.87	0.169	0.197	610	8.3	84	21	123	44
	1976	0	1.52	0.098	1.17	0.122							
	1970	630	1.57	0.159	0.67	0.223	0.236	910	7.0	126	23	132	48
	1976	630	1.25	0.118	0.62	0.189							
	1970	1260	1.61	0.207	0.73	0.246	0.269	1240	6.6	144	33	145	50
	1976	1260	1.39	0.153	0.69	0.195							
3	1970	0	1.67	0.106	0.92	0.171	0.200	695	8.4	93	25	146	54
	1976	0	1.37	0.091	1.11	0.115							
	1970	630	1.65	0.181	0.92	0.221	0.259	985	9.0	113	34	146	51
	1976	630	1.33	0.140	0.72	0.203							
	1970	1260	1.76	0.218	0.77	0.307	0.338	980	7.4	143	30	151	56
	1976	1260	1.26	0.163	0.75	0.172							

higher rate of 1260 kg ha^{-1} superphosphate on the basis of foliar P levels and favourable soil P-retention characteristics, but the results show that there is potential for significant increases in yields over a short period by applying superphosphate to established stands at the lower rate of 630 kg ha^{-1}.

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