DRY MATTER PRODUCTION OF A YOUNG STAND OF PINUS RADIATA: SOME EFFECTS OF NITROGEN FERTILISER AND THINNING

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ABSTRACT

The dry matter content of the above-ground components of a 7-year-old plantation of **Pinus radiata** D. Don was recorded for 4 years after treatment in a thinning × nitrogen fertiliser factorial experiment. Fertiliser application significantly accelerated maximum canopy development. Stem production was closely related to the amount of stem material present after initial treatment. Nitrogen fertiliser increased the fraction of dry matter allocated to crowns and especially to needles. Thinning increased the fraction of dry matter allocated to crowns in the year after treatment. As canopies closed there was a tendency to allocate an increasing fraction of dry matter to stems at the expense of branches. The increase in dry matter production after fertiliser application was related to an increase in foliage amount rather than to changes in foliage efficiency.

INTRODUCTION

Application of nitrogen fertiliser in conjunction with thinning is known to give stem growth responses in *Pinus radiata* plantations on a wide variety of sites in New Zealand (Mead & Gadgil 1978; Hunter 1982). Nitrogen application on species other than *P. radiata* has been found to increase foliage biomass (Heilman & Gessel 1963; Miller & Miller 1976; Ranger 1978; Brix 1981) by affecting either foliage production or needle longevity. Increased stem growth occurs as a result of a combination of increased total foliar biomass and foliage efficiency (Kellomaki *et al.* 1982; Brix 1983). The response after fertiliser can also include a shift in the relative distribution of growth, with increases in the ratios of branch to foliage (Madgwick 1975) and branches to stem production (Will & Hodgkiss 1977).

Thinning has been found to increase foliage efficiency (Brix 1983) and may also shift the relative distribution of growth from stems to branches (Satoo & Madgwick 1982).

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The purpose of the present study was to examine changes in the standing crop and productivity of a young *P. radiata* stand after thinning and fertiliser application. This paper contains information on response in terms of basal area, height, and dry matter growth. Later papers will include information on nutrient uptake and distribution.

STUDY AREA

The experimental area is in Eyrewell State Forest, approximately 60 km north of Chistchurch. The forest is situated on flat fluvio-glacial outwashes, kame terraces, and gravel river fans, at about 158 m above sea level. The soils are yellow-grey earths, mostly classified as Lismore stony silt-loam derived from Greywacke gravels and thin loess deposits (New Zealand Soil Bureau 1968). Annual precipitation for the 30-year period 1941–70 ranged between 468 and 1224 mm (mean 871 mm) and summer droughts are common (New Zealand Meteorological Service 1973). Average daily temperatures range between a winter minimum of 4.6°C in July and a summer maximum of 16.2°C in January (New Zealand Meteorological Service 1978).

The present second-rotation stand was established after windrowing and ripping, with alternate rows ripped to 1.2 m and 0.45 m, respectively. *Pinus radiata* was planted in 1970; after 1 year survival was 93% and dead trees were replaced to give a nominal stocking of 1680 stems/ha. The trees were hand-released in 1973.

METHODS

In June 1977, when the stand was 7 years old, twelve 0.205-ha plots were established between parallel windrows. All trees were pruned to a height of 1 m (less than 20% of tree height). The area was treated with 75 kg P/ha (as superphosphate) to ensure that a nitrogen response was not limited by phosphorus supply. Standard Forest Service sampling of foliage in February 1981 indicated that foliar phosphorus ranged from 0.135 to 0.186% among plots, suggesting an adequate level of phosphorus nutrition. In order to maintain good stem form, 5 kg Cu/ha (as copper sulphate) was applied to all plots; this nutrient was known to sometimes become limiting when high rates of nitrogen were applied.

Experimental treatments included thinning in September 1977 to remove approximately 50% of the stems and basal area, and applying 400 kg N/ha as ammonium sulphate. To minimise distribution variability and to ensure a good uptake, the nitrogen was applied as a split dressing during the spring with about 6 weeks between applications. The experiment was a 2 × 2 factorial with three replications in a randomised block design.

Measurement plots of 0.0375 ha were established in the centre of each treatment plot when the experiment was initiated. Diameter at breast height (d.b.h.) of all trees was measured when the plots were established and annually for the next 5 years. All trees were measured for height at the first measurement but in subsequent years only 10 trees per plot were measured and average plot height was estimated from Petterson height curves, of the form

$$\log (\text{height} - 1.4) = a + b/(\text{d.b.h.})$$

where a and b are constants calculated for each plot and sampling date.

Sample trees were taken to estimate plot dry weights at time of treatment, and 1, 2, and 4 years later. These samples were randomly selected from the treated surrounds. The first sampling included two trees from each thinned plot, and subsequent samples included two trees from all 12 plots.

On each of the first three sampling occasions each branch was removed and measured for length and basal diameter, and the needles were removed before drying. For two branches per cluster the needles were divided into separate age classes and the relative weights of each needle age were used to estimate the total weight of each age class for the remainder of the branch cluster. At the final sampling, the size of the trees precluded the drying of all material so the tree crowns were divided into needle-bearing shoots of each age class and into other branch material before weighing and subsampling for dry matter determination. After drying, needle-bearing shoots were further divided into needles and twigs for the estimation of total tree needle and branch weights. Data were recorded by position in the crown, based on the age (year) at which the branches were first formed.

The over-bark volume of each sample tree stem was obtained from sectional measurements.

Stems from the first sampling were cut into sections and dried prior to weighing. At subsequent samplings the fresh weight of stems was obtained and sample discs were removed to determine dry matter content.

Stand weights were estimated using the basal area ratio method (Madgwick 1981). For the first sampling, when trees were taken only in thinned plots, the over-all ratio of component weight to basal area based on all 12 sample trees was used to estimate the weight of each sample plot. For each subsequent sample, tests indicated that there were only minor differences in the estimated plot weights when calculated either by combining all six trees for each treatment or by using the ratios obtained for the pair of trees for each treatment plot. Consequently, after the first sampling, separate ratios for each plot were used as this maintained statistical independence of the plot data.

Plot means were examined by covariance analysis using basal area and mean height after initial treatment as covariates for subsequent basal area and height, respectively. The combined variable "basal area times height" (B.A. × Ht) was used in covariance analysis of plot component weights.

RESULTS

At age 7 years, when treatments were imposed, the stand had a mean height of 5.3 m and a mean basal area of 9.1 m^2/ha (Table 1) at a stocking of 1540 stems/ha. Compared with control plots, height growth was increased by thinning and decreased by nitrogen fertiliser (Fig. 1). The combined treatment resulted in a statistically non-significant depression in height growth.

Basal area growth was strongly stimulated by nitrogen fertiliser with or without thinning for the first 3 years, but this effect had almost disappeared 4 years after treatment (Fig. 2). The total response over 4 years was about 4.5 m^2/ha in both thinned and unthinned plots, which is equivalent to about 1 year's growth in plots without fertiliser.

TABLE 1—Stand characteristics before treatment (1977) and 4 years later

Year	Treatment		Stocking (stems/ha)	B.A. (m^2/ha)	Mean diameter (cm)	Height (m)
1977	None	Min.	1440	7.93	8.1	5.0
		Max.	1630	11.22	9.5	5.6
		Av.	1540	9.11	8.7	5.3
1981	Control		1540	28.0	16.0	12.1
	Plus nitrogen		1520	32.4	17.3	11.4
	Thinned		810	19.3	18.6	12.7
	Thinned + nitrogen		810	23.9	20.5	11.8

The estimated weight of 1-year-old needles in the control plots varied between 2.5 and 3.4 tonnes/ha with no consistent change with time (Table 2). The thinned plot without nitrogen built up to this level of 1-year foliage between the second and fourth year after treatment. Both thinned and unthinned plots given nitrogen additions carried over 4 tonnes of 1-year needles/ha 2 years after treatment, when both foliage production and basal area responses were approaching a maximum.

TABLE 2—Dry matter content of the above-ground portion of the stands 1977–80 (tonnes/ha)

Year	Treatment	Needles			Branches		Cones	Stems	Total
		1-year	2-year	Total	Live	Dead			
0	Control	3.10	1.92	5.65	5.18	0.00	0.00	12.34	23.28
	Plus N	2.95	1.82	5.38	4.93	0.00	0.00	11.74	22.16
	Thinned	1.60	0.99	2.92	2.68	0.00	0.00	6.37	12.03
	Thin. + N	1.58	0.98	2.88	2.64	0.00	0.00	6.29	11.86
1	Control	2.46	2.53	7.70	8.17	0.00	0.49	20.45	37.16
	Plus N	3.33	2.92	8.80	8.24	0.00	0.75	20.77	39.16
	Thinned	1.66	1.56	4.23	5.06	0.00	0.38	12.03	21.76
	Thin. + N	2.32	1.49	5.09	4.60	0.00	0.17	11.02	21.04
2	Control	2.69	2.30	8.66	10.08	0.00	1.51	32.35	54.34
	Plus N	4.84	3.26	11.71	12.92	0.00	1.04	33.39	60.69
	Thinned	2.00	1.81	6.30	7.21	0.00	0.15	18.20	33.15
	Thin. + N	4.44	2.32	8.42	9.06	0.00	0.39	21.26	39.92
4	Control	3.38	3.29	8.67	10.84	2.57	4.45	59.72	86.54
	Plus N	3.59	4.36	8.94	11.81	3.62	0.98	58.14	83.83
	Thinned	3.49	3.30	8.77	11.64	0.20	2.64	38.04	61.53
	Thin. + N	4.06	4.85	11.09	20.60	0.06	0.86	44.14	77.48

Total foliage mass increased from about 6 tonnes/ha in unthinned and 3 tonnes/ha in thinned plots after treatment (Table 2). The initial increase was greatest in plots with nitrogen applied, but at the end of 4 years the total foliage mass in the teatments without fertiliser and the unthinned fertiliser plots was similar at 8 tonnes/ha. Plotting foliage mass for one sampling against foliage mass for the same treatment in the

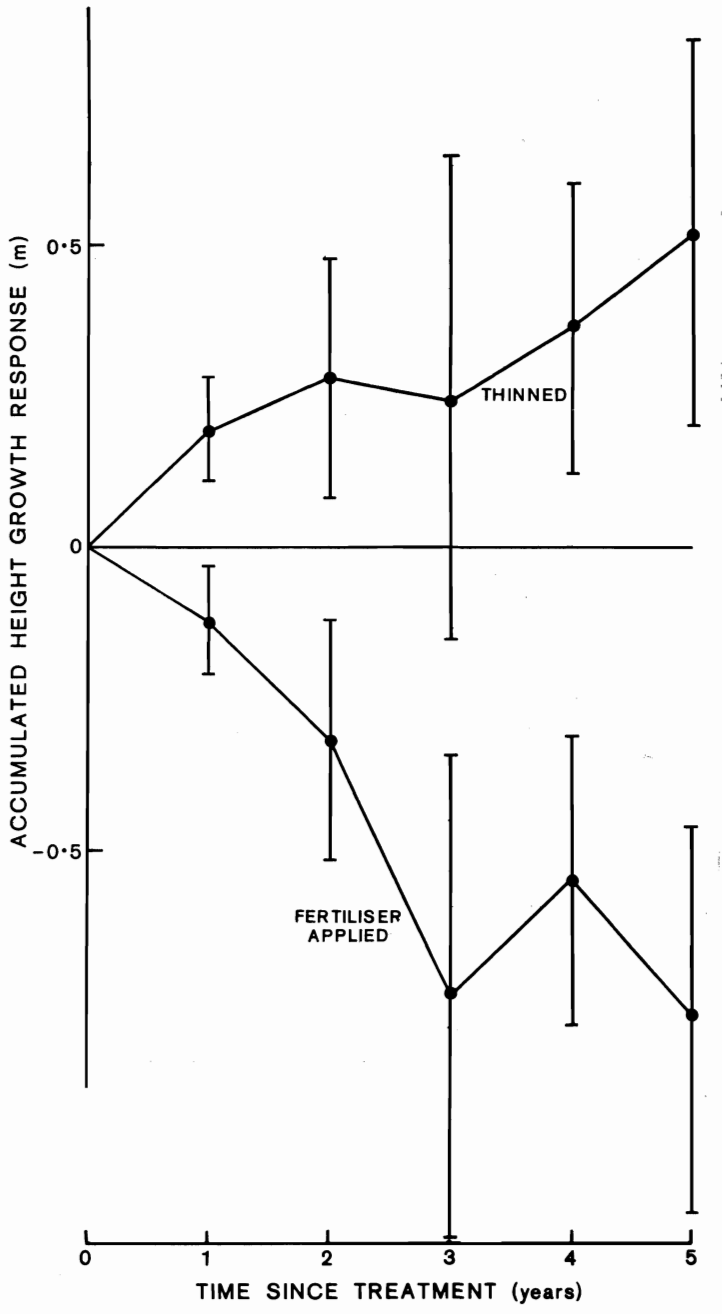

FIG. 1—Effects of thinning and nitrogen fertiliser on height growth, after accounting for effects of initial differences in mean height. Vertical bars indicate 95% confidence intervals.

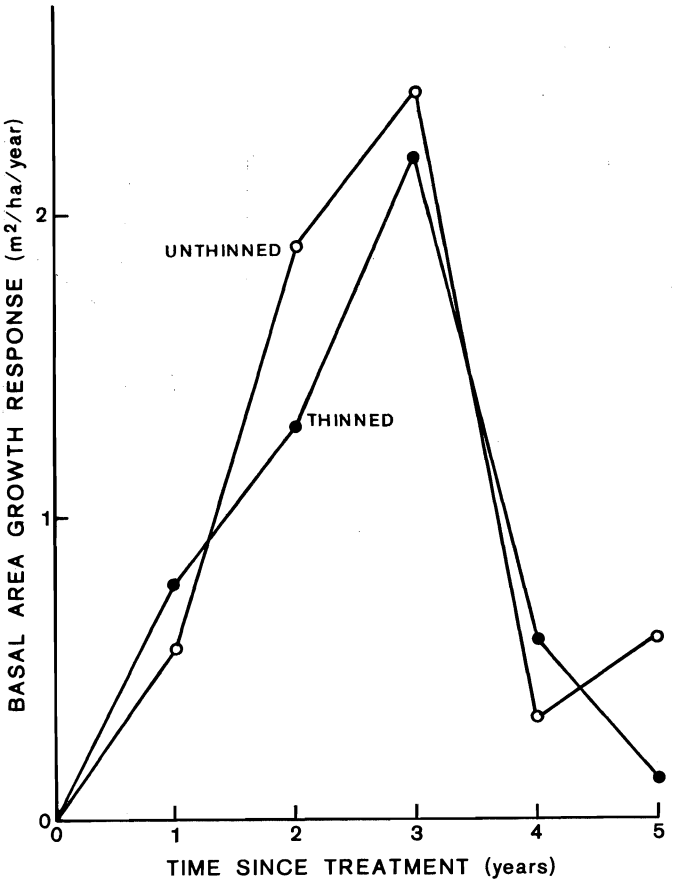

FIG. 2—Effects of nitrogen fertiliser, with and without thinning, on basal area growth, after accounting for effects of initial differences in basal area between plots.

previous sampling indicated a pattern of development which is similar across thinning treatments (Fig. 3). Plots with fertiliser tended to have a higher rate of build-up of total foliage mass.

Changes in total foliage mass among treatments were primarily due to changes in the production of new needles (Table 2). The weights of older needles increased between the first and third samplings as stands closed canopy. However, following any particular cohort of needles suggested no consistent differences in needle longevity between treatments.

Total branch weight increased more rapidly in nitrogen-fertilised plots than in control plots (Table 2) beginning in the second year from treatment. The increase was particularly marked in the thinned-plus-nitrogen plots which, at the end of 4 years, carried the largest branch mass. During the period between the second and fourth year

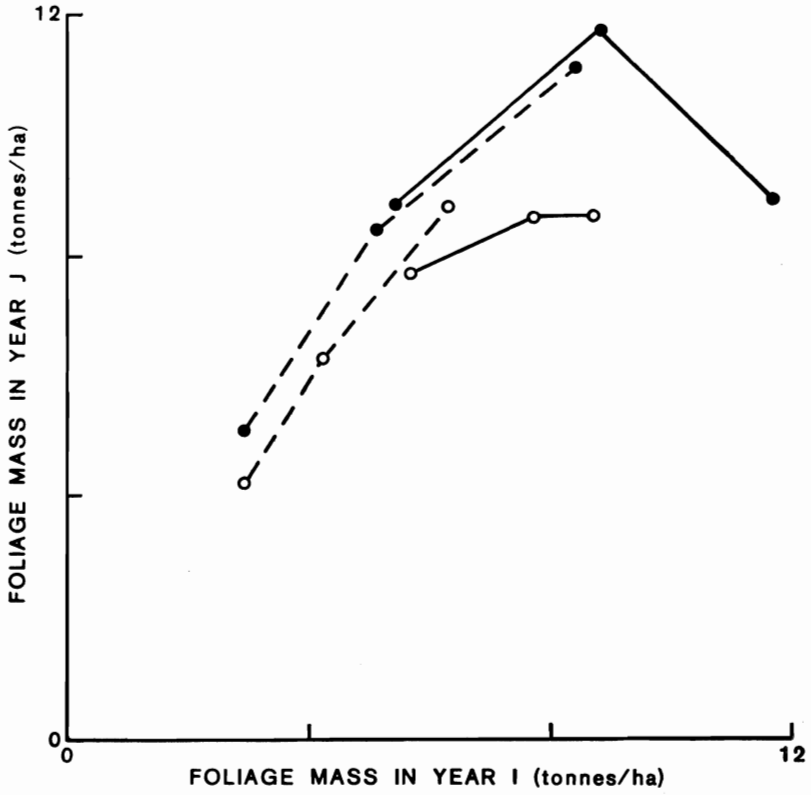

FIG. 3—Total foliage mass in year J **versus** that in year I, where I and J are two adacent sampling dates. Open circles = unfertilised; closed circles = fertilised; broken lines = thinned; unbroken lines = unthinned. The time difference (J - I) equals 1 year for the left-hand two data points and 2 years for the right-hand data point on each line.

from treatment, appreciable death of lower branches had occurred in the unthinned plots and live-branch biomass had apparently stabilised in these plots at about 11 tonnes/ha. Branch death in thinned plots was negligible.

Stem weight per plot increased almost five-fold in the unthinned plots and more than six-fold in the thinned plots over the 4-year period of observations (Table 2). In spite of significant increases in stem basal area in the unthinned fertiliser plots compared with the unthinned controls, there was virtually no difference in stem dry weights either at the beginning or at the end of the experiment – the unthinned fertilised trees had a stem basic density 6% lower than the controls 4 years after treatment, and a slightly smaller average height. In contrast, the thinned-plus-fertiliser plots accumulated stem dry weight almost 20% faster than the thinned plots without fertiliser.

Covariance analysis of stand weights indicated that, throughout the 4 years after treatment, plot stem weight was dominated by the amount of stem material present after initial treatment (Table 3). The covariate 1977 B.A. × Ht explained between 88%

and 94% of plot stem weight. For canopy components, 1977 B.A. × Ht explained over 80% of the plot weight of branches and of total foliage 1 year after treatment, but only 48% of 1-year-old foliage. After 4 years the covariate explained less than 9% of the weight of these three crown components. Throughout the experiment the interaction of fertiliser × covariate was usually the second most important factor and had a significant effect on the weight of 1-year-old foliage. Effects on total foliage and branches were more transitory.

TABLE 3—The fraction of variation in stem volume and component weight per plot explained by initial (Basal Area) × Height after treatment and the additional variation explained by the interaction of (Basal Area) × Height and Fertiliser (F)

Year		Stem volume	Weight				
			1-year foliage	Total foliage	Total branches	Stem	Total
1	B.A. × Ht	0.96***	0.48**	0.82***	0.83***	0.94***	0.93***
	B.A. × Ht × F	0.01	0.30**	0.08*	0.00	0.00	0.01
2	B.A. × Ht	0.86***	0.06	0.42*	0.44**	0.88***	0.79***
	B.A. × Ht × F	0.06*	0.76***	0.43***	0.24*	0.04	0.11*
4	B.A. × Ht	0.90***	0.08	0.00	0.03	0.91***	0.65***
	B.A. × Ht × F	0.03*	0.15*	0.03	0.26	0.01	0.03

Statistical significance is indicated for B.A. × Ht and for B.A. × Ht × F given B.A. × Ht.
* = significant at 5.0%
** = significant at 1.0%
*** = significant at 0.1%

The fraction of growth in needles, branches, and stems was calculated for each period between sampling by assuming that foliage growth occurred only in current-year needles and that there was no loss of branch or stem material. After arcsin transformation, analyses of variance suggested that several shifts in relative distribution occurred (Table 4). Nitrogen additions tended to increase the percentage of growth in crowns and caused a decrease in the fraction of growth in stems. Thinning increased branch growth at the expense of stems. The fraction of growth in stems tended to increase with time as the stands closed. These trends were strongly reflected in the sample trees collected 4 years after treatment. The ratio of branch to stem dry weight increased in the order control, fertiliser, thinned, thinned-plus-fertiliser, with magnitudes of 0.22, 0.26, 0.31, and 0.44, respectively. This effect appeared most pronounced in the large sample trees. For example, the largest sample trees in the control, thinned, and thinned-plus-fertiliser treatments all had stem weights between 71.9 and 72.8 kg but their branch weights were 12.8, 24.6, and 36.0 kg, respectively.

Needle efficiency for each plot was estimated for each period between sampling by dividing the dry matter increment by the average of total needle weight at the beginning and end of the period. Needle efficiency tended to increase with thinning (Table 4) but there was no apparent relationship with nitrogen fertiliser.

TABLE 4—Direction of the effects of nitrogen addition, thinning, and time since treatment on the allocation of dry matter increment and needle efficiency during a 4-year period after treatment. Numerical values are the probabilities associated with the F values in analyses of variance

Factor	Affected variable			
	Needles	Branches	Stem	Needle efficiency
Nitrogen	+ ve 0.02	+ ve 0.18	- ve 0.08	nil 0.99
Thinning	+ ve 0.13	+ ve 0.02	- ve 0.03	+ ve 0.19
Time	nil 0.78	- ve 0.09	+ ve 0.12	- ve 0.52

Thinning and fertiliser treatments both resulted in changes in canopy structure (Fig. 4). These changes in part reflect differences in competitive status of trees within the plots, which developed over the 4 years after treatment. The distribution of foliage within the canopy in unthinned plots was skewed towards the tree tops. This skewed distribution was accentuated in the fertilised unthinned plots and was accompanied by death of lower branches. All plots had similar amounts of branch material in the uppermost canopy but fertiliser plots, both thinned and unthinned, had greater accumulations of branch material in mid canopy. The thinned-plus-fertiliser plots had 1.3 to 1.7 times as much total branch material as the other plots (Table 2). This difference was the result of a much larger weight of branch material in the mid to lower canopy (Fig. 4).

DISCUSSION

The response of the stand to nitrogen fertiliser is typical of many plantations studied in New Zealand (Mead & Gadgil 1978; Hunter 1982); height growth response occurs only in very nitrogen-deficient stands (Hunter 1982). Basal area increment was increased for 3 years after the addition of nitrogen fertiliser, after which growth returned to a level comparable to the control plots. Such a growth response is often not found in unthinned stands (Hunter 1982) but it is clear from the data on foliage mass (Table 2 and Fig. 3) that the unthinned plots had not attained a fully closed canopy when the treatments were applied. The combination of thinning 50% of the stems and applying nitrogen fertiliser resulted in no loss of basal area growth over the unthinned control 4 years after treatment. The greater foliage mass on the thinned-plus-fertiliser plots at the end of the observation period suggests that this treatment may coninue to grow slightly faster than the control.

The primary response to fertiliser was an increase in foliage mass, as found in numerous other studies (Satoo & Madgwick 1982). In our study this response was caused by an increase in foliage production per unit of existing foliage and may in part have been due to a slight shift in dry matter allocation from stems to crowns. We found no effect on needle longevity, though Heilman & Gessel (1963) and Miller & Miller (1976) observed increases and Brix (1981) a decrease in needle longevity after

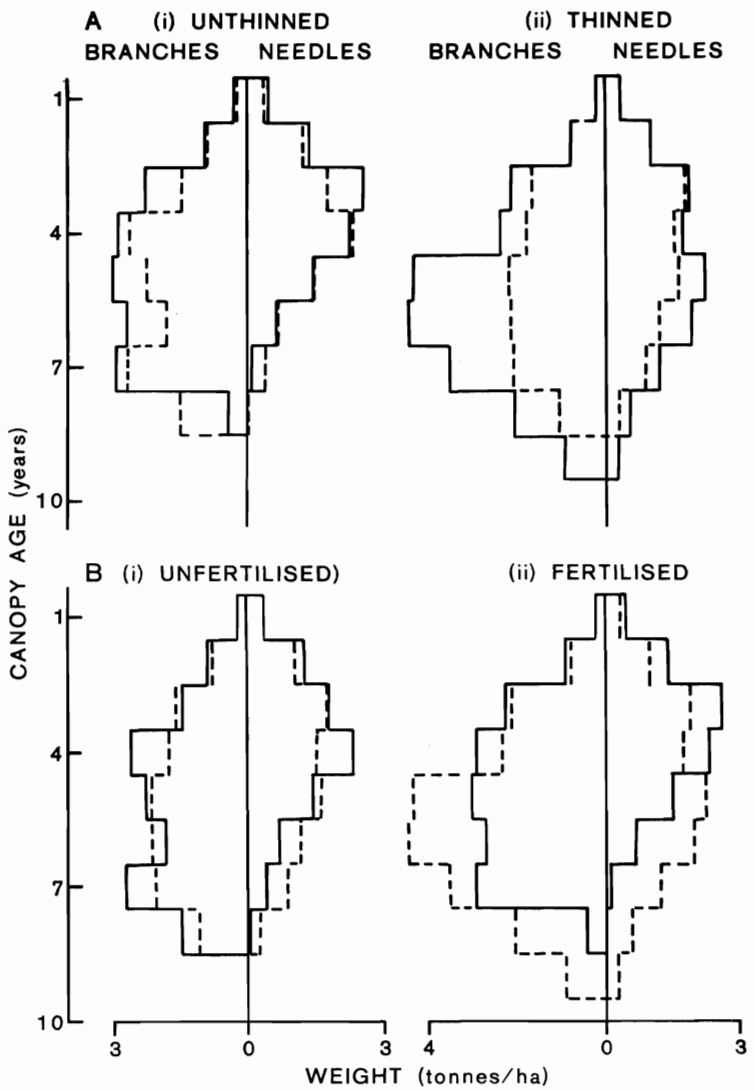

FIG. 4—Canopy structure 4 years after treatment. Canopy age refers to the year in which branches developed.

A = Comparison of fertilised (unbroken lines) and unfertilised (broken lines) canopy structure within thinning treatments.

B = Comparison of unthinned (unbroken lines) and thinned (broken lines) canopy structure within fertiliser treatments.

application of nitrogen fertiliser. The shift in the allocation of dry matter from stems to crowns is in agreement with earlier reports by Will & Hodgkiss (1977) for *P. radiata* and Brix (1981) for *Pseudotsuga menziesii* (Mirb.) Franco.

Thinning shifted dry matter increment from stems to crowns in the year after treatment and tended to result in a temporary increase in needle efficiency. As the plots closed canopy, there was an increasing fraction of growth in stems and a decreasing fraction in crown components as well as a tendency to a decline in needle efficiency. While these trends fit into an over-all pattern they were not always statistically significant. The pattern of response is difficult to elucidate because of the dynamic nature of the plots as they changed in nutritional status and degree of canopy closure with time. For instance it would appear that the percentage of dry matter allocated to stems increased with canopy closure, but no objective measure of canopy closure is available as the ability of the fertiliser plots to carry foliage changed with time. In this respect our study area is more volatile than the *Pseudotsuga menziesii* forest studied in detail by Brix (1981, 1983). However, both stands appear to have responded to nitrogen addition and thinning in a similar manner. In both the primary response to nitrogen fertiliser was an increase in foliage mass with a negligible effect on needle longevity, and an increase in needle efficiency which was small compared with changes in total foliage mass. Consequently, in both stands fertiliser produced trees with heavier crowns, while thinning delayed the death of branches.

Our stand responded in ways which were in contrast to the results of Miller & Miller (1976) working with nitrogen fertilisation of *Pinus nigra* subsp. *laricio* (Poir.) Maire. They found a marked increase in needle longevity and needle efficiency. However, both the *P. nigra* and the *P. radiata* stands treated with nitrogen showed an increase in the annual production of needles. The difference between the two studies could result from differences in the fertility of control plots – the *P. nigra* stand doubled basal area production for 2 years after heavy nitrogen additions, but basal area growth of our unthinned stand increased only 25% as a result of nitrogen additions over the same time period. Differences in response could also be because of inherent differences between the two species.

Ranger (1978) reported on a *P. nigra* stand which had been treated with a mixed fertiliser 15 years prior to his biomass study. The treated stand still showed a higher total foliage mass, a higher relative fraction of biomass in branches as opposed to stems, and a needle longevity which was similar to the control plot.

From the limited number of studies of responses in dry matter production to nitrogen fertiliser a consistent pattern is beginning to emerge. In order to synthesise these responses into a mathematical model of growth, several questions will need further clarification. These include the elucidation of mechanisms controlling needle longevity, the distribution of dry matter increment, and the changes in whole-canopy photosynthetic efficiency as affected by both foliage mass and foliar nutrition. Such information should assist the understanding of fertiliser application as a forest management tool.

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REFERENCES

BRIX, H. 1981: Effects of thinning and nitrogen fertilization on branch and foliage production in Douglas-fir. **Canadian Journal of Forest Research 11:** 502–11.

——— 1983: Effects of thinning and nitrogen fertilization on growth of Douglas-fir: relative contribution of foliage quantity and efficiency. **Canadian Journal of Forest Research 13:** 167–75.

HEILMAN, P. E.; GESSEL, S. P. 1963: The effect of nitrogen fertilisation on the concentration and weight of nitrogen, phosphorus, and potassium in Douglas fir trees. **Soil Science Society of America Proceedings 27:** 102–5.

HUNTER, I. R. 1982: Growth increases following application of nitrogen fertilisers to exotic forests. Pp. 131–5 **in** "Nitrogen Balances in New Zealand Ecosystems". Department of Scientific and Industrial Research, Palmerston North.

KELLOMAKI, S.; PUTTONEN, P.; TAMMINEN, H.; WESTMAN, C. J. 1982: Effect of nitrogen fertilization on photosynthesis and growth in young Scots pine – preliminary results. **Silva Fennica 16:** 363–71.

MADGWICK, H. A. I. 1975: Branch growth of **Pinus resinosa** Ait. with particular reference to potassium nutrition. **Canadian Journal of Forest Research 5:** 509–14.

——— 1981: Estimating the above-ground weight of forest plots using the basal area ratio method. **New Zealand Journal of Forestry Science 11:** 278–86.

MEAD, D. J.; GADGIL, R. L. 1978: Fertiliser use in established radiata pine stands in New Zealand. **New Zealand Journal of Forestry Science 8:** 105–34.

MILLER, H. G.; MILLER, J. D. 1976: Effect of nitrogen supply on net primary production in Corsican pine. **Journal of Applied Ecology 13:** 249–56.

NEW ZEALAND METEOROLOGICAL SERVICE 1973: Summaries of climatological observations to 1970. **New Zealand Meteorological Service, Miscellaneous Publication No. 143.**

——— 1978: Temperature normals 1941 to 1970. **New Zealand Meteorological Service, Miscellaneous Publication No. 149.**

NEW ZEALAND SOIL BUREAU 1968: General survey of the soils of South Island, New Zealand. **Department of Scientific and Industrial Research, Soil Bureau Bulletin 27.**

RANGER, J. 1978: Recherches sur les biomasses comparées de deux plantations de Pin laricio de Corse avec ou sans fertilisation. **Annales des Sciences Forestières 35:** 93–115.

SATOO, T.; MADGWICK, H. A. I. 1982: "Forest Biomass". Martinus Nijhoff, The Hague. 152 p.

WILL, G. M.; HODGKISS, P. D. 1977: Influence of nitrogen and phosphorus growth stresses on the growth and form of radiata pine. **New Zealand Journal of Forestry Science 7:** 307–20.