PINUS RADIATA GROWTH RESPONSES TO PRUNING, THINNING, AND NITROGEN FERTILISER IN KAINGAROA FOREST

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ABSTRACT

Growth responses of *Pinus radiata* D.Don to pruning, thinning, and fertiliser treatments in a factorial design were measured over a 19-year period at two Kaingaroa Forest sites (Goudies, site index 30 m; Matea, site index 25 m). As single-factor treatments:

- Pruning –(selective green-crown pruning without thinning) resulted in a considerable loss in basal area growth;
- Thinning – Trees that were thinned-only responded with increased diameter growth;
- Fertiliser – The application of nitrogenous fertiliser (at 200 kg N/ha) to trees that remained unthinned (at 2700–3000 stems/ha) gave no significant improvement in basal area growth.

For combined treatments, when nitrogen fertiliser was applied to trees that were also thinned, a moderate basal area response resulted. For trees that were pruned and thinned, there was evidence that nitrogen fertiliser assisted with growth recovery from green crown pruning. The response to nitrogen fertiliser applied at first thinning (age 5–6 years) appeared to be similar to the response achieved at second thinning (age 9–11 years). Where the fertiliser was applied at both first and second thinnings the response was very small—a result which cannot be explained. By tree age 24 the response to nitrogen fertiliser was inconsistent and statistically non-significant.

Height growth in this study was little affected by pruning or thinning treatments and unaffected by the application of nitrogen fertiliser.

Generally, thinning increased mean branch diameters in subsequent pruning lifts by 0.4 cm, and where nitrogen fertiliser was also applied the increase was 0.6 cm. When combined with stem diameter responses these treatments have generally increased the diameter over pruned stubs (DOS) by 1–2 cm. For these reasons it would be advantageous to apply nitrogen fertiliser after all pruning lifts are complete.

Analysis of these trials up to age 24 years has indicated that variation between replicates increased with time and that this trend should be considered when trial designs are developed. The analysis also confirmed that single trials are of little value because of the influence of local site factors. A trial series located on a range of site types is recommended for the testing of silvicultural and fertiliser treatments.

Keywords: pruning; thinning; nitrogen fertiliser; Kaingaroa Forest; *Pinus radiata*.

INTRODUCTION

The pruning of live branches to minimise the defect core and produce clear knot-free timber is widely practised in *P. radiata* plantations of New Zealand. Selective pruning in unthinned stands results in considerable growth loss for the pruned stems and often these trees become dominated by more-vigorous unpruned neighbours (Sutton & Crowe 1975). A practice adopted to assure the growth and dominance of the pruned stems is the early thinning (usually to waste) of all or most unpruned stems (Forest Research Institute 1979). Although this practice improves the growth of pruned stems it is evident that when pruning is at an intensity that limits the defect core of *P. radiata*, losses in tree growth will still occur. Subsequent research led to the development of a growth model that accounts for the effects of pruning and early thinning (West *et al.* 1982). This model and many others have been incorporated into a stand management modelling system—STANDPAK (Whiteside 1990)—which allows the economics of a wide range of pruning and thinning options to be evaluated.

Early research by Woollons & Will (1975) on fertiliser effects indicated that encouragingly large growth responses of *P. radiata* on pumice soils could be achieved with the application of nitrogen (N) fertiliser immediately after thinning. Kramer (1976) found that similar improvements were achieved in pruned stands of *Picea abies* (L.) Karsten in Germany.

Later work with *P. radiata* (Hunter 1982; Hunter *et al.* 1985) involving numerous field trials considerably enhanced knowledge of the site and stand prerequisites for nitrogen fertiliser response. These studies also quantified the expected period of response after application as 3 to 5 years, and the results were generalised into responses for pumice soils and responses for coastal sands (Andrew 1988). However, little new research has been reported on nitrogen fertiliser effects in New Zealand since these studies.

Stem diameter growth of *P. radiata* planted on sites with a history of intensive pastoral farming has been substantially faster than that on unimproved forest sites (West *et al.* 1982; Skinner & Attiwill 1982). Productivity levels of at least 38 m^3/ha MAI (R.L.Knowles & J.P.Maclaren, pers. comm.) are achieved on such sites, compared to 20–22 m^3/ha on traditional unimproved forest sites (Shirley 1984). The enhanced growth rate on farm sites is attributed to higher soil nitrogen levels resulting from biological nitrogen fixation by white clover (*Trifolium repens* L.) encouraged by applications of phosphorus fertiliser. These results indicate that, when given adequate nutrition, the productivity potential of *P. radiata* in New Zealand is substantially above the customary 20–22 m^3/ha MAI that is generally achieved.

Although many field trials have been established to examine individual treatments of pruning, thinning, and nitrogen fertiliser, very few have been designed to test all three together. Earlier silvicultural studies have shown that there are very often interactions between operations and interactions between operations and site (West *et al.* 1982).

This report presents results from two trials designed to examine the effects of pruning, thinning, and nitrogen fertiliser application, and their interactions, on the growth of *P. radiata*. Results from these trials for the first 2–3 years of growth after treatment, have been published previously by Sutton & West (1980) and Hunter *et al.* (1985).

MATERIAL AND METHODS

Trial Design

Because the principal objective of the trial was to determine whether there was a response rather than the magnitude of it, only two levels of treatment (untreated or treated) were included. The intensity of treatment applied was considered to be the most likely standard schedule at the time of trial initiation (1976).

The trial had a full factorial design which incorporated two levels (designated 0 and 1) of each of three factors: Pruning (P), Thinning (T), and Fertiliser (F). The effect of site was investigated by establishing the trial on two sites. Each treatment was replicated twice at each site.

As the timing of fertiliser application may be of importance, two additional treatments were included as a subsidiary study (Table 1).

(1) Prune and thin but apply fertiliser at second thinning only (TPF2)

(2) Prune and thin but apply fertiliser at first and second thinning. (TPF1F2)

At the time of the third pruning lift (c. 13 m MTH) the P and PF (selectively pruned) treatments were considered to be impractical and plots were thinned to 250 stems/ha. This effectively disrupted the full factorial design. After this thinning these treatments should therefore be considered as pruning with a single thinning treatment at the time of the third pruning lift (i.e., P(T2) and PF1(T2)).

TABLE 1–Summary of treatments

Treatments*	Factor†		
	Thinning	Pruning	Fertiliser
Control	0	0	0
P	0	1	0
F1	0	0	1
PF1	0	1	1
T	1	0	0
TP	1	1	0
TF1	1	0	1
TPF1	1	1	1
TPF2	1	1	0+1
TPF1F2	1	1	1+1

* P= pruned in three lifts T = thinned twice
F1 = fertiliser applied at first thinning F2= fertiliser applied at second thinning

† 0 = No treatment 1 = Standard practice applied.

Treatment Schedules

Pruning

Pruning was completed in three lifts:

Lift 1 The best 600 stems/ha were pruned to 2.6 m at c. 5.7 m mean crop height.

Lift 2 The best 375 stems/ha were pruned to 4.2 m at c. 9.3 m mean crop height.

Lift 3 The best 250 stems/ha were pruned to 6.4 m at c. 12.1 m mean crop height.

Care was taken to maintain equal pruning severity (percentage of stem pruned) in all pruned plots.

Thinning

All thinning was to waste (non-commercial) using a chainsaw. The first thinning (T_1) was at the time of first pruning to 600 stems/ha, and the second thinning (T_2) was at the third pruning lift to 250 stems/ha.

Fertiliser

F1 = Nitrogen fertiliser applied immediately after the first thinning and pruning treatments.

F2 = Nitrogen fertiliser immediately after the second thinning and third pruning treatments. Nitrogen was applied as urea at a rate of 200 kg N/ha in spring.

Trial Site Description

The trial was established at two locations in Kaingaroa Forest (Table 2). Both sites were planted in *P. radiata* in 1971.

TABLE 2–Details of trial sites

Site	Site index (MTH @ 20 yr) (m)	Altitude (m)	Rainfall (mm)	Soil type	Initial tree stocking (stems/ha)	Tree age at trial establishment (years)
Goudies	30	530	1500	Sand - air fall ashes	2700	5
Matea	25	670	1600	Sand - flow tephra	3000	6

The Goudies site was chosen to represent a site of average productivity for the central North Island pumice plateau; the Matea site represented a poor site, typical of the southern Kaingaroa region. The soils of the two sites were clearly different in their characteristics. The Goudies site offered deep rooting, plentiful moisture storage, and access to buried soils containing nutrients such as magnesium, which is deficient in the more recent ash showers (Knight & Will 1970). The southern flow tephra soils at Matea were frequently too deep to permit access to buried soils and, having a blocky and sometimes welded texture, appeared to restrict root access (Hunter *et al.* 1985).

To assist with the interpretation of tree growth results, foliage samples were periodically taken from the control plots for analysis of nutrient concentrations (1979 data as per Hunter *et al.* 1985). Base level foliage nutrient concentrations in the first 3–6 years of the trial are given in Table 3. Using the criteria of Will (1978) these data indicate that the trial sites could be considered: adequate–marginal for nitrogen at both sites, adequate for potassium at both

TABLE 3–Foliage nutrient concentrations from control plots without fertiliser

Trial	Year	Element				
		N	P (% d.w.)	K	Mg	Ca (ppm)
Goudies	Mar-79	1.43	0.19	1.08	0.08	0.14
	Mar-81	1.31	0.15			
	Apr-82	1.47	0.18		0.08	
Matea	Mar-79	1.45	0.13	0.61	0.06	0.22
	Mar-81	1.52	0.15			
	Apr-82	1.50	0.14		0.08	
Nutrient concentration criteria						
adequate		>1.5	>0.13	>0.5	>0.10	
marginal		1.2–1.5	0.10–0.13		0.07–0.10	
deficient		<1.2	<0.10	<0.3	<0.07	

sites, adequate for phosphorus at Goudies, adequate–marginal for phosphorus at Matea, marginal for magnesium at Goudies, and deficient–marginal for magnesium at Matea.

Trial Layout

Each plot consisted of a 0.04-ha (20 × 22-m) measurement plot plus a 10-m surround. Measurement of plot basal area at the time of trial establishment indicated scattered within-site variation which did not allow conventional blocking. To overcome this, plots with high and low values were paired to approximate the overall mean. Treatments were then randomly allocated to each pair of plots.

Tree Growth Measurements

Measurements of dbh, height, and stocking were taken annually up to tree age 17 and thereafter biennially to tree age 24. Total standing volume (TSV) was calculated for each plot using volume function 10 (New Zealand Forest Service 1953) derived for *P. radiata* in Kaingaroa, Whakarewarewa, and Rotoehu Forests. This function had the form:

$$V = dbh^{b1} \times (MTH^2/MTH - 1.4)^{b2} \times Exp^{b3}$$

where

dbh = diameter at breast height (1.4 m)

MTH = mean top height, i.e., the mean height of the 100 trees/ha with the largest diameter.

Branch Size and DOS

At the time of second and third pruning, branch size was measured with 15 trees per plot sampled in the second lift and 10 trees per plot sampled in the third lift. The horizontal diameter at the point of severance was measured on all branches in the lift. The maximum diameter over pruned stubs (DOS) (Knowles *et al.* 1987) and DOS height were also recorded for each lift.

Data Analysis

A previous analysis of early data from these trials (Sutton & West 1980) showed that initial plot basal area, prior to treatment, provided some measure of within-site variation.

Initial basal area of the best 600 stems/ha at plot establishment was therefore tested as a significant covariate for basal area growth, and initial MTH as a covariate for height growth. This methodology has been thoroughly examined and recommended by Woollons (1988). A further consideration in designing the analysis of these trials was the very large inherent difference in growth between thinned (250 stems/ha) and unthinned (≥2000 stems/ha) treatments. Woollons' (1988) analysis of a similar trial reported by Hunter *et al.* (1986) suggested that these treatments should not be separated and that a combined general linear model for the analysis of variance be used. To assist with this, basal area and volume values in this study were transformed by natural logarithms prior to the analysis of variance.

A more elegant approach to data analysis based on comparisons of regression functions fitted to each treatment (Woollons 1988) was considered but not adopted because of the large number of treatments and the complexity of responses that would require multi-parameter non-linear functions. Coefficients of such functions were likely to be difficult to interpret. By comparison, analysis of variance would offer a more conservative approach.

RESULTS

Basal Area and Height growth

At time of second thinning

At the time of second thinning (age 9.2 at Goudies and 11.2 at Matea) the P and PF treatments were thinned. Therefore, these were the oldest-aged data with which a full factorial analysis (combining treatments into main effects) was appropriate. The main treatment effects on the basal area of the crop 250 stems/ha and MTH at second thinning (third pruning) are given in Table 4. For the Control (unthinned) and unthinned Fertiliser treatments, the basal area of best 250 stems/ha selected crop element was used. Basal area and MTH at second thinning were adjusted by covariance using initial values measured at trial establishment. No significant interaction was found between treatments for basal area or MTH at either trial.

TABLE 4–Main treatment effects on basal area (m^2/ha) of the best 250 stems/ha and MTH (m) at second thinning.

Treatment level	Goudies				Matea			
	Basal area (m^2/ha)	% diff	MTH (m)	% diff	Basal area (m^2/ha)	% diff	MTH (m)	% diff
No pruning (0)	7.89		13.6		8.98		13.0	
Pruning (1)	6.58	–16.6*	13.0	–4.4*	7.98	–11.1*	12.7	–2.3ns
No fertiliser (0)	6.75		13.0		8.32		13.0	
Fertiliser (1)	7.72	14.4*	13.6	4.6*	8.65	4.0ns	12.7	–2.3ns
No thinning (0)	5.67		13.4		7.37		12.2	
Thinning (1)	8.81	55.4**	13.2	–1.5ns	9.59	30.1*	13.4	9.8**

ns = not significantly different
* = differences significant at p = 0.05
** = differences significant at p = 0.01

These results indicate that at both sites there was a strong negative basal area response to pruning and a strong positive response to thinning. A strong positive response to nitrogen fertiliser was apparent at Goudies but not at Matea.

Main treatment effects on height were generally small. They indicated a negative effect of pruning and a positive effect of fertiliser at Goudies and a positive effect of thinning at Matea.

Comparisons of basal area and height growth for individual treatments (Table 5) indicated that trees that had been selectively pruned (without thinning, treatment P) showed substantially lower basal area growth rates than trees thinned at first pruning (TP). This effect was most pronounced at the better Goudies site.

At both sites, the application of nitrogen fertiliser at first pruning to thinned stands appeared to compensate for some but not all of the loss in basal area growth from green crown pruning.

TABLE 5—Individual treatment effects on stand parameters immediately after second thinning. Treatments are ranked in order of basal area (covariance adjusted values).

Site	Treatment	Stems/ha	Basal area (m^2/ha)	Mean top height (m)
Goudies	F	2875	42.45 a	13.9 a
age 9.2	Control	3088	42.08 a	13.4 a
	TF1	250	10.34 b	13.7 a
	T	250	8.78 bc	13.3 a
	TPF1	250	8.21 bc	13.3 a
	TP	250	7.25 cd	12.2 b
	PF1 (T2)	238	5.63 de	13.4 a
	P (T2)	250	4.95 e	13.0 ab
Matea	Control	2700	43.62 a	12.4 cd
age 11.2	F	2200	40.17 a	12.4 cd
	TF1	250	10.58 b	13.6 ab
	T	250	10.00 bc	13.6 ab
	TPF1	238	9.12 bc	13.1 bc
	TP	250	8.36 cd	13.5 ab
	P (T2)	238	7.29 d	12.4 cd
	PF1 (T2)	250	6.97 d	11.8 d

Values followed by the same letter are not significantly different at $p = 0.05$

Nitrogen fertiliser application had little effect on the growth of selectively pruned stems in plots that had yet to be thinned (P (T2) *v*. PF1 (T2)).

Height growth showed contrasting trends depending on site. At the Goudies site, treatments involving thinning and/or pruning resulted in either a small loss in height growth or no effect. However, at the Matea site treatments involving thinning resulted in improved height growth. The Matea result was thought to be due to terminal bud attack by *Diplodia pinea* (Desm.) Kickx which was observed to be more prevalent in the unthinned treatment. Therefore, the Matea height growth result was confounded by a localised forest health issue and was considered anomalous in the context of the silvicultural treatments in this study.

Between age 5–6 and age 24

The development of Total Standing Volume (TSV) to age 24 years in the unthinned and delayed thinning treatments at the Goudies trial is shown in Fig. 1. Without early thinning no response to the nitrogen fertiliser (applied at age 5) was evident, with or without pruning. Volume growth of thinned treatments at Goudies showed marked differences between treatments with and without pruning and/or fertiliser (Fig. 2).

Development of TSV in the unthinned and delayed thinned treatments at the Matea site is shown in Fig. 3. Without early thinning no response to the nitrogen fertiliser (applied at age 6) was evident.

Thinned treatments at Matea showed marked differences in volume growth between treatments with and without pruning and/or fertiliser (Fig. 4).

At age 24 years

Stand parameters for each site at age 24 years are given in Table 6. The limited replication in this study meant that few of the treatment differences were statistically significant and yet

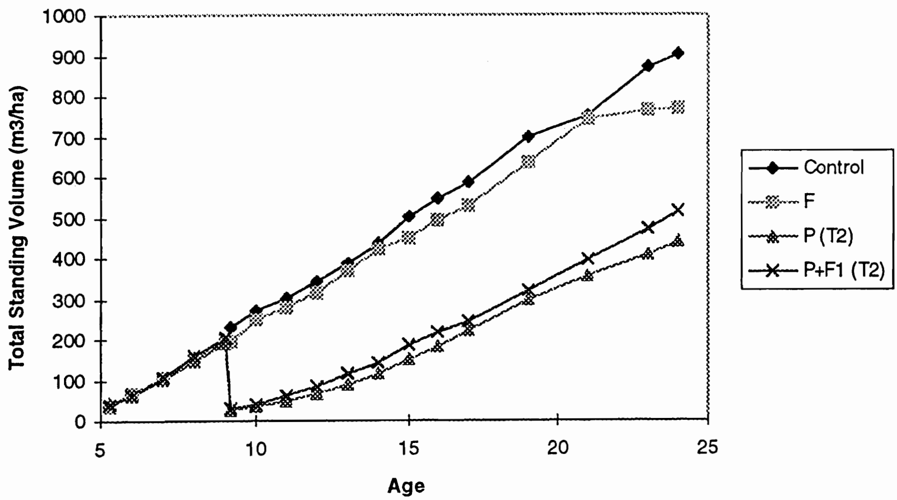

FIG. 1–Goudies—Volume growth in thinned and delayed thinned treatments.

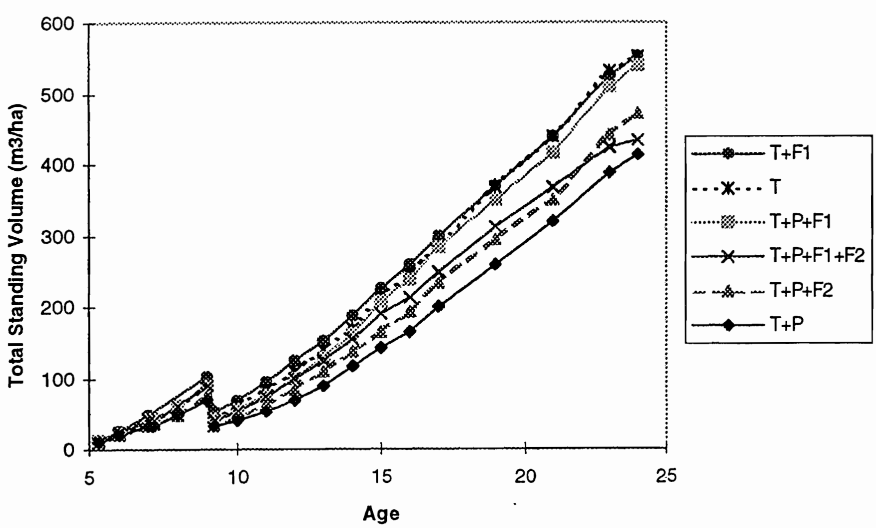

FIG. 2–Goudies—Volume growth by treatment; thinned at ages 5 and 9 years.

substantial volume differences were indicated. The Control and F (fertiliser only) treatments were not thinned and achieved the highest TSV, although stem diameter (dbh) was the smallest. All other treatments were thinned to 250 stems/ha and had significantly lower TSVs but larger stem diameters.

The response to nitrogen fertiliser was inconsistent. The single application of fertiliser at either first thinning or second thinning showed a considerable volume response at the Goudies site, and yet the response to the double application (TPF1F2) was negligible. Plots that were thinned (T) with no pruning, showed no gain from nitrogen fertiliser at this age. This was contrary to the results recorded at age 9.2. At the Matea site the volume response

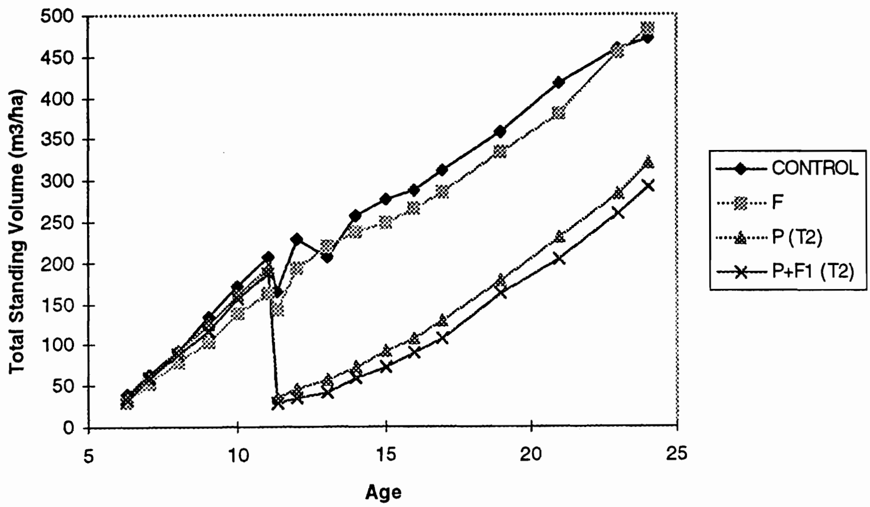

FIG. 3–Matea—Volume growth for unthinned and delayed thinned treatments.

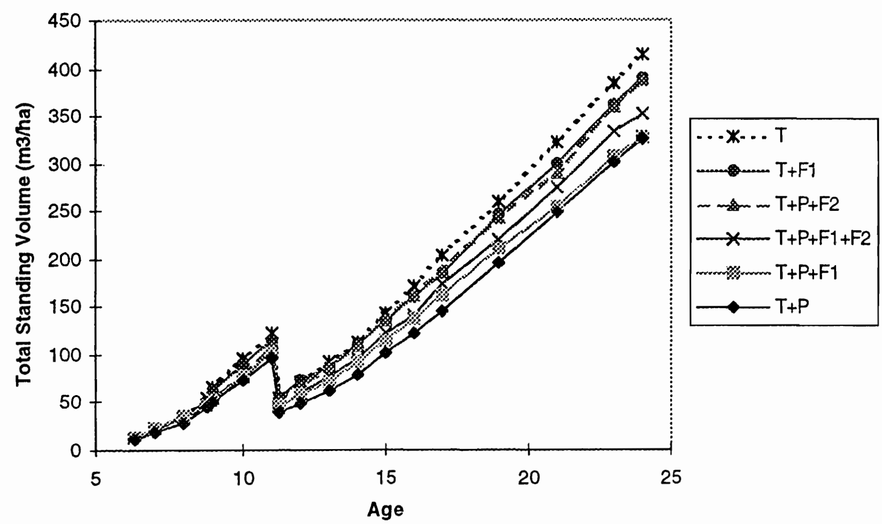

FIG. 4–Matea—Volume growth for treatments thinned at 6 and 11 years.

to nitrogen fertiliser was very small and negative for the TPF1 treatment. Pruning generally depressed growth, although not significantly or consistently.

Results of analysis of variance of basal area, MTH, and volume (TSV) by age and site are given in Appendix 1. Although the factorial design has been disrupted, comparisons between most treatments can still be achieved. Thinning and pruning treatments had a significant effect on basal area and volume but the MTH response was much less consistent. There was also a strong thinning and pruning interaction of depressing the growth of basal area and volume.

TABLE 6–Stand parameters at age 24 with treatments ranked by total standing volume at each site.

Site	Treatment	Stems/ha	Green crown height (m)	dbh (cm)	Basal area* (cm^2/ha)	Mean top height* (m)	Total standing volume* (m^3/ha)	Difference from TP treatment (m^3/ha)
Goudies	F	1238	23.5	26.7	73.74 a	34.0 abc	818 a	393
	Control	1488	22.2	24.7	71.63 a	34.8 abc	813 a	388
	T	250	19.3	49.9	49.12 b	35.4 ab	555 b	131
	TF1	250	19.8	50.7	46.62 bc	34.6 abc	516 bc	91
	TPF1	250	19.5	49.0	44.65 bc	35.9 a	510 bc	86
	PF1 (T2)	238	18.6	50.1	44.75 bc	34.7 abc	492 bc	67
	TPF2	250	18.8	45.5	40.17 bc	34.6 abc	471 bc	46
	P (T2)	250	18.7	45.0	41.66 bc	33.4 bc	460 bc	36
	TPF1F2	250	19.1	45.7	41.26 c	33.1 c	439 c	15
	TP	250	17.8	44.4	39.55 c	33.1 c	425 c	0
Matea	F	713	16.4	30.0	52.40 a	28.9 abc	513 a	175
	Control	813	14.7	27.8	50.25 a	28.8 bc	482 ab	144
	T	250	17.0	46.1	40.02 ab	30.8 ab	384 abc	46
	TF1	250	17.3	44.2	37.31 b	31.4 a	373 abc	35
	TPF2	263	13.8	43.4	38.24 b	30.6 ab	360 bc	22
	TPF1F2	250	14.5	43.8	36.65 b	29.2 abc	340 c	1
	TP	250	15.6	41.4	34.23 b	29.7 abc	338 c	0
	P (T2)	238	14.7	41.8	32.58 b	29.0 abc	326 c	–12
	TPF1	238	14.0	42.6	32.67 b	29.7 abc	313 c	–26
	PF1 (T2)	250	13.1	41.3	34.94 b	27.6 c	301 c	–37

* Covariate adjusted values using initial basal area and height
Within columns, values with the same letter are not significantly different at $p = 0.05$

Matea height data were confounded with disease effects (terminal shoot dieback caused by *D. pinea*). At Goudies, height growth was unaffected by nitrogen fertiliser application but was slightly reduced when pruning was combined with thinning. However, the height data were inconsistent and no statistically significant trends were apparent.

Combining Sites

As part of the initial trial design it was conceived that the two trials could be combined to strengthen the analysis. Analysis of variance was used to test for significant differences between sites. No significant interactions of site ¥ treatments were found, although the level of growth was significantly different between sites. Therefore sites could be combined and comparison of treatments re-analysed. Results are given in Table 7.

Combining trials made little difference to the treatments effects, with most treatments statistically clustered.

Branch Response

As tree growth rate (i.e., change in stem size) was modified by the silvicultural treatments in this study, it is also of interest to record how branch size at the time of pruning and subsequent diameter over pruned stubs (DOS) (Knowles *et al.* 1987) were influenced (Table 8).

TABLE 7–Combined stand volumes at age 24 for both sites by treatment

Treatment	Volume* (m^3/ha)	Difference from TP treatment (m^3/ha)
F1	647 a	268
Control	626 a	247
T	462 b	83
TF1	439 bc	60
TPF2	421 bc	42
TPF1	399 bc	20
P (T2)	387 c	8
TPF1F2	386 c	7
PF1 (T2)	384 c	5
TP	379 c	

* Covariate adjusted values using initial basal area
Values with the same letter are not significantly different at p = 0.05

TABLE 8–Effect of thinning and nitrogen fertiliser on branch response and DOS

Trial	Pruning lift	Treatment	No. of branches pruned per lift	No. of branches per metre of lift	Mean branch diameter (cm)	Branch sectional area per metre of pruning lift (cm^2)	DOS (cm)	DOS height (m)
Goudies	Medium	P	15.3 a	9.45 a	2.2 a	35.8 a	14.6 a	3.0 a
		T+P	17.2 a	9.69 a	2.6 b	53.0 b	16.0 ab	2.7 b
		T+P+F	17.0 a	9.33 a	2.9 b	60.7 b	18.2 b	2.7 b
	High	P	15.0 a	7.49 a	2.0 a	23.9 a	15.2 a	4.8 a
		T+P	18.9 ab	9.82 b	2.7 b	54.9 b	17.9 ab	4.6 a
		T+P+F	20.9 b	11.14 b	2.8 b	69.0 b	20.0 b	4.7 a
Matea	Medium	P	18.7 a	9.35 a	2.3 a	38.2 a	16.6 a	2.5 a
		T+P	23.0 a	11.09 a	2.7 b	61.5 b	18.2 a	2.4 a
		T+P+F	20.2 a	10.60 a	2.8 b	65.1 b	18.0 a	2.5 a
	High	P	15.1 a	8.81 a	2.4 a	41.6 a	18.7 a	4.7 a
		T+P	17.8 ab	10.01 ab	2.6 ab	54.8 ab	19.8 a	4.7 a
		T+P+F	21.0 b	11.48 b	2.8 b	69.9 b	19.8 a	*4.3 b

* Data from one plot only
Within columns, values with the same letter are not significantly different at p = 0.05

The effect of thinning (to 600 stems/ha) and, to a lesser extent, nitrogen fertiliser at first lift pruning, on the growth of branches in the second and third pruning lifts was substantial at both sites. Generally, thinning increased mean branch diameters in subsequent lifts by 0.4 cm and where nitrogen fertiliser was also applied the increase was 0.6 cm. The number of branches encountered was also increased by these treatments. When expressed as the sectional area of branches per metre of pruning lift (an indication of work content when pruning) the differences between treatments were considerable, particularly at high pruning.

The combination of stem diameter response and branch size response generally resulted in a increase of DOS size of 1–2 cm. DOS height is an important variable influencing DOS size and reflected the consistency of the pruning lifts between treatments.

DISCUSSION

Tree Growth

To mitigate the loss of diameter growth resulting from repeated selective pruning, it is current practice in New Zealand to thin most unpruned stems, usually in conjunction with the first and last pruning lifts. However, since it is essential to keep the size of the defect core to a minimum, pruning must be reasonably severe. The resultant growth of the pruned stems in this study, even with thinning, was still substantially depressed. Without thinning, selective pruning (only up to the time of T2 in this study) will substantially reduce basal area growth. This confirms early work on selective pruning by Sutton & Crowe (1975).

The application of nitrogen fertiliser at 200 kg N/ha improved the growth of pruned and thinned plots but did not totally compensate for the loss in basal area from green crown pruning. The absolute level of nitrogen fertiliser response could not be precisely defined in this study because of the limited replication and the level of site variation. However, using only the Goudies data it can be estimated that approximately 50% of the deficit between thinned (T) only and the thinned and pruned (TP) treatment was recovered by the application of nitrogen fertiliser.

Generally the response to nitrogen fertiliser differed at each trial, with the Matea site possibly influenced by deficiencies in other elements as discussed below. However, the Goudies trial showed a more consist trend (although not statistically significant) with the response to fertiliser application, in thinned and pruned plots, being maintained in most nitrogen fertiliser treatments through to age 24 years. Most treatment responses in volume diverged with time, with very few comparisons showing convergent trends or where trend lines crossed. Gains due to nitrogen fertiliser may be considered as a method of shortening the rotation length. The time gain with the Goudies trial appeared to be approximately 2 years (Fig. 2).

With such a long-term data set the effect of early treatments is diminished as local site influences begin to dominate. Variation between replicates increased with time in these trials. Root mean square error in volume increased from 4.9 m^3/ha at age 9 to 48.4 m^3/ha at age 24 at the Goudies trial, and from 13 m^3/ha at age 11 to 59.9 m^3/ha at age 24 at the Matea trial.

Results that were statistically significant at an early stage were later overwhelmed by between-plot variation. This was due to the variation between replicates increasing with age at a greater rate than the treatment effect. Therefore, when designing field trials, consideration of the number of replicates to allow for site variation should take into account likely variation at stand maturity.

As reported by Forest Research Institute (1979), Woollons (1988), and Woollons & Whyte (1989), initial measurements of basal area and height generally gave a good indication of future levels of growth for each plot. Although an attempt was made to account for site variation using initial measurements, the later volume growth trends for some treatments (particularly TPF1F2 - Goudies) appeared to be an anomalous result, possibly caused by micro-site influences.

Height growth appeared to be little affected by the broad range of treatments in this study and agreed to some extent with the results of Maclaren *et al.* (1995) that depressed height growth with lower stockings after thinning can be inconsistent, especially with small plots.

Treatment effects on tree form were not measured in this trial. Results from previous studies appeared to be somewhat confused. Mead & Gadgil (1978) reported no change in tree form in two trials aged 12 years (RO246) and 14 years (RO689). Conversely, a change in tree form at age 21 years was found by Woollons & Will (1975). Hunter *et al.* (1985) found that increases in diameter from fertiliser application were greatest at breast height and in the upper green crown; there was little variation along the length of the tree (RO1818). They concluded that the overall taper of the first three sawlogs had not been reduced by fertiliser treatment, but that there did appear to be a greater taper at the top 20% of tree height. This was not considered to be of practical significance.

DOS and Branch Size

The effect of thinning and fertiliser on pruned stems was to increase stem diameter growth (dbh) and to increase branch size. In this study (with high initial stockings) the effect of thinning was greater than the effect of nitrogen fertiliser. Both factors also influenced the resultant DOS sizes in the second and third pruning lifts after treatment, particularly at the more-productive Goudies site. As current pruning schedules aim to achieve a uniform DOS size in each lift, these results indicate that applying nitrogen fertiliser to pruned stands at first lift could result in subsequent lifts needing to be timed earlier to achieve the same target DOS size. The effect of this is likely to negate most of the growth benefits from the application of nitrogen fertiliser at first lift pruning. Clearly, applying nitrogen fertiliser after pruning is completed is a better strategy.

Nitrogen Fertiliser Response

Numerous trials have been undertaken in New Zealand that test the response of *P. radiata* to fertilisers that contain nitrogen. Woollons & Will (1975) summarised the results of the early trials and concluded that nitrogen fertilisers had to be applied in conjunction with (and not more than 2 years after) thinning. Two consecutive annual applications at a rate of 115 kg N/ha were considered optimal (in terms of sustaining growth response) rather than a single application. Total gains from plots treated with fertiliser at this rate over a 7-year period (i.e., to age 21 years) were estimated to be 61 m^3/ha at 540 stems/ha, and 36 m^3/ha at 320 stems/ha over untreated plots. No response in height growth was found with nitrogen fertiliser application.

In a later trial in Kaingaroa Forest, Mead & Gadgil (1978) reported volume gains of 33 m^3/ha at 620 stems/ha and 54 m^3/ha at 370 stems/ha from two applications of 125 kg N/ha (a balanced fertiliser was applied in the first dressing). As with other trials there was no significant difference in heights between fertiliser or stocking treatments.

Hunter *et al.* (1985) summarised several nitrogen fertiliser trials on pumice soils and concluded that a large proportion of forests on this soil type were responsive to nitrogen fertiliser, provided the stand had recently received silvicultural treatment. Where basal area gains had been projected forward using currently available growth models, the average volume gain appeared to be 35–50 m^3/ha for younger stands and 15–30 m^3/ha for older crops. However, sites that contain deep flow tephra soils (i.e., as at the Matea trial) seem to require more than nitrogen alone. Foliage analysis of nutrients in the plots without fertiliser in these trials (Table 3, and reported by Hunter *et al.* 1985) indicated that phosphorus and magnesium concentrations were lower at the Matea site. These elements may therefore be implicated in the results of this study by limiting the potential response to nitrogen. Other trials in the southern Kaingaroa area have also confirmed the deficiency in magnesium where the application of magnesium fertiliser to newly planted trees increased height growth by 35% and root collar basal area by 18% in 2 years (Hunter *et al.* 1985).

Use of Legumes

The results from this study and other similar studies discussed here, have implications for site management practices and clearly indicate there is a substantial opportunity to improve forest productivity if soil nitrogen levels can be improved. The use of leguminous plants such as Maku lotus (*Lotus uliginosus* Schkuhr.) has already brought substantial improvement in tree basal area growth in Kaingaroa Forest (West & van Rossen 1993). Oversowing with legumes at the time of replanting, to enhance nitrogen availability to the tree crop and reduce weed regrowth, may be an alternative to the use of nitrogen fertiliser and also achieve a number of environmental goals such as soil conservation and improved aesthetics of cutovers (West & Dean 1992).

CONCLUSIONS

Selective pruning of stems without thinning will substantially slow tree diameter growth.

Trees that were thinned-only responded with increased diameter growth. The application of nitrogenous fertiliser to trees that remained unthinned gave no significant improvement in basal area growth. However, when applied to trees that were thinned, nitrogenous fertiliser resulted in a early basal area response.

There is some evidence from this study that nitrogen fertiliser will assist with the growth recovery of stands after green crown pruning. This could not be precisely quantified in this study but, at age 24, it has been roughly estimated that some 50% of the loss in growth could be recovered by the application of 200 kg N/ha.

The response to nitrogen fertiliser applied at first thinning (T1) appeared to be similar to the response achieved at second thinning (T2). However, when nitrogen fertiliser application is combined with stand pruning it would be advantageous to apply the fertiliser after pruning is complete and the target DOS is achieved.

The response to nitrogen fertiliser applied at both T1 and T2 was very small, and could not be explained.

Generally, thinning increased branch diameters in subsequent pruning lifts by 0.4 cm and where nitrogen fertiliser was also applied the increase was 0.6 cm. When combined with stem diameter responses, these treatments generally increased the DOS size by 1–2 cm. For these reasons it would be advantageous to apply nitrogen fertiliser after completion of all pruning lifts.

This study supported results from a number of similar studies that examined nitrogen fertiliser treatments in the central North Island pumice plateau, viz growth responses of 30–60 m^3/ha are achievable provided other nutrients are not limiting.

Height growth in this study was not affected by the application of nitrogen fertiliser.

Although treatment effects increased with age, variation between replicates increased at a greater rate. Analysis of this long-term trial indicated that considerably more than two replicates were required to give meaningful analysis of early treatment effects. Also, analysis of single trials appeared to be of little value when the influence of local factors (such as low magnesium at Matea) was considered. For most silvicultural treatments a planned series of trials covering a desired matrix of site types (perhaps 6–10) should be considered to provide adequate data for analysis. The synthesis of these data into a predictive computer model for use by managers is probably the best method of utilising such data.

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APPENDIX 1

RESULTS OF ANALYSIS OF VARIANCE BY TREATMENT AND AGE

Trial	Goudies					Matea				
Age	12	15	19	21	24	13	15	19	21	24
Basal area										
F	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
T	**	**	**	**	**	**	**	**	**	**
F × T	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
P	**	**	**	**	**	**	**	**	**	**
F × P	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
T × P	**	**	**	**	*	**	**	ns	ns	ns
F × P × T	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
TP *v*. TPF1	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
TPF1 *v*. TPF1F2	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
TP *v*. TPF2	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
TPF1 *v*. TPF2	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Mean top height (MTH)										
F	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
T	ns	ns	*	ns	ns	**	**	*	*	ns
F × T	*	*	*	ns	ns	ns	ns	ns	ns	ns
P	**	ns	*	ns	ns	ns	ns	ns	ns	ns
F × P	ns	ns	**	ns	*	ns	ns	ns	ns	ns
T × P	ns	ns	ns	ns	ns	**	**	ns	*	*
F × P × T	ns	ns	ns	*	ns	ns	ns	ns	ns	ns
TP *v*. TPF1	ns	*	*	*	*	ns	ns	ns	ns	ns
TPF1 *v*. TPF1F2	ns	ns	ns	ns	*	ns	ns	ns	ns	ns
TP *v*. TPF2	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
TPF1 *v*. TPF2	ns	ns	*	*	ns	ns	ns	ns	ns	ns
Volume (TSV)										
F	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
T	**	**	**	**	**	**	**	**	**	**
F × T	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
P	**	**	**	**	**	**	**	**	**	**
F × P	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
T × P	**	**	**	**	*	**	**	ns	ns	ns
F × P × T	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
TP *v*. TPF1	*	*	ns	ns	ns	ns	ns	ns	ns	ns
TPF1 *v*. TPF1F2	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
TP *v*. TPF2	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
TPF1 *v*. TPF2	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns