FERTILISER TREATMENT OF PINUS RADIATA AT ESTABLISHMENT AND AT THINNING — AN EVALUATION OF ITS POTENTIAL IN AUSTRALIA

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ABSTRACT

A model of various aspects of fertiliser application throughout a 40-year rotation of **Pinus radiata** D. Don provides a framework with which options on whether to apply fertiliser can be examined at five stages: at establishment, at first thinning (age 16 years), second thinning (age 22 years), third thinning (age 28 years), and at fourth thinning (age 34 years). A yield table developed for Uriarra Forest near Canberra was applied to the framework and an assumption was made that a 40% increase in the relative rate of growth of stands with periodic annual increments of 16–19 m³/ha/year could result from application of nitrogen and phosphorus in the 16 years following establishment, or in any of the subsequent 6 years between harvests. The model was then used to evaluate the extra wood and increase in size of the harvested logs likely to result from fertiliser, and some of the economic aspects.

For a single application, fertiliser at the time of establishment resulted in the most extra wood, and at the last or next-to-last thinning it resulted in the highest internal rate of return on monetary capital invested.

The nature of the N×P interaction for specific soils and stands is likely to be a key factor on the generally phosphorus-deficient soils of Australia.

INTRODUCTION

Fertiliser is applied to over 90% of exotic plantations in Australia at or soon after planting. In the 1950s and 1960s the fertilisers used were mainly phosphatic, but since the late 1960s there has been an increasing use of multi-nutrient fertilisers which include nitrogen. Waring (1981) has the longest-term Australian data on nitrogen and phosphorus application to *P. radiata* at establishment. At 12 years of age, trees in the four key treatments of his LT4 experiment had the following volumes: control (no treatment) 44 m^3/ha, weedicide 142 m^3/ha, fertiliser 206 m^3/ha, and weedicide + fertiliser 311 m^3/ha. If the weedicide treatment is taken as the base-line mean annual increment (MAI) at 11.8 m^3/ha/year, then the effect of a once-only addition of nitrogen and phosphorus at establishment has been to increase growth by an average of 14.1 m^3/ha/year over 12 years, to an MAI of 25.9 m^3/ha/year (an increase of 120%). "Later-age" fertiliser application (i.e., after first crown closure) has been limited almost exclusively to operations aimed at correcting nutritional "disorders", or treating stagnant or relatively slow-growing phosphorus-deficient stands. There has been little development of practices now widely used in Scandinavia, Europe, and North America, where fertiliser is applied to coniferous stands of average or good health at the time of thinning to produce additional growth of non-juvenile wood.

Responses of *P. radiata* to later-age fertiliser treatments vary widely. In New Zealand, Woollons & Will (1975) obtained an average increase in growth of 8.7 m^3/ha/year over a period of 7 years after the application of nitrogen-phosphorus-potassium and trace elements to a thinned 13-year-old stand, the periodic annual increment (PAI) of which had been 47 m^3/ha/year before fertiliser. Mead & Gadgil (1978) recorded an increase of 18.6 m^3/ha/year over a period of 5 years after the application of nitrogen and phosphorus to a thinned 14-year-old stand with a previous PAI of 28 m^3/ha/year. Limited Australian data have also shown variable results. Waring (1981) reviewed a number of trials established in the 1950s and early 1960s, but most tested phosphorus alone in unthinned stands. In respect to nitrogen, Waring (1962) concluded that *P. radiata* would respond during the first 4 years after planting, but not at a later stage. By 1979, Boardman (1979) had concluded that there was little opportunity for rapid fertiliser-induced acceleration of growth in older stands after the stage of canopy closure – except where deficiency could be readily diagnosed. Waring (1981), however, measured an average increase in growth of 4.8 m^3/ha/year (27%) in a 9-year-old stand at Belanglo, New South Wales, in a 5-year period after thinning and nitrogen-phosphorus application, where the PAI without treatment had been 19 m^3/ha/year.

Crane (1981) did not obtain a response to nitrogen and phosphorus in a thinned 16-year-old stand at Belanglo. However, in two similar healthy stands which had been thinned by extracting only each third row at Uriarra and Kowen, A.C.T., responses averaged 5.9 m^3/ha/year over 4 years (PAI 16 m^3/ha/year without treatment). This represents relative growth responses of 37%. Four subsequent trials in well-thinned stands of various ages at Tumut and in the Australian Capital Territory, and in which volume was measured directly and more precisely along the full stem (rather than using a d.b.h.o.b./height volume table as for the previous trials), have shown relative growth responses of 40% or more over previous PAI of about 20 m^3/ha/year (unpubl. data). The evidence to date suggests that there is a positive N×P interaction on each trial, but that the magnitude and nature of the interaction varies between experiments and sites.

In south-eastern South Australia, R. V. Woods (pers. comm.) has also recently obtained substantial responses in thinned *P. radiata* after application of a complete mineral (NPK) fertiliser. The interim results of three experiments are as follows:

(a) On a first-rotation site (Site Quality V–VI), RT19 received after thinning at age 20 years two treatments of complete mineral fertiliser at rates of 150 kg N/ha and 300 kg N/ha. The average responses after 3 years were 10.1 m^3/ha/year for the 150 kg N/ha treatment (a 43% response), and 14.5 m^3/ha/year for the 300 kg N/ha treatment (a 69% response) where the PAI without fertiliser was 21 m^3/ha/year. Responses were measured directly by stem analysis.

(b) On a second-rotation site (Site Quality VI–VII), RT33A was treated after thinning at age 21 years with a complete mineral fertiliser at 220 kg N/ha. The average response after 2½ years was 12.6 m^3/ha/year (an 84% response); PAI without fertiliser was 15 m^3/ha/year. Response was measured indirectly by diameter/height volume tables.

(c) On another second-rotation site (Site Quality VII), RT33B was treated after thinning at age 24 years with a complete mineral fertiliser at 200 kg N/ha. The average response after 3½ years was 15.1 m^3/ha/year (a 131% response); PAI without fertiliser was 11.5 m^3/ha/year. Response was measured indirectly by diameter/height volume tables.

Based on these results on a range of Australian soils, there is now considerable interest in the commercial potential of later-age fertiliser treatment, particularly in the tableland area of New South Wales. This interest coincides with the establishment of several new major softwood-using industries (e.g., at Albury, at Wagga Wagga, and in the Bathurst region), and with an increase in the difficulty of acquiring further land suitable for plantations. This has encouraged the development of silviculture aimed at improving productivity on land already planted (Cromer *et al.* 1976).

The immediate questions concerning later-age fertiliser application are:

(a) What stands respond – particularly, what ages of stand and stages of thinning are likely to be most profitable in terms of the amount of extra wood and the monetary dividends resulting from fertiliser?

(b) What are the likely magnitudes and durations of response?

(c) Can potentially responsive and non-responsive stands be diagnosed?

(d) What nutrients, forms, and rates of application should be used?

(e) What is the interaction with climate, particularly rainfall, and what season of the year should fertiliser be applied?

(f) How are responses likely to vary on different types of soil?

The first question is of immediate interest, as some preliminary analysis is likely to help in determining where applied research efforts should be placed. A model was developed to establish a framework, which would allow examination of various strategies of management with fertilisers. Some limited Australian data were then examined in order to evaluate the potential of fertiliser in combination with thinning in Australia.

THE MODEL

The model is a framework (Fig. 1) which shows the options of fertiliser treatment at different stages through a 40-year rotation of *P. radiata*. Each box in Fig. 1 (except for those in the final column) represents a stand at a stage where a choice to apply fertiliser might be made. The boxes in the final column represent stands at clearfelling (age 40 years) which have resulted from various fertiliser strategies.

Five stages at which fertiliser was likely to give a response were defined for a typical 40-year rotation of *P. radiata* in the southern tableland region of New South

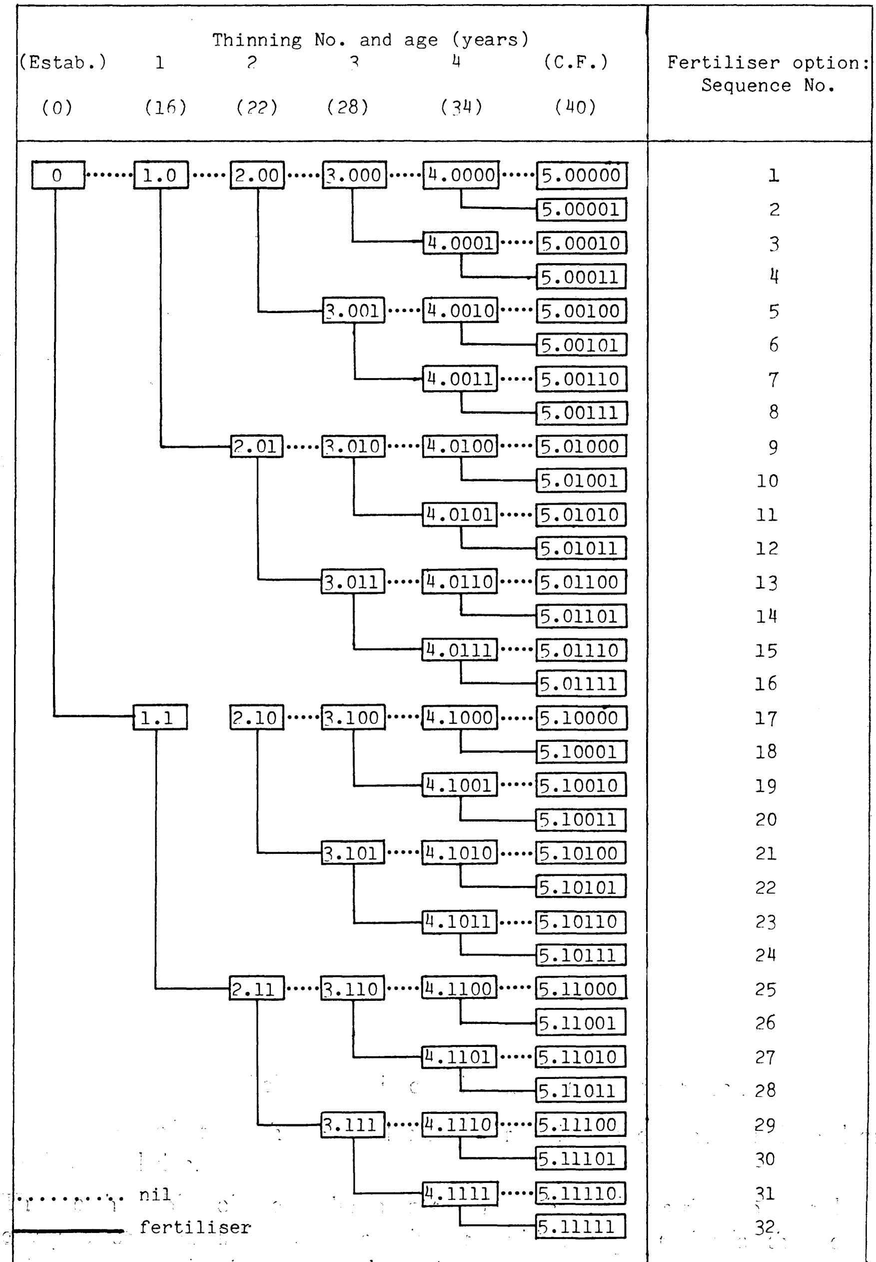

FIG. 1—Model of fertiliser application at various ages throughout a 40-year rotation of **P. radiata.**

KEY to stand numbering (N.XXXXX):

The first integer (N) depicts a stand at thinning No. N. The following fraction (XXXXX), where X = 0 or 1, depicts the fertiliser history at each potential point of application – 0 if not treated, 1 if treated. Thus, a 4.0101 is at fourth thinning and has had fertiliser at first and third thinnings.

Wales – at the time of establishment (age 0 years), at a first thinning (age 16 years), at a second thinning (age 22 years), at a third thinning (age 28 years), and at a fourth thinning (age 34 years). A bifurcation at each of these five stages, depending on whether the stand receives fertiliser or not, produces a total of 62 stands as follows:

2 alternative stands at age 16 years (first thinnings) – one with fertiliser at establishment, the other without;

4 alternative stands at age 22 years (second thinning);

8 alternative stands at age 28 years (third thinning);

16 alternative stands at age 34 years (fourth thinning);

32 alternative stands at age 40 years (clearfelling).

A numbering key to identify each stand is shown in Fig. 1.

Growth Without Fertiliser

A yield table based on data from *P. radiata* planted at 2.4 × 2.4-m spacing without fertiliser in the Blue Range Block at Uriarra Forest, A.C.T., was developed. This block is fairly typical of much of the plantation area on the tablelands, including the majority of the 60 000 ha planted in *P. radiata* at Tumut. The site index (mean height in metres of the 40 tallest trees/ha, i.e., top height, at age 20 years) at Blue Range in the first rotation ranged from 24 to 26. The data were derived from compartmental records of the Blue Range block, from two stands of 22 and 40 years of age which were destructively sampled for stand volume and individual tree taper on a sample plot basis (Crane & Raison 1980), and a computer growth model for both height and gross-basal-area-increment at Uriarra developed by Ferguson (1979).

Height, d.b.h.o.b., and both total and merchantable (top limit of 10 cm diameter under bark) volumes were determined using the initial full stocking, the number of stems thinned, and a tree volume table for *P. radiata* at Uriarra (Bary & Borough 1980). The standard deviation and variance ratios of the d.b.h.o.b. (hence a size-class (d.b.h.o.b.) distribution at each age) at the time of each harvest were determined from the sample plot data. The resulting yield table and details of the five stands are shown in Table 1. This represents a reference or "control" sequence of stands (fertiliser treatment option No. 1). In this sequence the growth rates (PAI) in the five periods between each point when fertiliser might be applied are 16, 18, 19, 18, and 16 m^3/ha/year for the first to fifth growth periods, respectively.

Yields and details of stands after fertiliser application at each stage were then calculated using the following assumptions:

(a) An increase in relative growth rate of 40% was assumed to be obtainable in the periods between fertiliser additions – independent of any previous application (the limitations of this assumption are fully discussed later). Thus the PAI for each period (Table 1) was increased by 40% after fertiliser to 22.4, 25.2, 26.6, 25.2, and 22.4 m^3/ha/year respectively, the absolute increases being between 6.4 to 7.6 m^3/ha/year.

TABLE 1—Yield table and stand details for **P. radiata** on Site Index 24-26 at Blue Range block, Uriarra Forest. Total merchantable volume 684 m^3/ha. [Fertiliser sequence No. 1 - no fertiliser]

		Age (years)			
	16	22	28	34	40
Yield:					
No. of stems BT	1682	565	400	290	188
T	1117	165	110	102	188
AT	565	400	290	188	0
Vol. (m^3/ha) BT	256	194	251	290	284
T	170	57	69	102	284
AT	86	137	182	188	0
Increments (m^3/ha): PAI	16.0	18.0	19.0	18.0	16.0
MAI	16.0	16.5	17.1	17.2	17.1
Stand: (Code, **see** Fig. 1)	1.0	2.00	3.000	4.0000	5.00000
Height of mean tree (m)	23.0	27.8	31.8	35.3	38.0
d.b.h.o.b. of mean tree (cm)	17.3	22.6	28.3	33.8	40.2
[variance ratio (%)]	[25.7]	[22.0]	[18.3]	[14.7]	[11.0]
Smallest d.b.h.o.b. of largest 30% of stems (cm)	19.6	25.2	31.0	36.4	42.5
Smallest d.b.h.o.b. of largest 15% of stems (cm)	21.9	27.8	33.7	39.0	44.8
Vol. of mean tree (m^3)	0.152	0.343	0.628	1.000	1.511

BT Before thinning
T Thinned
AT After thinning
Vol. Merchantable volume to top of 10 cm diameter under bark
PAI Periodic annual increment
MAI Mean annual increment

(b) It was assumed that height was insensitive to fertiliser treatment.

(c) The number of stems thinned and retained remained the same – independent of fertiliser addition.

The merchantable volume of the mean tree in each stand was then computed in the same way as for stands in the sequence without fertiliser. Taper tables for the mean tree in each stand were developed from d.b.h.o.b. and height, and the general form of the taper which had been determined from the destructively sampled trees at Uriarra. This enabled calculation of log sizes and royalty.

There is no purpose in tabulating each of the 62 stand tables. However, stands in sequence No. 32 (the full fertiliser option) are shown in Table 2. These represent the upper range at each stage and during each period, and sequence No. 1 in Table 1 represents the lower range.

TABLE 2—Yield table and stand details for **P. radiata** on Site Index 24-26 at Blue Range block, Uriarra Forest. Total merchantable volume 954 m³/ha.
[Fertiliser sequence No. 32 - full fertiliser programme]

	Age (years)				
	16	22	28	34	40
Yield:					
No. of stems BT	1682	565	400	290	188
T	1117	165	110	102	188
AT	565	400	290	188	0
Vol. (m³/ha) BT	358	271	352	406	397
T	238	79	97	143	397
AT	120	192	255	263	0
Increments (m³/ha): PAI	22.4	25.2	26.6	25.2	22.4
MAI	22.4	23.1	23.9	24.1	23.8
Stand: (Code, **see** Fig. 1)	1.1	2.11	3.111	4.1111	5.11111
Height of mean tree (m)	23.0	27.8	31.8	35.3	38.0
d.b.h.o.b. of mean tree (cm)	19.8	26.4	33.3	40.0	47.5
[variance ratio (%)]	[25.7]	[22.0]	[18.3]	[14.7]	[11.0]
Smallest d.b.h.o.b. of largest 30% of stems (cm)	22.5	29.5	36.5	43.1	50.2
Smallest d.b.h.o.b. of largest 15% of stems (cm)	25.1	32.4	39.7	46.1	52.9
Vol. of mean tree (m³)	0.213	0.480	0.879	1.401	2.112

BT Before thinning
T Thinned
AT After thinning
Vol. Merchantable volume to top of 10 cm diameter under bark
PAI Periodic annual increment
MAI Mean annual increment

RESULTS USING THE MODEL

Extra Wood Resulting from Fertiliser Application

The extra wood obtained from each of the 32 fertiliser treatment options is shown in Table 3, together with the d.b.h.o.b. of the mean trees harvested at clearfelling. The maximum gain of 272 m³/ha (40% increase in growth over the yield without fertiliser of 684 m³/ha for the full 40-year rotation) is indicated by sequence No. 32 in which fertiliser is applied at every stage. This sequence also produces an increase in mean d.b.h.o.b. of the final-crop trees of 7.3 cm (40.2 cm in Stand 5.00000 without fertiliser and 47.5 cm in Stand 5.11111 with a full fertiliser programme).

The most wood from a single fertiliser treatment was from application at the time of establishment; this resulted in 100 m³ extra wood per hectare, and a 15% increase in yield over the rotation. However, the 0.5-cm increase in d.b.h.o.b. of the final-crop trees

TABLE 3—Extra wood at each harvest and mean d.b.h.o.b. of final-crop trees resulting from 32 options of fertiliser treatment through a 40-year rotation of **P. radiata**

Fertiliser option sequence No. (Stand code at age 40)		Fertiliser at age (years)	Extra wood at each harvest due to fertiliser (m³/ha)						Mean d.b.h.o.b. of final-crop tree at age 40 years (cm)
			1st thin	2nd thin	3rd thin	4th thin	Clear-fell	Total	
1*	(5.00000)	—	0	0	0	0	0	0	40.2
2	(5.00001)	34					38	38	42.8
3	(5.00010)	28				15	28	43	42.1
4	(5.00011)	28, 34				15	66	81	44.6
5	(5.00100)	22			13	12	21	46	41.6
6	(5.00101)	22, 34			13	12	59	84	44.1
7	(5.00110)	22, 28			13	27	49	89	43.5
8	(5.00111)	22, 28, 34			13	27	87	127	45.9
9	(5.01000)	16		12	9	8	14	43	41.1
10	(5.01001)	16, 34		12	9	8	52	81	43.7
11	(5.01010)	16, 28		12	9	23	42	86	43.0
12	(5.01011)	16, 28, 34		12	9	23	80	124	45.5
13	(5.01100)	16, 22		12	21	20	36	89	42.6
14	(5.01101)	16, 22, 34		12	21	20	74	127	45.1
15	(5.01110)	16, 22, 28		12	21	35	64	132	44.5
16	(5.01111)	16, 22, 28, 34		12	21	35	102	170	46.8
17	(5.10000)	0	68	10	7	6	11	102	40.9
18	(5.10001)	0, 34	68	10	7	6	49	140	43.5
19	(5.10010)	0, 28	68	10	7	21	39	145	42.8
20	(5.10011)	0, 28, 34	68	10	7	21	77	183	45.3
21	(5.10100)	0, 22	68	10	19	18	33	148	42.4
22	(5.10101)	0, 22, 34	68	10	19	18	71	186	44.9
23	(5.10110)	0, 22, 28	68	10	19	33	61	191	44.3
24	(5.10111)	0, 22, 28, 34	68	10	19	33	99	229	46.7
25	(5.11000)	0, 16	68	22	15	14	26	145	41.9
26	(5.11001)	0, 16, 34	68	22	15	14	64	183	44.5
27	(5.11010)	0, 16, 28	68	22	15	29	54	188	43.8
28	(5.11011)	0, 16, 28, 34	68	22	15	29	92	226	46.2
29	(5.11100)	0, 16, 22	68	22	28	26	47	191	43.3
30	(5.11101)	0, 16, 22, 34	68	22	28	26	85	229	45.8
31	(5.11110)	0, 16, 22, 28	68	22	28	41	75	234	45.1
32†	(5.11111)	0, 16, 22, 28, 34	68	22	28	41	113	272	47.5

* The yield (in absolute units) of sequence No. 1 (no fertiliser) is given in Table 1

† The yield (in absolute units) of sequence No. 32 (full fertiliser programme) is given in Table 2

was relatively small. By contrast, although a single application at final thinning (age 34 years) as in sequence No. 2 resulted in only 38 m^3 of extra wood (a 6% increase in yield over the rotation), there was a relatively large increase of 2.6 cm in the mean d.b.h.o.b. of the final-crop trees.

Economic Analysis

The model was used to analyse profitability, with the costs of fertiliser treatment and the royalty for wood that are current in the Tumut region of the New South Wales tablelands. Although it is recognised that both costs and returns will change, the analysis indicates several principles which are likely to hold for a range of monetary values.

The current cost of applying fertiliser at a rate of 200 kg N/ha plus 50 kg P/ha in the Tumut area is likely to be about A$250/ha (D. Wheen, pers. comm.). These application rates are based on the Australian data available to date (unpubl. data) and on overseas work. The rate for nitrogen is an average for many overseas fertiliser operations in coniferous stands. There are few overseas guidelines that can be used for determining the rate of phosphorus that is likely to be optimum for Australian conditions, and the rate is likely to vary between sites. For royalty, the current rates at Tumut (M. Gatenby, pers. comm.) were used for the stands without fertiliser. However, as royalty is dependent on log size, a schedule of royalties for the 57 stands with fertiliser was developed. Although it is inappropriate to tabulate the royalties for all 62 stands, those for sequence No. 32 are shown together with those for sequence No. 1 in Table 4 to indicate the upper and lower range of royalties at each harvest.

The costs of fertiliser treatment and the royalty returns in wood were amortised by compound interest for each of the 32 sequences. For each sequence, the internal interest rate of return (IRR) which returned the original investment in fertiliser was calculated by iteration through each sequence (Table 5). The highest IRR of A$18.6%/year (over 6 years) was from sequence No. 2, a once-only fertiliser application at the

TABLE 4—Royalty structure for **P. radiata** based on current values at Tumut, New South Wales

Harvest	Type of log	Royalty value of mean tree (A$/m^3)	
		Fert. sequence No. 1 (lower limit)	Fert. sequence No. 32 (upper limit)
1st thinnings	Pulp log	8.90	8.90
2nd thinnings	40% pulp log 60% saw log	10.59	13.56
3rd thinnings	Saw log	16.24	18.11
4th thinnings	Saw log	18.22	20.31
Clearfelling	50% saw log 50% peeler log	24.15	26.19

TABLE 5—Internal rate of monetary return (IRR), and extra wood resulting from 31 options of fertiliser treatment through a 40-year rotation of **P. radiata**

Fertiliser at various ages (years)		Sequence No. (Stand Code No. at age 40)	Extra wood due to fertiliser (m^3/ha)	Mean d.b.h.o.b. of final-crop trees at age 40 (cm)	IRR (%)
5 applications at:	0, 16, 22, 28, 34	32 (5.11111)	272	47.5	8.8
4 applications at:	0, 16, 22, 28	31 (5.11110)	234	45.1	8.3
	0, 16, 22, 34	30 (5.11101)	229	45.8	8.4
	0, 16, 28, 34	28 (5.11011)	226	46.2	8.5
	0, 22, 28, 34	24 (5.10111)	229	46.7	8.8
	16, 22, 28, 34	16 (5.01111)	170	46.8	11.1
3 applications at:	0, 16, 22	29 (5.11100)	191	43.3	7.8
	0, 16, 28	27 (5.11010)	188	43.8	7.9
	0, 16, 34	26 (5.11001)	183	44.5	8.0
	0, 22, 28	23 (5.10110)	191	44.3	8.3
	0, 22, 34	22 (5.10101)	186	44.9	8.4
	0, 28, 34	20 (5.10011)	183	45.3	8.5
	16, 22, 28	15 (5.01110)	132	44.5	9.8
	16, 22, 34	14 (5.01101)	127	45.1	10.1
	16, 28, 34	12 (5.01011)	124	45.5	10.6
	22, 28, 34	8 (5.00111)	127	45.9	13.7
2 applications at:	0, 16	25 (5.11000)	145	41.9	7.3
	0, 22	21 (5.10100)	148	42.4	7.8
	0, 28	19 (5.10010)	145	42.8	7.9
	0, 34	18 (5.10001)	140	43.5	7.9
	16, 22	13 (5.01100)	89	42.6	8.3
	16, 28	11 (5.01010)	86	43.0	8.8
	16, 34	10 (5.01001)	81	43.7	9.1
	22, 28	7 (5.00110)	89	43.5	11.9
	22, 34	6 (5.00101)	84	44.1	12.7
	28, 34	4 (5.00011)	81	44.6	16.3
1 application at:	0	17 (5.10000)	102	40.9	7.2
	16	9 (5.01000)	43	41.1	5.7
	22	5 (5.00100)	46	41.6	9.6
	28	3 (5.00010)	43	42.1	12.3
	34	2 (5.00001)	38	42.8	18.6

time of the last thinning, which resulted in 38 m^3 extra wood per hectare. The next highest IRR of A$12.3%/year (over 12 years) for a once-only application was from sequence No. 3 where the trees were treated at the next-to-last (third) thinning. At the other end of the scale, fertiliser at establishment (sequence No. 17), although producing the most wood from a single treatment, resulted in a lesser monetary dividend of A$7.2%/year (over 40 years). The complete treatment option No. 32 brought a return of A$8.8% over the 40-year rotation.

DISCUSSION

The model has a number of assumptions and simplifications. A primary assumption is that, over (a) a 16-year period after establishment, and (b) the 6-year periods between harvests, the rate of volume growth can be increased by 40% over that of thinned *P. radiata* growing without fertiliser at PAI between 16 and 19 m^3/ha/year. As outlined in the Introduction, this assumption is based on experience in New Zealand and on limited Australian data. Both nitrogen and phosphorus are likely to be required in order to achieve a 40% increase in relative growth on most Australian soils and, as nitrogen is being added in major amounts, sulphur may impose a further nutritional limit (Turner & Lambert 1978).

For fertiliser application at establishment, Waring (1981) has shown gains of such magnitude, and Woods (1976) and Neilsen & Crane (1977) have similarly found gains in excess of 40%.

At "later-ages" (thinning × fertiliser), the magnitudes of responses reported in the literature vary widely, and one of the main factors in explaining the variance is site quality. Almost universally it has been found that lower-quality sites respond more in relative terms than high-quality sites. Consider in further detail the contrasting data of Woollons & Will (1975) and Mead & Gadgil (1978). The former established fertiliser × thinning trials on *P. radiata* in the North Island of New Zealand on fertile pumice soils which were not deficient in phosphorus and the latter established similar trials in the South Island on less fertile gravelly soils which were phosphorus-deficient. During the first 5 years after treatment, the controls without fertiliser grew at 47 m^3/ha/year and 28 m^3/ha/year, respectively. This indicates a major contrast in site. Woollons & Will increased PAI with nitrogen (the response was shown to be due to nitrogen alone) to 60 m^3/ha/year, and this represented a response of 28%. By applying both nitrogen and phosphorus Mead & Gadgil increased PAI to 47 m^3/ha/year, and this represented a much more "impressive" response of 67%. This illustrates the principle, and also shows that both absolute and relative responses (as percentages) should be considered in association with native site quality (i.e., rates of growth without fertiliser) when responses to fertiliser are being examined.

In Australia, most *P. radiata* is growing on sites which can be classified as lower quality. On these sites, phosphorus is likely to be required in addition to nitrogen to produce satisfactory responses. On the evidence presently available 40% responses after application of nitrogen and phosphorus to *P. radiata* growing at PAI of between 16 and 19 m^3/ha/year as developed in the model should be obtainable.

However, a second assumption of the model is that successive responses can be gained independently of previous fertiliser treatment. For nitrogen this assumption is most likely valid as, although some slow build-up of site may occur (Miller 1981) the response of pines to nitrogen has generally been shown to be relatively short-lived and of the order of 6–10 years (Hagner & Leaf 1973).

For phosphorus there is likely to be some continuous build-up in the soil, which may diminish the relative response as site quality improves. Waring (1981) reported a carry-over of phosphorus fertiliser applied in a first rotation into the second rotation at Woodburn State Forest, New South Wales, and Gentle *et al.* (1965) found that phosphate fertiliser resulted in substantial responses and still remained at a high level in soil 15 years after application to *P. radiata* at Penrose State Forest, New South Wales. Similarly, Flinn *et al.* (1979) obtained sustained responses over 11–13 years to phosphate applied to *P. radiata* aged between 9 and 13 years at Scarsdale, Victoria. However, Barrow (1980) found that there was a steady decline in effectiveness of phosphorus applied to a number of Australian soils, in relation to growth of successive annual crops of sorghum. Effectiveness was approximately 0.1 to 0.2 of that of freshly applied superphosphate 6 years after application. As for many agricultural crops, it is likely that continued additions of phosphorus to fast-growing *P. radiata* on typical Australian plantation soils will give responses above that due to residual values.

The model can be used to examine any necessary nutrients required to achieve responses of the order of magnitude assumed. The current analysis does not consider macronutrients other than nitrogen and phosphorus, or any micronutrients which may limit growth or become limiting as growth is increased by macronutrients. Sulphur is likely to become limiting if increasing amounts of nitrogen are used, and micronutrients such as boron, copper, and zinc may also impose limits to growth or disordered stands as the demands on native soil nutrients are increased. There is an obvious limitation on growth imposed by available moisture which is likely to be a major factor on many *Pinus* sites in Australia (Waring 1970; Butcher 1977; Ferguson 1979). Moisture will interact with fertiliser on the majority of sites, and dry seasons may reduce potential responses.

The model assumes that height is relatively insensitive to fertiliser treatment. This is not a serious limitation. At later-ages on high-quality sites, Woollons & Will (1975) found that there was no height response to fertiliser. Absolute differences are not likely to be large within healthy stands. However, the assumption is a simplification made for ease of computation and because of the paucity of reliable data. This assumption may not reflect reality, particularly on sites of lower quality.

The number of stems that are removed by thinning has been made similar for stands in the model with and without fertiliser. This is a simplification which would probably not apply in operational practice. Fertiliser application can change almost any aspect of plantation management, and the manager is faced with myriad options (Dargavel 1978). Included amongst these is the "allowable cut effect" (Schweitzer *et al.* 1972), where some stands are specifically harvested at the same time as others have fertiliser applied, on a basis of expected future growth due to fertiliser. Allison (1978) developed the concept of "normalised stands" as a management tool in this complex area. However, for the purposes of the model and its present applications, the assumption of similar stockings after thinning regardless of fertiliser treatment is unlikely to affect the broadly based conclusions.

The mean-tree approach used in developing yields in the model may reduce the precision of estimation, but the errors are unlikely to exceed 7% (Crow 1971).

CONCLUSIONS

Using the model to evaluate the potential of fertiliser in association with thinning in Australia shows that:

(a) The most wood likely to result from a single treatment is from application at establishment, but the greatest increase in size of the final-crop trees occurs if fertiliser is applied at the last thinning.

(b) The maximum increase in growth occurs if fertiliser is applied at every opportunity. This treatment resulted in 272 m^3/ha additional to 684 m^3/ha, and represents the full 40% increase in growth assumed in the model over the 40-year rotation.

(c) Fertiliser appeared to be potentially profitable if applied at any stage, but for single applications the highest monetary dividends of 18.6%/year over 6 years and 16.3%/year over 12 years, resulted from treatment at the last and next-to-last thinnings respectively. These conclusions agree with those from Sweden (Svendsrud 1973) and the United States (Miller & Fight 1979) where the economic advantage of carrying interest on fertiliser treatment for only the final growing period, and adding extra wood to the largest and most valuable trees, has been shown. It should be emphasised, however, that as costs, returns, and economics are changeable, these dividends should be interpreted more qualitatively than quantitatively, i.e., as guidelines.

(d) Miller's (1981) conclusions that fertilisers are most likely to be of value prior to canopy closure or towards the end of the rotation appear to be theoretically well justified, in that application at these times is likely to result respectively in considerable dividends in extra wood, and maximal return on money invested in fertiliser treatment.

(e) The nature of the N×P interaction in relation to specific soils and stands is likely to be a key to understanding the likely responses to fertiliser, and in determining profitability. This question should be given priority in the next phase of nutritional research if the considerable potential of fertiliser application at various stages through a rotation is to be successfully realised in Australia.

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