LONG-TERM GROWTH RESPONSES IN PINUS RADIATA FERTILISER EXPERIMENTS

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ABSTRACT

The ability to forecast increases in crop productivity reliably over a whole rotation is frequently restricted by a lack of experimental data measured consistently over a long enough period of time. Four long-term trials in Australasian plantation **Pinus radiata** D. Don, in which responses to fertiliser have been measured for between 10 and 18 years, are analysed here to examine whether responses increase, decrease, or are maintained with the passage of time.

Three of the four experiments showed a diverging and compounding response to fertiliser throughout the periods of measurement. Such a finding appears to be in complete accord with widely held principles of crop growth and yield. Nevertheless, the same result was not achieved in the fourth trial; after a highly significant response of 4.5 m^2/ha in stand basal area 4 years after fertiliser application, the response eroded to 2.0 m^2/ha after a further 6 years of growth. Other examples are cited where fertiliser responses were either compounded or partially lost with time. Sites with marginal or marginally-induced nitrogen deficiency seem likely to exhibit sustained responses but grossly deficient sites may not necessarily behave similarly.

Examination of the residual errors in the trials, and their effects over time, suggests that experimental variation is a function of site, as well as a response to basic growth and size factors.

Keywords: fertiliser; nitrogen; basal area; biomass; **Pinus radiata**.

INTRODUCTION

Nutrition researchers are often asked the following critical question: given a demonstrable short-term fertiliser response in a specific field experiment, to what extent is this response maintained or increased over time, up even to time of clearfelling? Attempts to answer this query are usually and necessarily full of broad assumptions: very few researchers have long-term experiments which measure such effects directly, and all are continually forced to use implicit methods to secure estimates of later-age response. Such efforts frequently involve simulation by way of existing growth models; several such New Zealand systems have been modified to some extent to cater especially for fertiliser addition (for example, Lowell 1986) but some others have not (I. R. Hunter, pers. comm.).

The dearth of reliable data must place some doubt on the reliability of these simulations, which may be further compromised by the mode of fertiliser response. Woollons & Will (1975), Whyte & Mead (1976), and Hunter *et al.* (1985) have all demonstrated that in New Zealand there are clear fertiliser responses in basal area and occasionally in form-factor development, but not normally in height. Gordon & Graham (1986) have demonstrated these form changes may be small (less than 2.5%), but no published growth model can model any changes in stem form factor or taper that sensitively. Forest managers thus find it difficult to quantify the likely increased yields through fertiliser and so tend to dismiss the operation as a viable means of increasing their wood supplies.

In this study we report fertiliser responses in four Australasian *Pinus radiata* fertiliser experiments measured periodically between 10 and 18 years after initial fertiliser application. The sizes of response are examined with the passage of time, as are changes in experimental variability affecting statistical significance of treatments, and then the implications of the results are discussed.

SELECTED EXPERIMENTAL DATA

Trial No. 1

Woollons (1985) analysed a *Pinus radiata* thinning × fertiliser experiment established by H. D. Waring at Belanglo, New South Wales. In this study, fertiliser responses in basal area of 4.1 and 2.0 m^2/ha were obtained in unthinned (1425 stems/ha) and thinned (639 stems/ha) stands over 14 years, between 1967 and 1981. These responses appeared to be slowly compounding over time (*see* Fig. 3, Woollons 1985), a claim that is re-examined here in more detail.

The experiment was a randomised complete block involving eight replications of four treatments: (1) thinned, (2) with fertiliser and thinned, (3) unthinned, (4) with fertiliser and unthinned. A composite fertiliser was applied to designated plots in each of years 1967 (trees then aged approximately 23 years), 1968, and 1969; annual diameter at breast height measurements were available for all plots. Each experimental plot was 20 × 20 m, with an additional 10-m buffer surround. Further trial details are given by Woollons (1985).

Trial No. 2

Woollons & Will (1975) presented results from a *Pinus radiata* thinning × fertiliser experiment established by N.Z. Forest Products Limited in 1967 when the crop was aged 13 years, and where a composite fertiliser was or was not applied in both 1967 and 1968 to two residual stockings of 571 and 357 stems/ha. They deduced that by 1974 sustained responses of 61 and 36 m^3/ha over bark had occurred. Woollons & Whyte (1988) examined basal area responses in this same trial further until 1976, using multiple covariance techniques, and concluded that highly significant responses of 6.2 and 3.9 m^2/ha were present. This study is partly reproduced here, but augmented to include experimental variation over 1967–86.

Four replications of each treatment were available, laid out in a completely randomised design. Plots were 20 × 20 m, with additional 10-m surrounds. In 1976, the plots representing the 571 stems/ha regime were thinned from below to an average stocking of 306 stems/ha; no fertiliser application was attempted at this time. More details of the experiment are given by Woollons & Will (1975) (*see* their Trial No. 1).

Trial No. 3

In 1975, N.Z. Forest Products Limited established a fertiliser trial in thinned *Pinus radiata* regeneration aged 13 years, to investigate rates and timings of nitrogen, applied as urea. The experimental design was completely randomised, incorporating five replications of four treatments:

A – control, no fertiliser;

B – 250 kg urea/ha applied 1975, plus 250 kg urea/ha applied 1976;

C – 250 kg urea/ha applied 1975, plus 500 kg urea/ha applied 1977;

D – 500 kg urea/ha applied 1975.

Experimental plots were 20 × 20 m, with additional 10-m buffer surrounds. Initial stockings were all 494 stems/ha, but the trees became increasingly infected with *Dothistroma pini* Hulbary which, together with light physical damage, subsequently reduced the merchantable stocking to 398 stems/ha. Mensurational data taken included diameter at breast height measurements for all trees, for the periods 1975–78, 1980–81, and 1986. Spatial distances and bearings of all trees were also taken, which allowed indices of plot competition to be calculated, as explained by Woollons & Whyte (1988).

Trial No. 4

Mead *et al.* (1984) gave results from a *Pinus radiata* thinning × fertiliser trial established at Eyrewell State Forest, North Canterbury, when a stand was aged 7 years, and where a total of 400 kg N/ha as ammonium sulphate was applied in 1977. They reported that by 1981, a basal area response of 4.5 m^2/ha had occurred in both thinned and unthinned stands of 1540 and 810 stems/ha. The study is continued here by examining basal area responses through 1977–87.

The experiment was a randomised complete block, with each treatment replicated three times. Experimental plots were 19.3 × 19.3 m with additional 26-m buffer surrounds. Diameter at breast height measurements were available for all trees 1977–83 and 1986–87. Further details of the experiment are given by Mead *et al.* (1984).

METHODS

The four trials were analysed using linear regression models, largely following the methodology developed by Woollons (1985); some of the procedures are common to all experiments, and can be summarised accordingly.

In all trials, the response variable utilised was net basal area growth per tree, and the covariate or independent variable, initial net basal area per tree. Contingency-table analyses confirmed that no mortality was attributable to fertilisers applied. All experiments were first analysed by a model

$$E(Y_i) = \sum_{i=1}^{t} a_i + \sum_{j=1}^{t} \beta_j X + \sum_{k=1}^{r} \delta_k R \qquad (1)$$

where in (1),

Y = average growth in net basal area per tree for any year i
X = initial basal area per tree
R = blocks (if present)
a_i, β_j = intercepts and regression coefficients associated with the t treatments
δ_k = coefficients associated with the r blocks
E = statistical expectation

Analyses of variance of each Model (1) showed that:

(1) Where a block layout had been used, the effects of blocking were inconsequential and so blocking structures were ignored in all consequent analyses;

(2) With the exception of Trial 3, no disparate slopes existed between fertiliser and control treatments, *within* a specific thinning regime.

For all experiments, and for all years of measurements, the coefficient of variation (CV) was calculated from

$$CV = (S/\bar{Y}) \times 100\% \qquad (2)$$

where in (2),

S = estimated root mean square, obtained from the relevant analysis of variance, and
$\bar{Y}$ = mean net basal area per tree, of all treatments.

In addition, the multiple correlation squared statistic, R^2, was extracted for each analysis. Treatment responses were all converted to and finally expressed in net basal area/ha.

RESULTS

Trial No. 1

Final analyses were carried out for the years 1968–81 using the model

$$E(Y_i) = \alpha_{ft} + \alpha_t + \alpha_{fu} + \alpha_u + \beta_u X + \beta_t X \qquad (3)$$

where in (3) the subscripts

i = 1968, 1969,…, 1981
f,t,u, = fertiliser, thinned, and unthinned treatments.
Column (a) of Table 1 denotes the rejection levels of the hypotheses

$$H_o : E(Y_{tf} \mid \bar{X}_t) = E(Y_t \mid \bar{X}_t) \text{ and } E(Y_{uf} \mid \bar{X}_u) = E(Y_u \mid \bar{X}_u)$$

where the conditional $\bar{X}_t$, $\bar{X}_u$ indicate that the tests were evaluated at each thinning regime's mean initial value, and not the overall mean (*see* Woollons 1985). Column (b) denotes the rejection level of the hypothesis, $H_o : \beta_t = \beta_u$.

There was a slowly compounding response to fertiliser, for both regimes, with the effects becoming progressively more significant with time (Table 1). The use of separate regression coefficients is justified from 1970 onwards, while the R^2 and coefficient of variation suggest relatively less experimental variation occurs as time passes.

TABLE 1–Results of analyses undertaken with Trial 1 data

	(a) Thinned	(a) Unthinned	(b)	(c)	(d)	(e) Thinned	(e) Unthinned
1968	–	–	–	0.896	12.6	–	–
1969	–	–	0.167	0.942	10.6	–	–
1970	0.035	–	0.026	0.956	10.4	0.5	–
1971	0.040	0.140	0.024	0.957	10.1	0.7	1.1
1972	0.052	0.111	0.011	0.962	9.7	0.8	1.4
1973	0.080	0.110	0.012	0.963	9.4	0.8	1.6
1974	0.069	0.056	0.019	0.963	9.2	0.9	2.1
1975	0.077	0.054	0.017	0.964	9.0	1.0	2.4
1976	0.098	0.046	0.012	0.967	8.6	1.0	2.7
1977	0.054	0.043	0.018	0.967	8.4	1.3	3.0
1978	0.024	0.030	0.015	0.970	8.1	1.6	3.4
1979	0.030	0.030	0.015	0.970	8.0	1.7	3.7
1980	0.026	0.022	0.014	0.971	7.9	1.8	4.0
1981	0.016	0.017	0.012	0.971	8.0	2.0	4.1

(a) Probability of no response to fertiliser (p >F).
(b) Rejection level of hypothesis, $H_o : b_t = b_\mu$.
(c) R^2 values for utilised model.
(d) CV% of response variable.
(e) Estimated responses (m^2/ha).

Trial No. 2

Final analyses were carried out over 1968–86 using multiple covariance techniques with initial basal area per tree and an initial measure of stand competition as covariates (*see* Woollons & Whyte 1988). For 1986, no significant difference between the 357 and 306 stems/ha treatments was apparent, so these treatments were pooled in analysis (Table 2).

TABLE 2–Results of analyses with Trial 2 data

	(a)	(b)	(c)	(d)* 571 stems/ha	(d)* 357 stems/ha
1968	0.0068	0.845	9.3	0.6	0.4
1969	0.0008	0.873	8.5	2.0	1.1
1970	0.0001	0.908	7.4	3.0	1.9
1971	0.0001	0.918	7.3	4.0	2.5
1972	0.0002	0.911	7.5	4.6	2.9
1973	0.0003	0.917	7.2	4.9	3.1
1974	0.0008	0.910	7.7	5.2	3.2
1975	0.0013	0.904	7.9	5.6	3.5
1976	0.0015	0.897	8.2	6.2	3.9
1986	0.0633	0.425	11.0	-	5.6

* The stand at 571 stems/ha was thinned to 306 stems/ha in 1986. Woollons & Will (1975) gave 540 and 320 stems/ha as the residual stockings. The differences reflect further measurements, and re-editing of the data.
(a) Probability of no response to fertiliser (p >F).
(b) R^2 values for utilised model.
(c) CV% of response variable.
(d) Estimated responses (m^2/ha).

There is clear evidence of divergent responses over the periods 1968 to 1976 for both stockings with the 306 stems/ha stand continuing to give an estimated sustained response out to 1986. Inspection of the R^2 and coefficient of variation statistics, however, suggests a period of relative stability between 1968 and 1976, but by 1986 variability had increased abruptly to the extent that the significance of treatment differences fell below the 5% level. The sharp decline in the R^2 statistic is associated with a corresponding fall in the absolute value of the regression coefficient (*see* Draper & Smith 1981, p.45).

Trial No. 3

In 1976, no response could be detected. For 1977, however, a model

$$E(Y) = \alpha_A + \alpha_B + \alpha_C + \alpha_D + \beta X \qquad (4)$$

gave an ANOVA.

Source	d.f.	SS($\times 10^6$)	p>F
Initial basal area/tree	1	24.07	0.0007
Intercepts	3	10.87	0.0786
Error	15	19.86	

(Earlier analyses confirmed that only a pooled regression coefficient was justified.) The effect of the covariate is strongly significant, and the intercepts are weakly significant at the 8% level. In 1978, Model (2) was augmented to

$$E(Y) = \alpha_A + \alpha_B + \alpha_C + \alpha_D + \beta X + \delta Z \qquad (5)$$

where Z = plot competition index

which gave an ANOVA

Source	d.f.	SS($\times 10^6$)	p>F
Initial basal area/tree	1	48.01	0.0003
Plot competition	1	6.72	0.0908
Intercepts	3	20.39	0.0504
Error	14	28.54	

The intercepts are significant at the 5% level, and the second covariate is weakly significant at the 9% level.

For 1980, 1981, and 1986, a moderately complex model was required. A test of parallel slopes for initial basal area per hectare with treatments was rejected. Tests of the hypothesis

$$H_o : \beta_{A+D} = \beta_{B+C}$$

where β_{A+D}, β_{B+C} represent separate regression coefficients for the indicated treatment groups, were rejected, at least at the 1% level, for all 3 years. Similarly, tests of the hypothesis

$$H_o : \delta_{A+D} = \delta_{B+C}$$

were also rejected, at least at the 2.5% level, for all 3 years, giving a model

$$E(Y) = \alpha_A + \alpha_B + \alpha_C + \alpha_D + \beta_{A+D}X + \beta_{B+C}X + \delta_{A+D}Z + \delta_{B+C}Z \qquad (6)$$

Tests for the equality of the intercepts in (6) were rejected, as denoted in Table 3, in which the analyses between 1976 and 1986 are summarised.

There was a compounding response to Treatment B, 250 kg urea/ha applied at thinning in 1975, and a further 250 kg urea/ha one year later. The variation in the experiment was relatively large in early years, becoming more stable in 1980–81, but with signs of increased variation re-emerging in 1986, 11 years after thinning.

TABLE 3–Results of analyses with Trial 3 data

	(a)	(b)	(c)	(d)
1976	–	–	–	–
1977	0.0786	0.708	6.8	0.6
1978	0.0503	0.822	5.5	0.9
1980	0.0003	0.965	2.7	2.6
1981	0.0008	0.962	2.6	2.8
1986	0.0313	0.905	3.8	3.8

(a) Probability of no response to fertiliser (p >F)
(b) R^2 values for utilised model.
(c) CV% of response variable.
(d) Estimated response of Treatment B (m^2/ha).

Trial No. 4

Analyses were carried out for the years 1978–83, 1986–87 (Table 4), using the model

$$E(Y_i) = \alpha_{ft} + \alpha_t + \alpha_{fu} + \alpha_u + \beta X \qquad (7)$$

where in (7) the subscript i denotes 1978, 1979, . . . 1987, and all other notation is as defined previously. Model (7) was accepted, after previously establishing that no disparate regression coefficients were justified, either within fertiliser levels, or among thinning regimes. Response to fertiliser was strongly significant ($p<0.0001$) in both regimes, for all years.

Over 1978–81, very large responses occurred in both regimes, but proportionally (to initial basal area per hectare) more in the thinned plots (Table 4). Response continued to compound in the unthinned, but appeared to level off by 1987. In the thinned stand, however, the absolute response peaked during 1981 to 1983, then sharply declined through 1986–87, losing over one-half of the estimated response achieved in 1983.

TABLE 4–Results of analyses with Trial 1 data

	(a)	(b)	(c)	
			Thinned	Unthinned
1978	0.978	3.78	0.72	0.59
1979	0.991	2.57	1.90	2.34
1980	0.978	3.37	3.95	4.65
1981	0.991	2.91	4.51	4.94
1982	0.990	3.18	4.32	5.66
1983	0.992	2.59	4.40	6.21
1986	0.996	1.92	2.66	6.34
1987	0.996	2.10	1.98	6.13

(a) R^2 values for utilised model.
(b) CV% of response variable.
(c) Estimated responses (m^2/ha).

DISCUSSION

A major result established in the first three experiments was that fertilisers applied at, or soon after, trial installation produced responses which were maintained and indeed enhanced over time, up to 18 years after treatment. This outcome agrees with the conclusions of Schonau (1977) who demonstrated divergent basal area development with *Eucalyptus grandis* Maiden, and Lowell (1984) whose Nelson *Pinus radiata* fertiliser growth model suggested that volume response is continued up to clearfelling ages. Mead & Gadgil (1978) also reported sustained responses to phosphorus fertiliser over 24 years on a very deficient site. We are certain these results are in accordance with normal established principles of stand yield development over time. For example, the net basal area projection equation proposed by Clutter (1963)

$$\ln(G_2) = \ln(G_1)(T_1/T_2) = \alpha(1 - (T_1/T_2)) + \beta S(1 - (T_1/T_2)) \quad (8)$$

where G_2, G_1 = net basal area per hectare at ages T_2, T_1

S = site index

α, β = estimated parameters representing upper limits to yield

or variants thereof (for example, Clutter & Jones 1980; Clutter *et al.* 1983; Pienaar *et al.* 1985; Woollons & Hayward 1985) have been successfully utilised to predict net basal area per hectare in several growth models of even-aged crops of various species. The dynamics of (8) can be taken to reflect normal stand development with time. Inspection shows that, excluding extraordinary mortality over the period, if $G_1' > G_1$ at time T_1 then $G_2' > G_2$ for all $T_i > T_1$. Moreover, from the structure of (8), $(G_2'/G_2) > (G_1'/G_1)$ thus supporting the above conclusions.

Results from Trial 4, however, restrain us from concluding that the phenomenon of compounding responses to fertiliser can be expected in all stands and conditions. In this experiment, the response in the thinned stand dropped by 55% between the sixth and tenth year after fertiliser application. Hunter *et al.* (1986) reported results from a nitrogen fertiliser trial on sand-dunes in the Manawatu, where a response of 5.3 m^2/ha 5 years after topdressing had eroded to 3.7 m^2/ha after a further 5 years. In this paper we offer only a little speculation on the reasons for these declines; we currently do not possess sufficient data to do otherwise. On recent wind-blown sands, the bigger biomass resulting from fertiliser may not be maintained because of severe nitrogen and possible moisture stress (in this trial, foliar nitrogen concentrations fell to acutely deficient levels within 1 year after fertiliser application). At Eyrewell where Trial No. 4 is located, the soils are infertile, stony, and prone to seasonal drought; the situation is further complicated here by the lack of decline (to date) in the unthinned plots. A possible explanation is that trees with fertiliser applied invest less in root activity. When the fertiliser effect begins to run out they need to rectify the neglect of their roots. It has been suggested by Hunter (pers. comm.) that unthinned plots with their tighter canopy and moister forest floor probably have a better nitrogen cycle, enabling them to recycle nitrogen faster and hence to maintain their advantage.

Our purpose here is to emphasise the management ramifications of the combined results. In three experiments, sustained and compounding responses were evident, present up to 18 years after fertiliser application. Two of these trials were installed on productive pumice soils, but the third was established on a less thrifty site in an area liable to periodic drought. The trial of Mead & Gadgil (1978) mentioned above, likewise dramatically enhanced growth, despite the location being hitherto badly impoverished. We therefore subscribe to the thesis that many forest sites in Australasia, once fertiliser has been applied, will produce enduring responses typified by the principles of Equation (8). However, the results of Trial 4 and those of Hunter *et al.* (1986) warn us that these results cannot be completely generalised; on selected marginal sites further fertiliser may be periodically required to sustain early responses. Alternatively, response to one fertiliser (or element) may induce deficiencies in other elements.

The experimental variation in the four trials and its effect over time give sharply contrasting results. Whereas Trial 1 exhibited proportionally better precision and significance between treatments with successive years, Trial 2 and, to a lesser extent, Trial 3 were characterised by a period of high significance between treatments for 4 to 7 years after fertiliser application, followed by a tendency to lose precision and to lower levels of significance. Trial 4, however, was characterised by very high precision and no real evidence of losing this consistency with time.

These discrepancies are a little difficult to describe in general terms, and it may be that long-term experimental variation is primarily (1) site-specific, and that sufficient replication must be installed to meet each local condition. The results above also suggest trial variability can be attributed to (2) size of observed responses, (3) available degrees of freedom, and (4) basic growth trends. Effective replication of treatments for an expected size of response is fundamental to sound experimental design, and this is borne out by the results we quote; residual degrees of freedom to estimate error in the first three experiments are 26, 12, and 13 respectively, and go some way to explaining the differing results of these studies. Trial 4 has only 7 degrees of freedom available, but here the measured response exceeds 15%, compared to 4–8% in the other trials. Trials 2 and 3 were installed at age 13 soon after peak increment in basal area per hectare in unthinned conditions. Subsequent growth up to ages 24–30 was very productive, averaging over 2.5 m^2/ha a year. In these thrifty growing conditions, some individual plots were possibly prone to abnormal micro-site fertility, and individual trees of the same dominance exhibited differing rates of decline in growth, the effects of which compounded with time. In contrast, Trial 1 was not initiated until age 23, and subsequent annual growth was less than 2 m^2/ha. While the latter was obviously a function of age and a less fertile site, the variation among comparable plots was appreciably less.

In practical forest management terms, we believe that the returns from applying fertiliser have not been properly evaluated in the past, in terms of either yield or money, because of a lack of both long-term mensurational evidence and adequate means of forecasting future yields. This is partly the reason behind the claim by Whyte *et al.* (1978) that managers need information on responses which can be incorporated into existing yield forecasting methods so that the gains can be properly quantified over the life of the crop. In the ensuing decade there has been a reluctance among decision-makers to apply fertiliser to *P. radiata* crops, at least partly because any experimental evidence or gains could not be translated into amounts of realisable yields operationally. The results presented here suggest that although there is a pressing need to distinguish clearly between forest areas which will carry fertiliser gains to clearfelling age and those which require remedial dressings during a rotation, the decision to defer fertiliser application may have been unwise in many regions. This is particularly pertinent in view of the current scarcity of wood for an industry that needs to expand its processing capability as soon as possible.

CONCLUSIONS

Results from three of four fertiliser experiments confirm that response to dosages of fertiliser applied at mid-rotation ages can be sustained and enhanced over time. It is envisaged that these principles are likely to be applicable to a majority of sites, although responses in some deficient stands can decrease. Long-term fertiliser trials are sometimes characterised by high variation which may affect levels of significance between treatments. Returns from fertiliser application can be properly evaluated only when experimental evidence can be translated into future yields.

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