LUPIN, FERTILISER, AND THINNING EFFECTS ON EARLY PRODUCTIVITY OF PINUS RADIATA GROWING ON DEEP PINAKI SANDS

D. S. JACKSON, H. H. GIFFORD and J. D. GRAHAM

Forest Research Institute, New Zealand Forest Service,
Private Bag, Rotorua, New Zealand

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ABSTRACT

A balanced application of nitrogen, phosphorus, potassium, calcium, magnesium, and sulphur fertilisers significantly increased height growth of **Pinus radiata** D. Don on Pinaki sands at Woodhill State Forest, but the presence of **Lupinus arboreus** Sims (yellow tree lupin) did not. Lupin died out of all stands ranging from 741 to 2224 stems/ha by tree age 5 years, but the benefits for basal area and volume increment continued to accumulate up to tree age 11. Stands that have had both lupin and fertiliser can produce 35–40 m^3 annum on 2224 stems/ha, or double the increment of untreated stands at any stocking.

The maximum benefits from thinning were obtained only on fertiliser-treated stands, which were three or four times more responsive than untreated controls, particularly at stockings exceeding 1500 stems/ha. It is possible to increase the volume of the dominant trees by 40–50% by pre-competitive thinning in conjunction with fertiliser application, but there is a commensurate sacrifice of total production.

INTRODUCTION

The basal area growth of young *Pinus radiata* stands in Woodhill State Forest (36° 45′S, 174° 26′E) is subnormal (Levy & St. John 1964). One of the main silvicultural problems has been to secure sufficient diameter increment on main crop stems, even in thinned stands. Fertiliser treatment, particularly with nitrogen, has been of some benefit but the relative importance of artificial and natural sources (e.g., lupin) was uncertain until recently (Gadgil 1977; Mead & Gadgil 1978). It has also been considered that soil moisture stress could be a limiting factor, at least during the late summer and autumn (Jackson *et al.* 1976), on deep free-draining phases of the sand dunes (Pinaki sand) that underlie most of the Woodhill plantations. At the forest headquarters there is a mean annual rainfall of 1313 mm, and an annual mean temperature of 14.3°C.

In 1968 an experiment was established to ascertain:

(1) The extent of the contribution made by lupin to the productivity of the artificial *P. radiata* ecosystem established on Pinaki sands;

(2) Whether, and to what extent, this productivity could be increased by supplementary fertiliser application;

(3) What early thinning regime would permit the maximum concentration of volume increment on a "final crop" element of 371 stems/ha (150 stems per acre at the time the experiment was established);

(4) Whether nutritional factors or seasonal soil moisture deficits were more critical in limiting productivity on these deep Pinaki sands.

It was also intended to provide an appropriate experimental framework for intensive studies of seasonal soil moisture fluctuations and of the effects of lupin on nitrogen accretion within the stand and its environment.

This report contains a summary of only the basic mensurational information up to age 13. The more intensive studies of nitrogen status and nutrition (Mead & Gadgil 1978; Gadgil 1977, 1983) and of seasonal soil-moisture interactions (Jackson 1977; Jackson *et al.* 1983) have been reported separately and that of biomass development will be reported later.

METHODS

Design

The experiment was based on a split-plot design. The main plot treatments comprised a simple 2 × 2 factorial having blocks with (l) or without lupin, times blocks with (f) or without fertiliser; thus the treatment combinations could be represented (0), (l), (f), (lf). Each main-plot treatment was twice replicated and was 0.566 ha in extent, excluding its surrounding buffer-zone. The treatments were randomised within each replicate over an area that had been uniformly planted with *P. radiata.* Each plot was further subdivided into four sub-plots to permit thinning to different densities, starting from a common stocking of 2224 stems/ha. To determine the onset of competitive stress, each successive thinning was done before there was any supression of the basal area of the dominant stems at the previous higher stocking. To achieve this, each such thinning reduced the stocking to half that at which competition had become evident – as indicated by a significant reduction in the basal area increment of the 371 largest-diameter stems/ha at the age concerned. This series of manipulations was intended to ascertain the maximum stocking that could be maintained without check to the diameter growth of the main crop trees up to about 10 years old.

Lupin was to be excluded from plots (0) and (f) by initial spraying, followed by annual removal of regeneration. The fertiliser regime was designed to provide a complete, balanced supply of major nutrients (nitrogen, phosphorus, potassium, calcium, magnesium, sulphur) on blocks (f) and (lf) from the first year after planting.

Location and Management

The site of this experiment (A 287) is the west-facing slope of a large dune in Cpt 138 approximately 1.3 km from the sea. The compartment had been planted with marram grass (*Ammophila arenaria* (L.) Link.) at 1.5 × 1.5 m in June 1965, topdressed with "Nitromoncal" (granulated lime-ammonium-nitrate mixture) the following

November, sown with lupin seed at approximately 3.36 kg/ha in April 1966, and planted by machine with *P. radiata* (Seedlot R64/729) at 2.4 × 1.8 m in June 1968. The experimental layout was surveyed and established immediately afterwards, and in December 1968 the lupin in the (0) and (f) plots and their surrounds was crushed (between the rows of trees) and manually sprayed with a 2,4,5-T/2,4-D mix. This not only killed the lupin, but also resulted in die-back of all new growth on about half the trees in all (0) and (f) plots – i.e., in Plots 1, 4, 5, and 7. The marram grass was not affected.

The fertiliser regime was devised by Dr D. J. Mead to supply the following quantities of nutrients over each 2-year interval: 224 kg N/ha, 93 kg P/ha, 94 kg K/ha, 67 kg Mg/ha, 49 kg S/ha, 46 kg Ca/ha. These were given as biennial applications (beginning August 1969) of the following fertilisers: 336 kg Magamp/ha, 181 kg diammonium phosphate/ha, 72 kg potassium sulphate/ha, 207 kg dolomite/ha. In alternate years these quantities were augmented by an additional 112 kg potassium sulphate/ha and 122 kg urea/ha. This dressing of nitrogen was repeated in the middle of each growing season, beginning February 1970. Initially, only equivalent quantities were applied, around the base of each tree, in order not to encourage competition from lupin and/or marram grass. The change-over from individual fertiliser treatment to broadcast distribution was made in January 1972, after the pines had become dominant. Fertiliser applications were discontinued in September 1978 when the trees were 10 years old.

Post-planting mortality ranged from 5% over-all to 10% in the sprayed plots 1 and 5, and all plots were blanked up in the winter of 1969 with stock of Seedlot R65/760. Prior to this, the young pines in the lupin plots were given a light release-cutting. In October 1969 a further spraying with 2,4,5-T to kill lupin regrowth and regeneration on Plots 1, 4, 5, and 7 caused some distortion of new growth on the pines. Thereafter, control was maintained by occasional spot-spraying of older plants and manual removal of seedlings that survived the spray.

Vigorous growth by the dense lupin in Plots 2, 3, 6, and 8 necessitated release-cutting around the young pines during November 1969 in order to reduce suppression. This intense competition during the peak of the growing season became negligible after midsummer, as kowhai moth (*Uresiphita polygolanis maorialis* (Felder)) populations built up and defoliated the lupin bushes. Suppression and loss of young trees in the lupin plots were nevertheless sufficiently acute both to create problems in achieving the prescribed stocking, and to reverse the advantage gained over the non-lupin plots damaged during spraying.

In April 1970 an assessment plot of 405 m^2 (one-tenth acre) was established in each of the four sub-plots in each plot. These 32 assessment plots were used for each annual remeasurement of stand parameters, beginning with the measurement of total height of all trees in each assessment plot during July 1970. After enumeration (every third tree was tagged) and assessment of stocking, sub-plots were allocated places in the precompetitive-thinning plan (Table 1). Initially (July 1970) three of the four sub-plots in each plot were reduced to a nominal stocking of 2224 stems/ha; the fourth was thinned to 1483 stems/ha. In each plot the sub-plot with the lowest current stocking was allotted this first thinning, while the sub-plot with highest stocking was retained as the unthinned control at 2224 stems/ha (*see* Table 1). Unfortunately, suppression of the young trees by lupin had been so severe in Plot 6 that only 1878 stems/ha had survived on Sub-plot 63, instead of the prescribed 2224. Departures from prescription on other sub-plots were minor but Sub-plot 42 unavoidably included part of an old "blow-out" in the south-east corner. This had never carried any vegetation, and the young trees planted on it have always been small and unthrifty. The data for this assessment plot will have been affected accordingly.

TABLE 1—Thinning schedule as indicated by nominal stocking (stems/ha) of each sub-plot in all main treatment plots at midwinter from 1970 (tree age 2 years) to 1976 (tree age 8 years)

1970	1971	1972	1973	1974	1975	1976
2224	2224	2224	2224	2224	2224	2224
1483	1483	1483	1483	1483	1483	1483
2224	2224	2224	741	741	741	741
2224	2224	2224	1483	1483	1483	371

After the June 1972 remeasurement, it was apparent that current basal area increment (b.a.i.) of the 371 dominant trees in a stand of 2224 stems/ha was now significantly less than at a stocking of 1483 stems/ha. During September 1972 one of the three dense sub-plots in each plot was accordingly given an anticipatory thinning to 741 stems/ha, while another was reduced to 1483 for comparison. By June 1975 dominant trees in the latter sub-plots were again being affected appreciably, so a final pre-competitive thinning to 371 stems/ha was done during January–February 1976. This had been preceded by low pruning of all trees to a height of 2 m. The timing of each thinning is summarised in Table 1.

In 1971–72 two aluminium access tubes were installed to depths of 3 and 4 m in each assessment plot, and the soil-moisture status has been monitored with a Wallingford neutron probe every 3 months, at 10-cm intervals down the profile to 1 m, and below that at 20-cm intervals. This aspect of the investigation is reported in a separate paper (Jackson *et al.* 1983).

Methods of Assessment

Every assessment plot was remeasured in June each year. Until all trees exceeded 1.4 m, only the height of each tree was recorded (to the nearest centimetre); once they had overtopped 1.4 m, the diameter at breast height (d.b.h.) was also measured to the nearest millimetre. From age 5 years it became too time-consuming to measure heights of all trees with a measuring rod, and from 1974 onwards only the heights of the 15 trees of greatest d.b.h. were taken, with a Blume-Leiss hypsometer. The calculated mean of these heights is referred to as the mean dominant height (H_i) for each assessment plot (i), and the corresponding d.b.h. is defined as the mean dominant d.b.h. (D_i).

In order to calculate volumes it was necessary to fit a mean height curve. It was found that the height/d.b.h. distribution within most assessment plots was so irregular that individually fitted height curves were frequently incompatible with each other.

In order to avoid absurd results, all the height values for each year (at least 480 in any one year) were therefore pooled, and a common height/d.b.h. curve was fitted (cf. Fig. 1, for the 1981 data), using the equation:

$$h = 1.4 + (d/a + b.d))^2 \qquad (1)$$

where "h" is the height (metres) of any tree with d.b.h. "d" (centimetres), and the fitted values of the coefficients "a" and "b" are given in Table 2 for each of the years from 1977 to 1981. The height on this common curve corresponding with D_i for any assessment plot (i) may be denoted h_i; and the difference $x_i = H_i - h_i$. The common height curve* may then be adjusted to fit each individual assessment plot by adding the difference x_i to the height computed from the d.b.h. of any tree in the assessment plot.

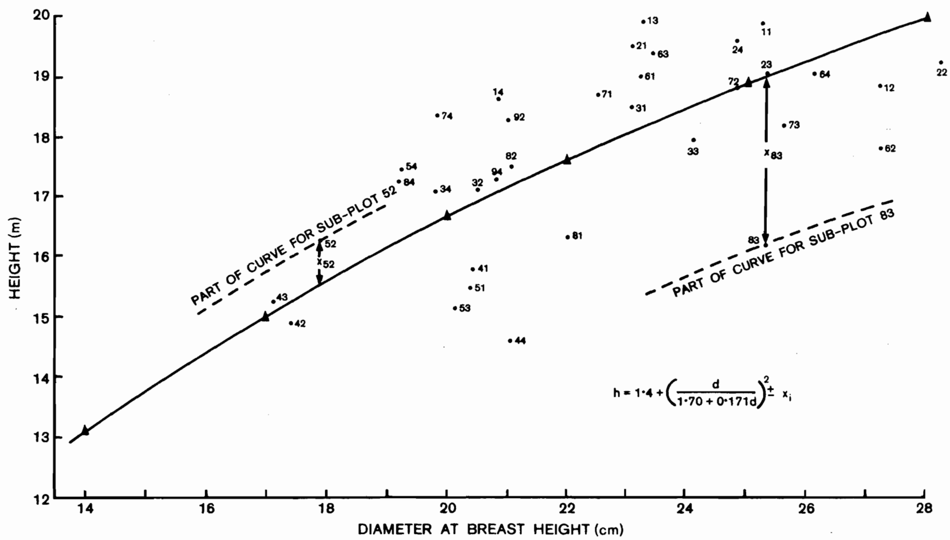

FIG. 1—The common mean height curve for June 1981 (based on 525 sample trees), together with the plotted mean dominant heights for each sub-plot and part of the height curves for Sub-plots 52 and 83.

Volumes were computed for each tree, based on its measured d.b.h. and its corresponding height derived as above, inserted in the general volume equation:

$$\log_e V = A \log_e d + B \log_e (h^2/(h - 1.4)) + C \qquad (2)$$

where $A = 1.79$
$B = 1.11$
$C = -10.17091.$

Aggregated volume of the 15 largest trees ("dominant volume") and that of all trees in the assessment plot were obtained by summation of individual tree volumes, and then converted to a per hectare basis before the statistical analyses were executed.

* Two of our referees have queried this use of a height curve fitted to the dominant trees only. We accept that it is unconventional, but submit that the experiment was centred on the growth and responses of the dominant element, and that the best assessment of these was paramount.

TABLE 2—Coefficients of Equation (1), for each of the years 1977 to 1981

Year	Coefficient (a)	Coefficient (b)
1977	1.61	0.208
1978	1.78	0.193
1979	1.675	0.189
1980	1.530	0.185
1981	1.700	0.171

Statistical Analyses

Analysis of variance is based on the following model:

$$X_{ijk} = \mu + R_i + T_j + S_k + (TS)_{jk} + \delta_{ijk} \quad (3)$$

where X_{ijk} = the individual assessment plot value
R = replication (i = 1, 2)
T = the main plot treatments (j = 1, 2, 3, 4)
S = the effects of stocking differences (k = 1, 2, 3, 4).

Sources of variation within the data for any particular year may be tabulated as follows:

	Source of variation	*d.f.*	*Mean squares*
Between plots:	Replication	1	$\delta_e^2 + 4\ \delta_p^2 + 16\ \delta_R^2$
	Main-plot treatments	3	$\delta_e^2 + 4\ \delta_p^2 + 8\ \delta_T^2$
	Plot error	3	$\delta_e^2 + 4\ \delta_P^2$
Between sub-plots:	Stocking	3	$\delta_e^2 + 8\ \delta_S^2$
	Treatment × stocking	9	$\delta_e^2 + 2\ \delta_{TS}^2$
	Sub-plot error	12	δ_e^2
Total		31	

The sum of squares for T is readily broken down into three orthogonal comparisons between individual treatments, each with one degree of freedom. The ratio (F) of each such comparison to the plot variance is used to assess significant differences between main treatments, being denoted * if $F > 10.13$ ($p = 0.05$) and ** if $F > 34.12$ ($p = 0.01$). Differences between the means of sub-plots at different stockings were broken down and assessed similarly except that, with more degrees of freedom available, the significant ratios are much lower, i.e., denoted * if $F > 4.75$ and ** if $F > 9.33$.

RESULTS

Establishment Phase

When the height of all trees in each sub-plot was measured in 1970 (Table 3), a highly significant difference between the four plots with and those without lupin confirmed the field observation that many of the trees in the latter plots were still handicapped by the adverse effects of the 1968 spraying with 2,4,5-T (Fig. 2A).

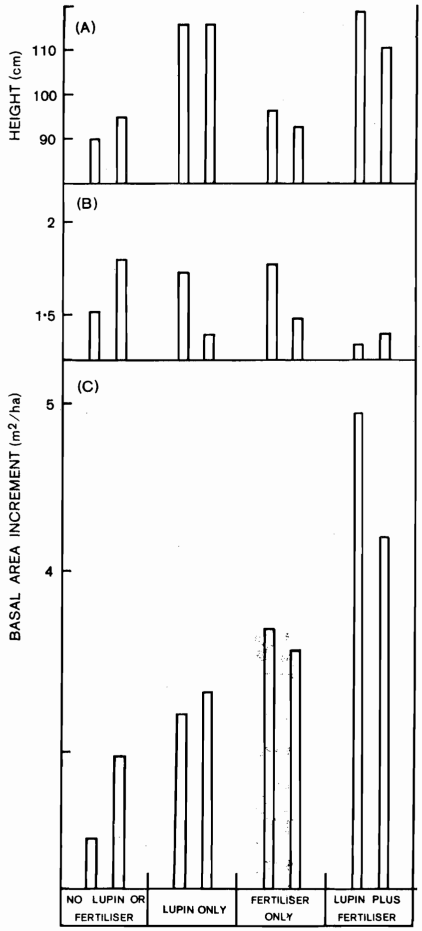

FIG. 2 (A)—1970 mean height, showing initial loss of growth on plots sprayed with 2,4,5-T in 1968–69 to eradicate lupin.

(B)—1971–72 basal area increment, showing effects of competition by uncontrolled lupin growth, overriding the initial advantages of nil spray damage.

(C)—1973–74 basal area increment with earlier influences now completely superseded by nutritional benefits of both lupin and fertiliser. Analysis of variance shows that (l) and (f) effects are now both statistically significant, but the (lf) interaction is not.

Each pair of bars represents replication means for the 30 largest trees in each of four sub-plots.

However, during the first year (1971) when diameters at breast height could be measured, the initial height advantages of the unsprayed plots were lost because of the negative effects of lupin on diameter growth. Intense competition with the young pines had caused a differential reduction of their basal area increment during 1971–72 (Fig. 2B) but, owing to greater variability between the sub-plots, the differences were not statistically significant. During the 1972–73 growing season, the pines overcame competition from the lupins, as noted by R. L. Gadgil (pers. comm.): "Between November 1972 and May 1973 lupin plants died throughout the experiment . . . there was no evidence of a gradual decline, and even the most vigorously growing stands died out completely within 6 months." From this stage onward the establishment changes, outlined above, became submerged by the over-all nutritional differences between plots.

In the sixth year (1973–74) differences between basal area increments (Fig. 2C) were statistically significant at the 5% level for fertiliser effects, and at the 1% level for the comparison between stockings of 2224 and 741 stems/ha (Table 4). There was

TABLE 3—Mean height (m) of largest trees* 1970–81

Treatment and stocking	Sub-plot No.	1970	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981
Control														
2224 stems/ha	43	0.84	1.03	2.25	3.76	5.69	7.45	9.19	9.88	11.03	12.21	13.09	14.33	15.26
	52	0.88	1.04	2.41	4.15	6.15	7.81	9.82	11.29	12.51	13.10	14.15	15.23	16.42
1483 stems/ha	42	0.69	0.85	1.87	3.24	4.75	6.30	8.29	9.36	10.78	12.08	12.96	14.30	14.87
	54	0.87	1.05	2.40	4.35	5.94	7.99	9.85	11.21	12.64	13.34	14.78	15.97	17.42
2224 stems/ha; thinned to 741 stems/ha 1972	41	0.88	1.02	2.40	4.00	^{T}5.80	7.29	8.77	10.36	11.30	12.59	13.33	14.84	15.79
	51	0.87	0.97	2.36	4.06	^{T}6.04	7.72	9.28	10.53	11.33	11.66	12.63	13.84	15.49
2224 stems/ha; thinned to 1483 stems/ha 1972, 371 stems/ha 1976	44	0.86	1.02	2.19	3.75	^{T}5.49	7.06	8.67	^{T}9.22	10.41	11.20	11.91	13.38	14.61
	53	0.89	1.05	2.49	4.32	^{T}6.18	7.83	9.57	^{T}11.06	11.54	11.95	12.84	14.27	15.11
Lupin														
2224 stems/ha	34	1.13	1.37	2.56	4.14	5.94	7.77	9.83	11.26	12.65	13.84	14.88	16.40	17.13
	84	1.03	1.24	2.25	2.84	5.59	7.37	8.70	10.79	12.05	13.41	14.55	16.12	17.25
1483 stems/ha	32	1.01	1.13	2.18	3.84	5.43	7.32	9.42	11.12	12.48	13.29	14.43	16.03	17.11
	82	1.08	1.29	2.46	4.03	5.61	7.24	9.34	10.99	12.19	13.73	15.03	16.22	17.49
2224 stems/ha; thinned to 741 stems/ha 1972	31	1.07	1.23	2.39	4.09	^{T}5.82	7.47	9.42	11.36	12.80	13.68	14.97	17.23	18.47
	81	1.01	1.23	2.13	3.57	^{T}5.06	6.51	8.41	9.99	10.75	12.20	13.46	14.78	16.35
2224 stems/ha; thinned to 1483 stems/ha 1972, 371 stems/ha 1976	33	1.11	1.33	2.60	4.38	^{T}6.08	8.20	10.27	^{T}11.81	12.48	13.34	14.64	16.69	17.99
	83	1.06	1.25	2.42	4.13	^{T}5.93	7.87	10.04	^{T}11.73	12.56	13.33	14.53	15.70	16.17

TABLE 3—Mean height (m) of largest trees* 1970–81 (continued)

Fertiliser														
2224 stems/ha	14	0.99	1.09	2.55	4.27	6.06	7.74	9.62	11.52†	13.01	14.25	15.61	17.64	18.63
	74	0.82	1.02	2.37	3.99	5.97	7.58	9.45	11.21	12.76	14.05	15.87	16.91	18.33
1483 stems/ha	13	0.94	1.08	2.62	4.22	6.18	8.30	10.34	12.32	13.71	15.25	17.31	18.77	19.93
	71	0.81	1.07	2.25	3.79	5.60	7.39	9.36	11.22	12.43	14.02	15.61	17.16	18.72
2224 stems/ha; thinned	11	0.81	0.97	2.28	3.85	T5.87	7.84	9.99	11.63	13.59	14.95	16.76	18.49	19.92
to 741 stems/ha 1972	72	0.88	1.03	2.30	3.83	T5.61	7.40	9.24	10.86	12.50	13.75	15.31	16.93	18.82
2224 stems/ha; thinned	12	0.83	0.95	2.30	3.74	T5.99	7.95	9.96	T12.18	13.18	14.09	16.11	17.54	18.89
to 1483 stems/ha 1972	73	0.87	1.02	2.32	3.99	T6.05	8.00	10.04	T11.82	12.81	14.41	16.34	17.14	18.23
371 stems/ha 1976														
Lupin + fertiliser														
2224 stems/ha	21	1.11	1.31	2.21	3.79	5.51	7.51	9.48	11.43	12.49	14.76	16.33	17.85	19.51
	63	1.10	1.27	2.24	3.79	5.83	7.79	9.83	11.36	12.30	14.57	16.24	17.62	19.41
1483 stems/ha	24	1.08	1.33	2.09	3.52	5.43	7.36	9.37	11.38	13.31	14.88	16.38	18.40	19.61
	61	0.94	1.17	2.18	3.69	5.73	7.89	9.34	12.07	13.56	14.70	16.25	17.62	19.02
2224 stems/ha; thinned	23	1.09	1.35	1.97	3.17	T5.13	6.97	9.05	11.41	12.96	14.63	16.08	17.63	19.05
to 741 stems/ha 1972	64	1.02	1.30	2.29	3.78	T5.41	7.31	8.88	11.37	12.65	13.86	15.87	17.60	19.05
2224 stems/ha; thinned	22	1.07	1.32	2.26	3.79	T5.67	7.61	9.44	T11.69	13.09	14.24	15.86	17.52	19.29
to 1483 stems/ha 1972	62	0.94	1.15	2.08	3.47	T5.16	7.07	9.30	T10.75	11.73	12.84	14.93	16.03	17.84
371 stems/ha 1976														

* Fifty trees measured at initial measurement in 1970, 10 trees measured in 1971, 15 trees at all other measurements

† Mean of 13 trees only

T = thinned

also a sudden deterioration in the appearance of the trees in the control (0) plots (Plots 4 and 5). These trees looked most chlorotic, with crowns distinctly more sparse and shorter-needled than the other plots. The marram was senescent almost throughout, even in the sub-plots thinned to 741 stems/ha. The contrast with the other two plots without lupin (i.e., Plots 1 and 7 (f)) was most marked: the marram there had obviously benefited from the fertiliser application, being larger and more vigorous. At the same time there was a marked reduction in the basal area increment of lupin-only plots, a year earlier than the other treatments (Fig. 3). These attained their peak basal area increment during 1973–74, just before the foliage on lowest branches was completely shed.

TABLE 4—Years in which significant differences between basal area increment of dominant 371 stems/ha first appeared: orthogonal comparisons between treatments and between stockings, to June 1976

	1971–72	1972–73	1973–74	1974–75	1975–76
Main treatments:					
Lupin effect	NS	NS	*	NS	*
Fertiliser effect	NS	NS	*	*	**
Interaction	NS	NS	NS	NS	NS
Stocking differences:					
2224 v. 1483 stems/ha	NS	NS	NS	**	**
2224 v. 741 stems/ha	NS	NS	**	**	**
1483 v. 741 stems/ha	NS	NS	NS	**	**

* Significant at p = 0.05
** Significant at p = 0.01
NS Not significant

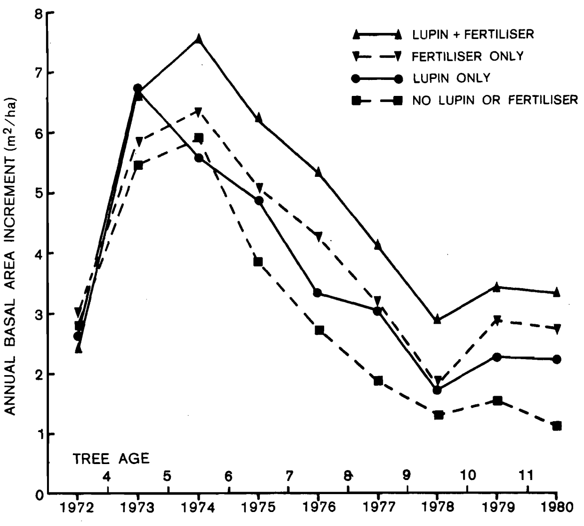

FIG. 3—Total basal area increment of all trees in sub-plots at a nominal stocking of 2224 stems/ha. Each point is the mean of two sub-plots in each treatment.

After Canopy Closure

Because of the great differences in stocking between the four sub-plots within each treatment after 1976 (being respectively ×2, ×4, and ×6 the final stand density of 371 stems/ha), the main comparisons of treatment effects can be most explicitly related to the 15 stems of largest d.b.h. in each assessment plot, representing the 371 largest stems/ha (the "dominant element") (Tables 3 and 5). In the most heavily thinned sub-plots these stems constitute the whole of the residual stand, whereas in the unthinned sub-plots they represent only about one-sixth of the trees remaining.

The main experimental effects are summarised in Table 6 as a series of orthogonal comparisons (each with a single degree of freedom) of the four expressions of growth: mean dominant height (in metres), basal area increment (square metres per hectare), basal area (square metres per hectare), and volume (cubic metres per hectare) of the dominant element. The variance attributable to each comparison is expressed as a multiple of the appropriate variance attributable to experimental error – i.e., plot error (with 3 d.f.) for main-plot treatment comparisons and sub-plot error (with 12 d.f.) for the stocking comparisons. These F-ratios are significant at the 5% and 1% levels when they exceed 10.13, 34.12, or 4.75, 9.33 respectively.

Lupin effects: Although Fig. 4 indicates an appreciable increase of mean dominant height as compared with controls, the difference has not been significant at any time since canopy closure (Table 6). At age 8, basal area increment was significantly greater

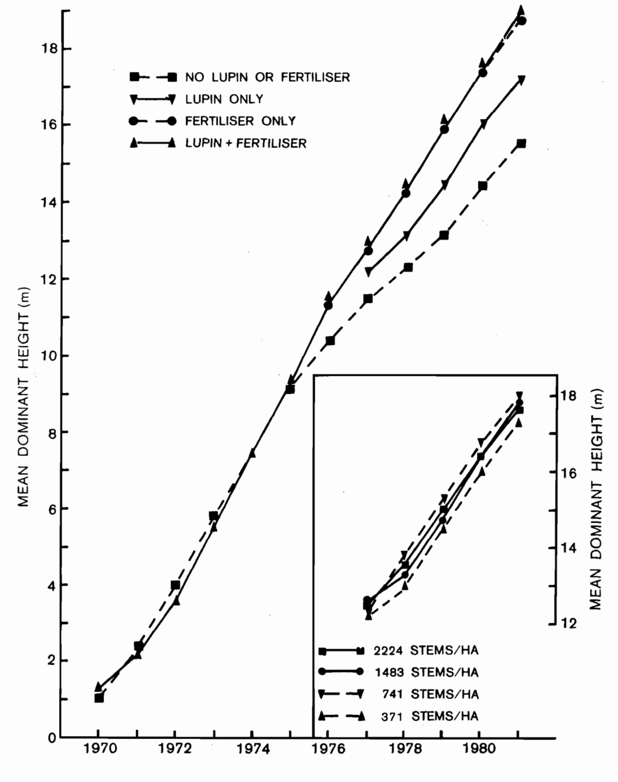

FIG. 4—Course of mean dominant height growth of 15 largest-diameter trees, by treatment and by stocking. Each point is the mean over eight sub-plots.

TABLE 5—Total volumes and volumes of 371 dominant trees only (m^3/ha) for each sub-plot 1977–81

Treatment and stocking	Sub-plot No.	1977		1978		1979		1980		1981	
		Total	371	Total	371	Total	371	Total	371	Total	371
Control											
2224	43	89.4	28.4	106.0	34.0	120.8	39.3	139.5	45.8	156.7	52.5
	52	118.8	37.5	126.5	41.0	142.0	46.4	155.4	52.9	172.3	60.5
1483	42	62.3	26.1	76.5	32.3	89.8	38.1	107.4	46.1	119.7	52.6
	54	110.9	40.6	122.8	45.6	143.6	53.5	165.3	63.2	188.9	74.2
741	41	63.1	35.9	77.9	44.2	90.9	52.2	110.9	63.7	128.2	74.3
	51	72.6	38.2	79.2	42.6	91.4	49.6	108.1	59.4	130.4	72.9
371	44	36.8	32.7	41.5	37.1	51.0	45.5	66.5	59.2	81.6	72.8
	53	45.7	34.3	51.8	39.1	62.0	47.0	77.7	59.1	90.5	69.6
Lupin											
2224	34	131.4	41.8	146.7	49.5	168.7	57.4	198.3	68.8	212.7	76.5
	84	117.6	38.4	141.5	46.1	164.6	53.5	194.9	63.7	215.9	72.9
1483	32	113.6	41.5	129.9	49.2	151.7	58.0	182.7	70.6	201.5	81.4
	82	111.1	44.7	134.8	54.7	160.3	64.8	185.2	75.5	211.3	87.2
741	31	89.1	51.6	104.5	60.8	124.4	75.0	158.8	93.6	181.2	108.5
	81	68.6	39.7	84.6	49.0	102.8	59.8	124.3	72.6	148.7	88.2
371	33	55.2	46.1	67.3	56.4	85.8	72.1	113.8	95.6	135.6	114.2
	83	64.2	53.2	79.2	65.5	98.2	80.3	120.4	98.6	136.4	111.8

TABLE 5—Total volumes and volumes of 371 dominant trees only (m^3/ha) for each sub-plot 1977–81 (continued)

Fertiliser												
2224	14	151.0	44.5	172.1	53.2	201.2	64.3	246.0	80.5	264.6	91.3
	74	126.6	41.6	149.8	49.8	183.4	61.8	209.0	71.0	234.3	82.3
1483	13	146.3	56.0	179.3	69.2	223.1	86.6	265.7	104.5	296.3	119.2
	71	106.2	49.3	130.5	61.7	159.0	75.0	190.0	90.4	218.1	105.1
741	11	113.18	62.3	139.1	76.7	171.7	95.2	209.9	118.0	242.1	137.6
	72	97.4	57.5	118.2	69.9	144.8	85.7	176.1	104.7	210.1	125.9
371	12	67.3	59.1	86.0	76.0	112.9	100.2	139.6	124.6	165.5	148.9
	73	60.8	51.8	84.2	71.7	111.9	95.3	131.7	112.3	151.2	129.5
Lupin + fertiliser												
2224	21	151.2	51.3	191.8	66.5	228.0	80.8	270.9	98.1	305.8	114.7
	63	146.5	52.0	188.3	70.1	228.9	85.8	267.6	101.2	305.3	117.1
1483	24	128.2	61.2	155.3	75.3	187.7	91.7	230.7	114.8	256.6	131.4
	61	121.7	57.1	142.7	67.8	172.0	82.6	196.1	98.1	222.3	113.2
741	23	98.7	58.7	124.4	74.6	153.0	92.6	187.0	113.9	215.7	132.3
	64	103.8	65.7	125.6	78.7	159.8	100.2	193.6	121.3	222.5	140.0
371	22	74.8	68.1	94.9	86.3	120.7	109.7	150.1	136.7	178.6	162.8
	62	65.9	53.3	87.8	71.0	119.6	96.0	145.8	116.5	176.1	140.9

TABLE 6—Summary of orthogonal comparisons of treatment and stocking effects on growth of dominant trees: variances expressed as multiple of appropriate error mean square (= F ratio)

	Year (Age)					
	1976 (8)	1977 (9)	1978 (10)	1979 (11)	1980 (12)	1981 (13)
Lupin effects:						
Dominant ht.	—	0.84 NS	3.76 NS	3.86 NS	5.52 NS	4.74 NS
B.A.I.	11.6 *	15.7 *	18.9 *	36.7 **	23.6 *	2.47 NS
B.A.	11.7 *	25.2 *	43.8 **	74.8 **	63.2 **	49.6 **
Volume	—	9.23 NS	22.0 *	28.1 *	24.5 *	23.8 *
Fertiliser effects:						
Dominant ht.	—	7.28 NS	29.9 *	38.9 **	40.6 **	34.6 **
B.A.I.	49.0 **	76.2 **	125.2 **	186.7 **	87.0 **	11.8 *
B.A.	28.0 **	73.1 **	146.3 **	265.8 **	226.0 **	179.4 **
Volume	—	37.4 **	96.5 **	149.9 **	116.0 **	118.3 **
L × F interaction:						
Dominant ht.	—	0.90 NS	4.15 NS	4.16 NS	5.30 NS	3.28 NS
B.A.I.	0.56	1.64 NS	2.22 NS	1.15 NS	3.29 NS	1.63 NS
B.A.	0.12	0.51 NS	1.27 NS	2.19 NS	2.40 NS	2.38 NS
Volume	—	0.81 NS	1.95 NS	2.93 NS	2.74 NS	2.22 NS
Stocking 2224 v. 1483:						
Dominant ht.	—	0.03 NS	0.41 NS	0.69 NS	1.60 NS	1.03 NS
B.A.I.	14.8 **	10.2 **	5.59 *	16.5 **	32.4 **	10.4 **
B.A.	1.29 NS	4.56 NS	6.08 *	8.27 *	11.2 **	13.1 **
Volume	—	4.28 NS	4.66 NS	6.48 *	7.77 *	9.62 **
Stocking 1483 v. 741:						
Dominant ht.	—	1.67 NS	1.40 NS	0.96 NS	0.0 NS	0.16 NS
B.A.I.	93.6 **	45.9 **	28.4 **	135.9 **	170.6 **	68.7 **
B.A.	21.5 **	28.5 **	36.7 **	52.4 **	68.2 **	81.1 **
Volume	—	14.0 **	16.8 **	24.3 **	32.2 **	46.3 **
Stocking 741 v. 371:						
Dominant ht.	—	0.0 NS	1.36 NS	0.69 NS	1.53 NS	2.23 NS
B.A.I.	21.5 **	26.7 **	97.9 **	223.7 **	176.0 **	51.6 **
B.A.	0.25 NS	0.94 NS	0.88 NS	6.28 *	14.2 *	20.9 **
Volume	—	0.30 NS	0.09 NS	2.49 NS	3.62 NS	5.14 *

* Significant at $p = 0.05$
** Significant at $p = 0.01$
NS Not significant

on those plots where lupin had grown (but had died out 3 years earlier) and this benefit reached a maximum at age 11 (variance ratio 36.7). It diminished rapidly over the ensuing two growing seasons, however, and by age 13 was no longer significant. The cumulative effect on standing basal area (Table 7) followed that for increment, also peaking at age 11 and, although diminishing, was still highly significant at age 13. Effects on standing volume have been similar, but did not become apparent until 2 years later than for basal area.

Fertiliser effects: In marked contrast to the lupin plots, plots that had received fertiliser began to exhibit a substantial increase in height increment during their eighth growing-season, and this had become highly significant by age 10, with dominant height continuing to diverge in each subsequent year (Fig. 4). Effects on basal area increment and standing basal area have been highly significant since 1976, with the variance ratio reaching a maximum at 11 years, and declining thereafter. It is still significant at latest remeasurement. Since first estimation of volume in 1977 (at age 9), differences in stand volume have parallelled those for basal area, and are four or five times more significant than the effects of lupin alone.

No lupin × fertiliser interactions have become statistically apparent at the main-plot level during the experiment, indicating simple additivity of lupin and fertiliser effects.

Thinning effects: Over-all, the effect of stocking on mean dominant height has been negligible (Fig. 4), and none of the comparisons have been significant.

In all except the 1978 measurement of 2224 *v.* 1483 stems/ha, there were highly significant differences in dominant basal area increment between each stocking comparison in all years since thinning (scarcely surprising, in view of the criterion used for initiating this operation). Up to age 9, the greatest differential response occurred between stockings of 1483 and 741 stems/ha (Table 6); but the most impressive response by the dominant element followed the reduction from 1483 to 371 stems/ha at age $7\frac{1}{2}$ years. The development of the pair of 1483 sub-plots in each treatment up to this date had been almost identical (Fig. 5). After age 10 (1978) the maximum statistical response shifted to the 741 *v.* 371 comparison, but in the last year or two there has been some attenuation of the effects for all stocking comparisons.

The cumulative effects of these incremental differences on dominant basal area were not significant until age 10 for the 2224 *v.* 1483 stems/ha comparison, and a year later for 741 *v.* 371 (Table 6). As with basal area increment, the major effects of thinning on dominant basal area appear to lie between 1483 and 741 stems/ha, and at age 13 this differential effect is still double that between 741 and 371 stems/ha, although both are still increasing. Much the same picture emerges for dominant tree volume, with the effects even more delayed. In fact, the difference in dominant volume between stockings of 741 and 371 stems/ha has only just become significant (at age 13), and one of the questions that arises is whether there has been a needless sacrifice of stand productivity. In order to answer this, it is necessary to examine the treatment × stocking interactions.

Treatment × stocking interactions: There are insufficient degrees of freedom to separate out differential responses to thinnings within treatment for any one year of measurement but, when the data are examined over a series of years, it is obvious that there are strong interactions, with important silvicultural implications.

Thus, Fig. 5 depicts the course of dominant basal area increment (1971–81) for two pairs of sub-plots in each treatment thinned to 1483 stems/ha just prior to age 4. The annual basal area increment peaked in the control sub-plots during the fifth growing-season, and a year later in the fertiliser and lupin + fertiliser sub-plots, the latter at about double that of the controls. Thereafter all sub-plots diminished in parallel until February 1976, when one pair of sub-plots in each treatment was thinned to 371 stems/ha. There was an immediate response by the dominant trees in the sub-

TABLE 7—Total basal areas (m^2/ha) of all living trees in each sub-plot 1971–81

Treatment and stocking	Sub-plot No.	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981
Control												
2224 stems/ha	43	0.30	2.71	7.24	12.83	16.37	18.79	20.95	22.69	24.58	26.11	28.11
	52	0.54	3.63	10.02	16.20	20.36	23.40	25.01	25.89	27.12	27.86	29.57
1483 stems/ha	42	0.07	1.36	4.72	7.70	10.67	12.57	14.54	16.23	18.05	19.81	21.74
	54	0.46	3.23	8.84	13.67	17.26	20.37	22.59	24.15	25.71	27.66	29.48
2224 stems/ha; thinned to 741 stems/ha 1972	41	0.48	3.60	^{T}5.18	8.05	10.41	12.17	13.99	15.79	17.69	19.59	21.63
	51	0.51	3.87	^{T}5.77	9.33	12.62	14.88	16.17	17.50	18.87	20.60	22.60
2224 stems/ha; thinned to 1483 stems/ha 1972 371 stems/ha 1976	44	0.35	3.22	^{T}8.13	12.35	15.83	^{T}6.67	7.84	9.17	10.81	12.79	14.62
	53	0.52	3.93	^{T}9.01	13.24	16.98	^{T}9.05	9.71	10.81	12.24	14.00	15.67
Lupin												
2224 stems/ha	34	0.57	3.83	11.54	16.93	21.08	24.66	27.54	28.60	30.96	33.23	34.91
	84	0.33	2.40	8.14	13.96	19.60	22.73	25.97	28.42	30.67	32.88	34.66
1483 stems/ha	32	0.33	2.56	7.44	12.41	16.85	20.68	23.51	25.83	28.10	30.70	32.29
	82	0.40	2.66	8.03	12.86	17.72	20.83	23.95	26.24	28.71	30.97	33.32
2224 stems/ha; thinned to 741 stems/ha 1972	31	0.47	3.12	^{T}5.42	9.05	12.40	15.55	17.95	20.02	22.05	24.65	26.63
	81	0.32	2.13	^{T}3.68	6.97	10.77	13.67	16.20	17.94	20.05	22.33	24.53
2224 stems/ha; thinned to 1483 stems/ha 1972, 371 stems/ha 1976	33	0.62	3.93	^{T}10.22	15.45	19.52	^{T}9.64	11.07	12.89	15.29	18.07	20.25
	83	0.37	2.65	^{T}7.47	13.29	19.05	^{T}10.78	13.10	15.54	17.92	20.65	23.01

TABLE 7—Total basal areas (m^2/ha) of all living trees in each sub-plot 1971–81 (continued)

Fertiliser												
2224 stems/ha	14	0.65	4.38	10.94	17.65	22.84	27.29	30.58	32.00	34.97	38.05	39.60
	74	0.34	2.57	7.73	13.71	18.72	22.85	25.98	28.22	31.03	33.44	35.16
1483 stems/ha	13	0.50	3.25	8.57	15.02	19.66	24.24	28.12	31.52	34.79	38.55	41.14
	71	0.24	1.93	6.54	11.42	15.69	19.76	22.98	25.50	28.08	30.66	32.76
2224 stems/ha; thinned	11	0.35	2.73	T6.27	10.36	14.45	18.60	21.90	24.80	27.60	30.89	33.51
to 741 stems/ha 1972	72	0.37	2.71	T5.54	9.70	13.86	17.50	20.48	22.99	25.59	28.42	30.81
2224 stems/ha; thinned	12	0.32	3.14	T7.82	13.74	19.26	T10.23	13.12	16.05	18.76	21.61	24.09
to 1483 stems/ha 1972,	73	0.38	2.68	T8.33	13.85	18.08	T9.27	12.07	15.27	18.22	20.72	22.58
371 stems/ha 1976												
Lupin + fertiliser												
2224 stems/ha	21	0.27	2.62	9.05	16.79	23.44	29.10	33.25	35.84	39.11	42.76	44.90
	63	0.33	2.80	9.75	17.11	22.94	28.04	32.18	35.40	39.00	42.01	44.42
1483 stems/ha	24	0.26	1.98	6.61	13.36	18.60	23.00	26.14	28.92	32.04	35.24	37.48
	61	0.23	1.93	6.51	11.90	16.69	20.70	24.04	26.47	29.17	30.79	32.83
2224 stems/ha; thinned	23	0.18	1.81	T4.15	8.79	12.66	16.87	19.94	22.70	25.75	29.04	31.35
to 741 stems/ha 1972	64	0.31	2.16	T5.31	10.21	14.43	18.32	21.84	24.67	27.67	30.40	32.67
2224 stems/ha; thinned	22	0.31	2.56	T8.52	16.82	22.65	T11.84	14.77	17.71	20.55	23.41	25.52
to 1483 stems/ha 1972,	62	0.22	1.78	T6.61	12.45	17.65	T11.03	14.52	18.22	21.71	24.96	27.38
371 stems/ha 1976												

T = thinned

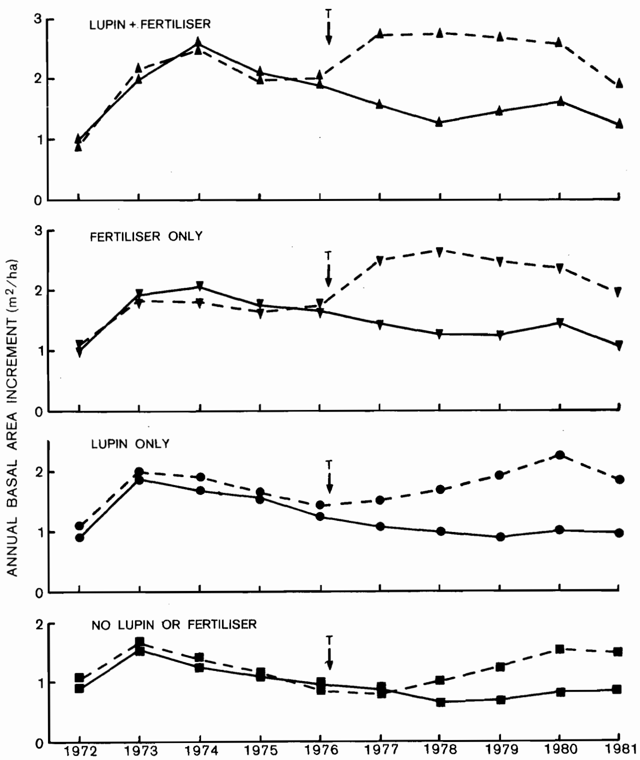

FIG. 5—Annual basal area increment of the largest 371 stems/ha, by treatment, showing relative responses to thinning from 1483 to 371 stems/ha at age 7½ years. Each point is the mean for a pair of sub-plots; both pairs at a common stocking of 1483 stems/ha until February 1976.

plots with fertiliser (Fig. 5), and they doubled the increment of their unthinned pairs within 2 years. The sub-plots without fertiliser took 4 years to attain maximum response, remaining substantially below the fertiliser sub-plots throughout the period of measurement.

This greater differential response to thinning, by dominant trees in the fertiliser sub-plots, is reflected in a comparison of their standing volume for each of the years 1977–81 (Fig. 6). The difference in additional dominant volume, attributable to thinning, between the (f) sub-plots and the controls (0) is particularly striking in the latest 3 years.

DISCUSSION

A critical question for stand management, that arises from these results, concerns the amount of production over the whole stand that is sacrificed in order to attain increased volume on the dominant element. Corresponding total stand volumes are represented for the same years in Fig. 7 (taken from data in Table 5). By age 13, between 36% and 46% of total stand productivity had been sacrificed in order to obtain dominant responses of the order shown in Fig. 6. However, it would also seem that the proportional loss of volume differs in relation to treatment. To explore this further, we extracted the volume increments for each sub-plot over the growing-seasons 1977–81 (Table 8), and plotted them for each stocking for the untreated controls and

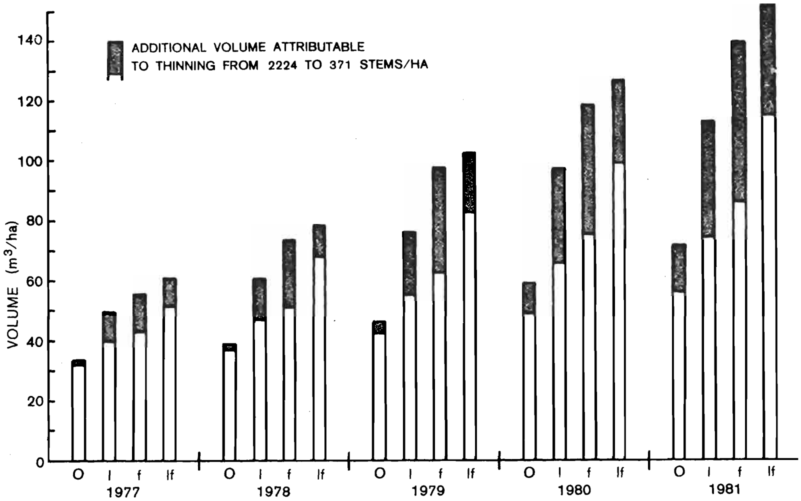

FIG. 6—Volume of the largest 371 stems/ha in stands at 2224 and 371 stems/ha. Each bar is the mean for two sub-plots of each treatment: lf - with lupin and fertiliser; f - with fertiliser only; l - with lupin only; 0 - controls, with neither fertiliser nor lupin.

for the lupin + fertiliser treatment (Fig. 8). Despite the annual variability, it is clear that for the same thinning regime the volume increment of the (lf) sub-plots is at least double and may be up to four times that of the controls. There is also a much wider range of response to differences of stocking within the (lf) plots, and this is reflected to a lesser extent also in the plots with lupin or fertiliser alone (not plotted in Fig. 8).

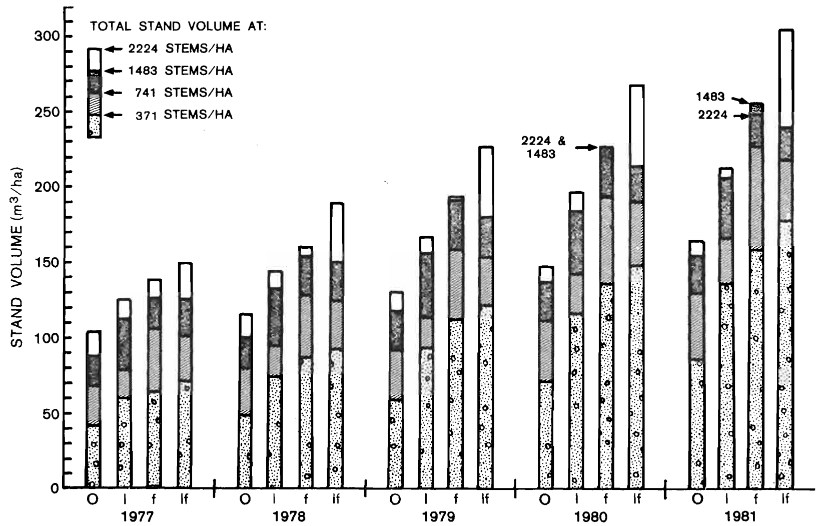

FIG. 7—Total stand volume for each treatment/stocking combination in June 1977–81. The top of each bar represents the mean value for two sub-plots of each combination. (A data anomaly is indicated in the f (fertiliser only) values for 1980 and 1981).

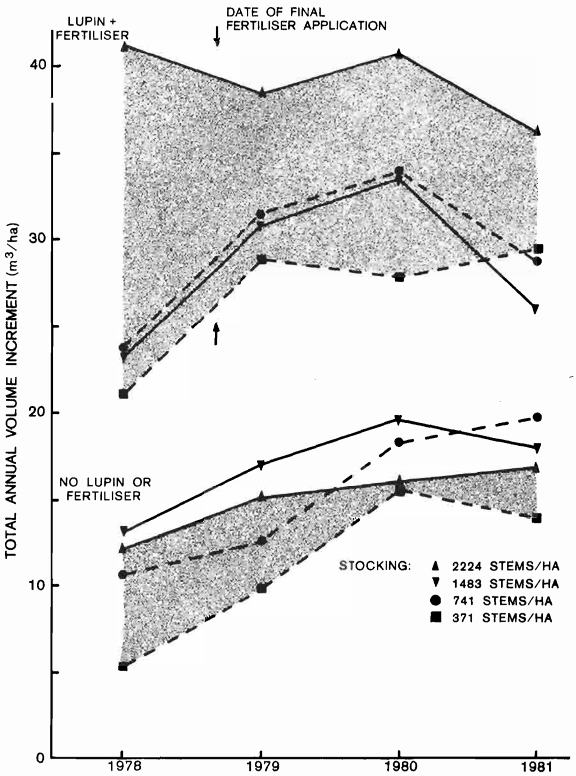

FIG. 8—Comparisons of volume increment response to stocking differences for the two extremes of treatment (with or without lupin and fertiliser). Area between the extremes of stocking shown hatched.

Because the variability between years rather obscures such comparisons, we have pooled the data for the 4 years 1978–81 (thereby introducing unavoidable effects of autocorrelation). However, with the 127 degrees of freedom thus obtained, there are now 48 d.f. available for more sensitive testing of the treatment × stocking interactions. The resulting analysis of variance is presented in Table 9. This confirms the year-by-year analyses, summarised in Table 6, with regard to the main effects, i.e., the highly significant influence of both lupin and fertiliser, as well as of stocking, and the lack of any discernible difference between the replications. There is a significant difference between years, but not in their interactions with treatment or stocking. The main point of the exercise appears in the highly significant first-order interaction between lupin and stocking, and likewise that of second order, between fertiliser, lupin, and stocking. In order to examine these in more detail, we plotted the means of the interacting effects, corrected for other influences (Fig. 9). Differences are significant in the first-order effects if they exceed 4.27 (5% level) or 7.84 (1% level).

If, during this phase of stand development (9–13 years), we take total volume increment as the criterion of stand productivity, we may summarise these interactions as follows:

(1) Only when sub-plots have benefited from fertiliser application or have supported lupin are they able to sustain a total volume increment of 30 m^3/annum on a stocking of 2224 stems/ha;

TABLE 8—Total annual volume increment (m^3/ha) for individual sub-plots, by treatment and stocking for 1978–81

Treatment and stocking	Sub-plot No.	1978	1979	1980	1981
Control					
2224	43	16.6	14.8	18.7	17.2
	52	7.7	15.5	13.4	16.9
1483	42	14.2	13.3	17.6	12.3
	54	11.9	20.8	21.7	23.6
741	41	14.8	13.0	20.0	17.3
	51	6.6	12.2	16.7	22.3
371	44	4.7	9.5	15.5	15.1
	53	6.1	10.2	15.7	12.8
Lupin					
2224	34	15.3	22.0	29.6	14.4
	84	23.9	23.1	30.3	21.0
1483	32	16.3	21.8	31.0	18.8
	82	23.7	25.5	24.9	26.1
741	31	15.4	19.9	34.4	22.4
	81	16.0	18.2	21.5	24.4
371	33	12.1	18.5	28.0	21.8
	83	15.0	19.0	22.2	16.0
Fertiliser					
2224	14	21.1	29.1	44.8	18.6
	74	23.2	33.6	25.6	25.3
1483	13	33.0	43.8	42.6	30.6
	71	24.3	28.5	31.0	28.1
741	11	25.3	32.6	38.2	32.2
	72	20.8	26.6	31.3	34.0
371	12	18.7	26.9	26.7	25.9
	73	23.4	27.7	19.8	19.5
Lupin + fertiliser					
2224	21	40.6	36.2	42.9	34.9
	63	41.8	40.6	38.7	37.7
1483	24	27.1	32.4	43.0	25.9
	61	21.0	29.3	24.1	26.2
741	23	25.7	28.6	34.0	28.7
	64	21.8	34.2	33.8	28.9
371	22	20.1	25.8	29.4	28.4
	62	21.9	31.8	26.2	30.3

(2) If the stand has benefited from both lupin and fertiliser, it should be possible to attain a productivity of 35 to 40 m^3/annum on *c.* 2224 stems/ha;

(3) In the absence of both lupin and fertiliser, the reduction of productivity is most apparent at the highest stocking of 2224 stems/ha, and under these circumstances 1483 stems/ha is about optimal, with lower rates of stocking significantly reducing productivity.

TABLE 9—Analysis of variance for total volume increment of 32 sub-plots, pooled for the years 1978–81

Source of variation	d.f.	Sum of squares	F-ratio
Between plots:			
Years (Y)	3	1097	9.63 **
Replications	1	43	1.14 NS
Treatments	3	5202	45.67 **
Years × treatments	9	219	0.64 NS
Plot error	15	570	E.M.S. = 37.97
	31	7129	
Between sub-plots:			
Stockings (S)	3	683	15.77 **
Years × stocking	9	224	1.72 NS
Fertiliser × stocking	3	105	2.42 NS
Lupin × stocking	3	311	7.18 **
L × F × S	3	238	5.50 **
Y × F × S	9	67	0.52 NS
Y × L × S	9	59	0.45 NS
Y × F × L × S	9	125	0.96 NS
Sub-plot error	48	692	E.M.S. = 14.42
TOTALS	127	9633	

In comprehending these results, it should be borne in mind that all fertiliser applications were terminated in September 1978, and that reference to the "lupin treatment" or "lupin effect" does not imply that *Lupinus arboreus* is still present on any of the sub-plots. In fact, even for the earliest data presented in Figs 8 and 9, it was 4 years since there had been a fully viable stand of lupin in the (l) and (lf) plots, and by 1981 all superficial traces of lupin had long disappeared. The only exceptions concern those sub-plots thinned to 371 stems/ha in February 1976: in the following spring there was vigorous regeneration of lupin in the (l) sub-plots, but relatively less in the (lf) treatment where the understorey vegetation comprised ragwort, grasses, and vetches, but only patchy lupin. Ironically, lupin regeneration has been most recurrent in the control (0) sub-plots at 371 stems/ha, which have required regular hand-weeding to keep them free of lupin.

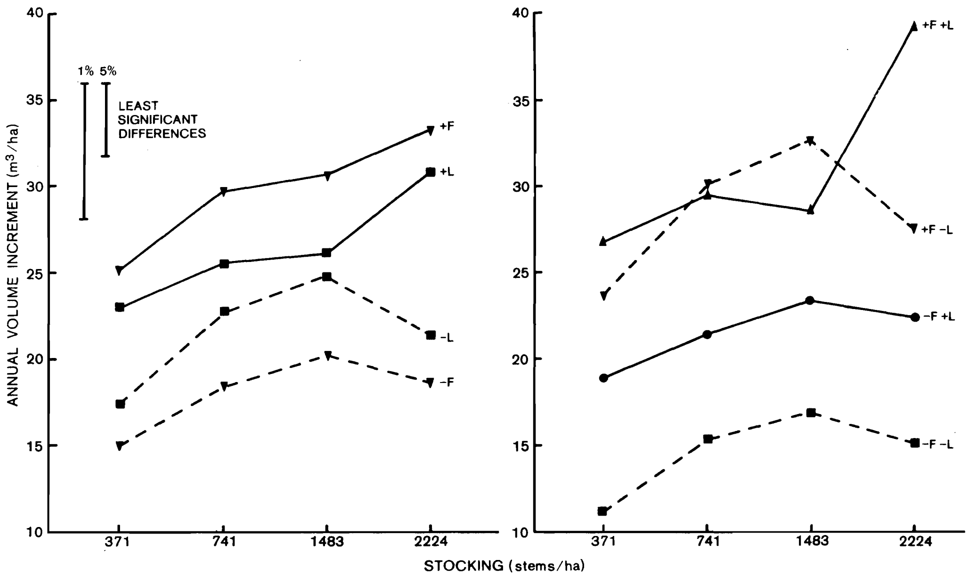

FIG. 9—Effects on annual volume increment of (A) first-order interactions between stocking and treatment, (B) second-order interactions of stocking, lupin, and fertiliser. L signifies mean effect with (+) or without (-) lupin; F, for fertiliser.

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