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Fertilization and Thinning Effects on a Douglas-fir Ecosystem at Shawnigan Lake

9 Year Growth Response

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Abstract

The responses of tree and stand growth to thinning and nitrogen (urea) fertilization of a 24-year-old Douglas-fir stand near Shawnigan Lake, British Columbia over a 9-year period are documented. These responses are analyzed in four ways: land area basis, individual tree basis, stand structure analysis, and crop tree analysis.

Fertilization has increased diameter, height, gross volume, and merchantable volume increments over all levels of thinning on both an individual tree and land area basis. Thinning has also increased diameter and volume increments on an individual tree basis. On a land area basis, the volume increments were decreased by thinning. This reduced-volume growth resulted from the initial removal of growing stock and the consequently reduced base for volume production.

The effects of fertilization alone still outweigh the effects of thinning alone on the volume increments of the 200 and 600 largest trees per hectare. The 9-year gross volume increments, as percentage above control, of the 200 largest trees per hectare are 31, 59, and 107 for heavy thinning alone, heavy fertilization alone, and heavy thinning plus heavy fertilization, respectively. When adjusted by covariance analysis for differences in initial dbh, these volume increments become 46, 75, and 120%, respectively. On a land area basis, the 9-year gross volume periodic annual increments (PAI) responses were -4.1, +6.5, and +2.3 m^3/ha/a, respectively. The 9-year mean stand diameter increments, as percent above control, for these same treatments were 180, 115, and 335, respectively, for the plot trees.

Annual measurements taken on the volume sample trees indicate that diameter increments from all treatments, except controls, initially increased and that height increments from all treatments, except controls and T_2F_0, initially increased. Both diameters and heights then declined again until 1977 and then increased again. The controls remained constant during this initial increase, declined with the other treatments, and subsequently increased again along with the other treatments. This is probably explainable in terms of summer rainfall and indicates the need to include weather data in analyses such as this one.

Stem form at 9 years has been significantly affected by thinning, but not by fertilization. This necessitated the calculation of separate equations for volume calculations for each treatment. Thinning produced a more tapered stem form. Thinning also had a distinct effect on crown length. Crown lift-off was pronounced in unthinned plots but only slight in heavily thinned plots, yielding longer crown in these latter plots. Fertilization increased crown length to a lesser extent.

Tree mortality increased with fertilization, decreased with thinning, and was mostly confined to the trees of smaller dbh.

Résumé

Les auteurs examinent les effets sur une période de neuf ans d'une éclaircie et d'une fertilisation azotée (urée) sur la croissance de l'arbre et du peuplement dans un peuplement de Douglas taxifolié de 24 ans près de Shawnigan Lake, en Colombie-Britannique. Ils analysent les effets à divers niveaux: à l'échelle de la superficie, à l'échelle de l'arbre, structure du peuplement, et arbres du peuplement final.

Quelle qu'ait été l'intensité d'éclaircie, la fertilisation a eu comme effet d'augmenter l'accroissement en diamètre, en hauteur, en volume brut, et en volume marchand à l'échelle de l'arbre et à l'échelle de la superficie. L'éclaircie a également entraîné une augmentation pour le diamètre et le volume au niveau de chaque arbre, mais une diminution pour le volume par unité de superficie du fait de l'extraction initiale de certains arbres qui a diminué le matériel en croissance.

Les effets de la simple fertilisation sont encore supérieurs aux effets de la simple éclaircie en ce qui concerne l'accroissement en volume à l'hectare des 200 et 600 plus gros arbres. L'accroissement en neuf ans du volume brut à l'hectare des 200 plus gros arbres est de 31% plus élevé par rapport aux témoins dans le cas d'une simple éclaircie intense, de 59% dans le cas d'une simple fertilisation intense, et de 107% dans le cas d'une éclaircie intense accompagnée d'une fertilisation intense. Après ajustement des données par analyse des covariances pour tenir compte des différences de dhp initial, on obtient des valeurs de 46, de 75, et de 120%, respectivement. En fonction de la superficie, les effets sur l'accroissement du volume brut au cours des neuf années ont été de -4,1, +6,5, et +2,3 m^3/ha/a, respectivement. Pour les trois mêmes traitements, les accroissements moyens du diamètre en neuf ans dépassaient de 180, de 115, et de 335% l'accroissement moyen des témoins.

Chez les arbres d'échantillonnage du volume, l'accroissement annuel en diamètre a augmenté au début pour tous les traitements, et il en a été de même de l'accroissement en hauteur pour tous les traitements, sauf T_2F_0. Il y a eu ensuite diminution pour le diamètre et la hauteur jusqu'en 1977 puis augmentation de nouveau. Chez les témoins, les accroissements en diamètre et en hauteur sont demeurés constants pendant qu'ils augmentaient chez les arbres des parcelles traitées, puis ont suivi les diminutions et augmentations observées dans ces parcelles. Cela s'explique probablement par les précipitations estivales et fait ressortir la nécessité d'inclure des données météorologiques dans des études comme celle-ci.

L'éclaircie a eu un effet significatif sur la forme des tiges après neuf ans, mais non la fertilisation. Il a donc fallu établir des équations distinctes pour les calculs du volume pour chaque traitement. L'éclaircie a donné une forme plus effilée et a eu un net effet sur la longueur des cimes. Le relèvement du houppier est prononcé dans les parcelles non éclaircies et il est faible dans les parcelles fortement éclaircies où les cimes sont plus longues. La fertilisation a eu un effet moindre sur la longueur du houppier.

La mortalité des arbres a augmenté avec la fertilisation, a diminué avec l'éclaircie et était principalement limitée aux arbres à plus faible dhp.

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Introduction

Thinning and nitrogen fertilization are being increasingly used to improve yields and shorten rotation times. These practices are hampered, however, by a lack of detailed knowledge of the physiological and ecological consequences of such treatments and by a lack of documentation of the long-term yield effects. A major problem of investigations of these procedures is the time required to observe the total response after treatment; response periods of up to 14 years, and in a few cases longer, have been observed for nitrogen fertilization of Douglas-fir (Miller and Webster 1979) and even longer periods are common for thinning and spacing procedures.

The thinning and fertilization project in a young, even-aged Douglas-fir stand at Shawnigan Lake, British Columbia is an attempt to elucidate mechanisms involved in the overall effects of thinning and fertilization on tree growth. This project monitors growth and yield, tree physiology, nutrient distribution in the trees, soil and undergrowth, competitive interactions among trees and between trees and undergrowth, nitrogen movement in the soil, soil fauna, and soil microflora (Crown and Brett 1975). The purpose of the project is to gain a holistic understanding of the response of the total ecosystem to these management practices. The experimental design has been described in detail by Crown and Brett (1975) and by Crown *et al.* (1977); briefly it is as follows. In each of 1971 and 1972, 18 plots of 0.0405 ha (0.1 acre) each were established on a poor site (site index 21 m at 50 years). Plots were assigned to treatments on a completely random basis and there were three levels of urea fertilization applied at 0 (F_0), 224 (F_1), and 448 (F_2) kg N/ha and three levels of thinning in which 0 (T_0), 1/3 (T_1), and 2/3 (T_2) of the original basal area of 23.1 m^2/ha were removed, providing 9 treatment combinations. There were two replicate plots per treatment combination and year. Around each plot was a 15 m treated buffer strip to allow measurement of competitive stress indices and to ensure physical separation of the plots. This report deals with treatment effects on growth and yield based on 9 years of measurements in each of 1971 and 1972 plots and follows the format and type of analysis of the 6-year report (Hall *et al.* 1980).

Volume Determination

Tree measurements at Shawnigan Lake include two distinct categories:

(a) On a plot basis with measurements at 3-year intervals of diameter at breast height (dbh), height, and height to live crown on all plot trees.

(b) On an individual tree basis with measurements made annually of dbh and height on a subset of 464 (now down to 424) trees called volume trees. Every three years, stem diameters at selected taper steps are also made on the volume trees to allow calculation of stem form and tree volume by means of Newton's formula. These volume trees were selected 3 years after establishment of the plots, with care taken to ensure representative coverage of the range of fertilization, initial dbh, competitive position in the stand as defined by Competitive Stress Index (CSI) (Arney 1973), and change in CSI.

Differences between the 1971 and 1972 9-year diameters, heights, and form quotients were not significant and the data were pooled across years to yield four replicate plots per treatment combination.

STEM FORM

Stem form was calculated on the basis of taper measurements. Form quotients (Husch *et al.* 1972) were calculated as:

$$D_{upper}/dbh$$

at 10%, 30%, 50%, 70%, and 90% of total height above breast height. Table A1 in the Appendix shows these form quotients and the probability levels obtained from analyses of variance for differences among treatments. Thinning significantly reduced the form quotients, except for 10% of height above dbh, whereas fertilization had no effect.

VOLUME EQUATIONS

Since the form quotients showed significant differences across treatments, new volume equations were derived based on the volume sample trees at 9 years, but not including the 105 trees originally selected for this purpose since they were no longer alive. One equation was derived for each treatment level using the volumes calculated with Newton's formula for the volume trees and then regressing log volume against log dbh and log height; the coefficients for these volume equations are given in the Appendix in Table A2. The general form of these equations is a linear regression:

$$\log(V) = a_1 + a_2\log(D) + a_3\log(H)$$

where: V = gross volume in m^3
D = dbhob in cm
H = total height in m

These new equations were used to calculate the volumes for the 9-year data but volumes for previous years were left unchanged. Merchantable volume factors were determined, as in the 6-year analysis, using the merchantable volume factors developed by the B.C. Forest Service (Browne 1962) and then calculating regressions from them for interpolation when calculating merchantable volumes.

9-Year Growth Response

Data for all subsequent analyses were pooled from the 1971 and 1972 plots since the diameters, heights, and form quotients showed no significant differences between plot establishment years.

LAND AREA BASIS

The growth response on a land area basis provides measures of actual standing volumes (m^3/ha) and volume increments (m^3/ha/a), as well as corresponding measures for merchantable volume and diameter.

Volume

The 3-, 6-, and 9-year responses of gross and merchantable volume (B.C. Min. of Forestry close utilization) on a per hectare basis and volume increments are shown in Tables 1 and 2 and in graphical form in Fig. 1. As in the 6-year report, for a given thinning level, both gross and merchantable 0- to 9-year volume increments increase with level of fertilization. Again, however, on a land area basis, the effect of thinning on volume increments for a given level of fertilization was negative, except for the case of T_1F_2 which showed the highest gross and merchantable volume increments of any treatment (Tables 1 and 2). This decrease in volume increments is due to the initial removal of growing stock; the response on an individual tree basis increases for both fertilization and thinning (see next page), and this is reflected in the increase in percent growth over initial growing stock for both fertilization and thinning (Tables 1 and 2). In actual amounts (m^3/ha/a), the PAI for gross volume over 9 years was decreased 4.1 with T_2F_0 and increased 6.5 and 2.3 with T_0F_2 and T_2F_2, respectively, relative to control. Generally, fertilization had slightly more effect on gross volume at all thinning levels in the first 3-year period than in later 3-year periods, whereas the thinning effect increased with time.

Diameter

Mean tree dbh and dbh increments per treatment are shown in Table 3 and Fig. 2. Although initial mean dbh was not homogenous over treatments,

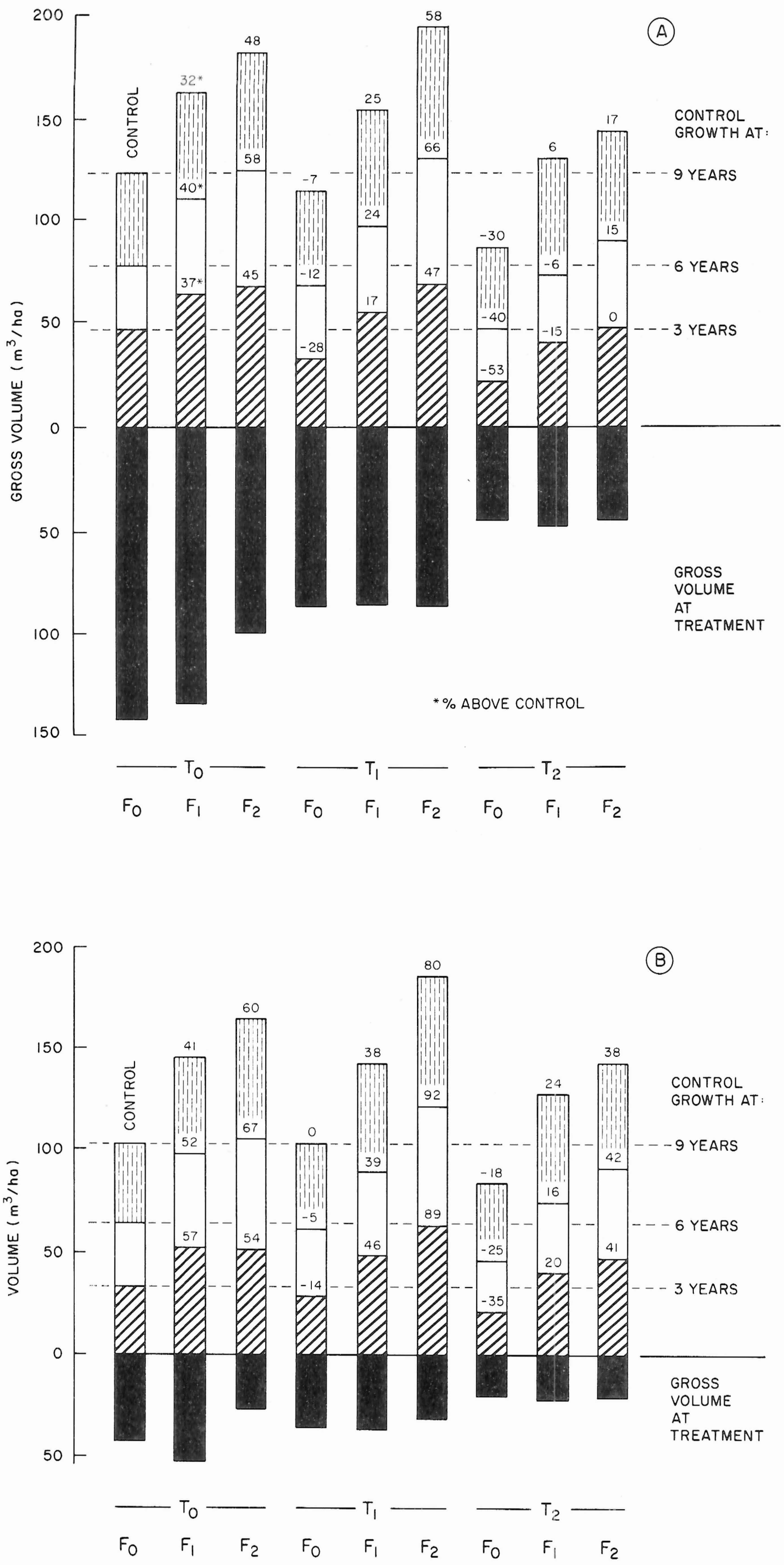


Fig. 1. Land area growth responses by treatment.

(a) Gross volume/ha—initial gross volumes at treatment are shown below the solid line. Accumulated volumes at 3, 6, and 9 years appear above the line together with accumulated percent increases above control.

(b) Merchantable volume/ha—the format is the same as for gross volume.

Table 1. Gross volume (m^3/ha) and volume increment (m^3/ha/a) response by treatment—land area basis.

	Treatment								
	T_0			T_1			T_2		
	F_0	F_1	F_2	F_0	F_1	F_2	F_0	F_1	F_2
Mean									
– (Initial) – m^3/ha	144	136	101	88	87	88	46	49	46
– (3-year) – m^3/ha	191	201	170	123	143	158	68	89	94
– (6-year) – m^3/ha	223	246	226	158	185	219	93	123	137
– (9-year) – m^3/ha	270	302	287	204	243	286	133	182	195
Increment									
– (0 to 3 years) – m^3/ha	48	65	69	34	56	70	22	41	48
– % initial*	33	48	68	39	64	79	48	83	103
– (3 to 6 years) – m^3/ha/a	31	45	56	35	42	61	25	34	43
– % initial	22	34	56	39	48	69	56	69	93
– (6 to 9 years) – m^3/ha	45	53	58	46	57	65	39	57	54
– % initial	31	39	58	53	65	74	84	117	117
– (0 to 9 years) – m^3/ha	124	164	183	115	155	196	87	131	145
– % initial	86	121	181	131	178	223	189	267	315
PAI									
– (0 to 3 years) – m^3/ha/a	15.9	21.8	23.0	11.4	18.6	23.4	7.4	13.5	15.9
– (3 to 6 years) – m^3/ha/a	10.4	15.1	18.6	11.7	13.9	20.2	8.4	11.2	14.4
– (6 to 9 years) – m^3/ha/a	15.1	17.5	19.4	15.4	19.0	21.8	12.9	19.2	14.4
– (0 to 9 years) – m^3/ha/a	13.8	18.2	20.3	12.8	17.2	21.8	9.7	14.6	16.1

* % of initial volume after treatment

Table 2. Merchantable volume (m^3/ha) and volume increment (m^3/ha/a) response by treatment—land area basis.

	Treatment								
	T_0			T_1			T_2		
	F_0	F_1	F_2	F_0	F_1	F_2	F_0	F_1	F_2
Mean									
– (Initial) – m^3/ha	43	53	27	36	37	32	20	22	21
– (3-year) – m^3/ha	77	106	79	65	87	96	42	62	69
– (6-year) – m^3/ha	108	152	135	98	128	156	68	97	113
– (9-year) – m^3/ha	148	202	194	140	183	220	105	152	168
Increment									
– (0 to 3 years) – m^3/ha	34	53	52	29	49	64	22	41	48
– % initial*	77	99	189	80	132	198	112	186	226
– (3 to 6 years) – m^3/ha/a	31	46	56	33	41	61	26	35	45
– % initial	72	86	205	90	110	188	134	160	212
– (6 to 9 years) – m^3/ha	39	48	58	42	54	63	37	54	52
– % initial	91	91	214	117	146	197	183	244	247
– (0 to 9 years) – m^3/ha	104	147	166	104	144	187	85	129	144
– % initial	242	277	615	289	389	584	425	586	686
PAI									
– (0 to 3 years) – m^3/ha/a	11.2	17.7	17.3	9.7	16.4	21.2	7.4	13.5	15.8
– (3 to 6 years) – m^3/ha/a	10.4	15.2	18.7	10.9	13.7	20.2	8.8	11.6	14.9
– (6 to 9 years) – m^3/ha/a	13.1	16.2	19.3	14.0	18.0	21.0	12.2	17.9	17.3
– (0 to 9 years) – m^3/ha/a	11.6	16.3	18.4	11.6	16.0	20.8	9.4	14.3	16.0

* % of initial volume after treatment

Table 3. Mean stand diameter response by treatment.

	Treatment								
	T_0			T_1			T_2		
	F_0	F_1	F_2	F_0	F_1	F_2	F_0	F_1	F_2
Mean									
– (Initial) – cm	7.81	8.60	8.04	9.65	9.91	9.53	10.63	10.71	10.69
– (3-year) – cm	8.54	9.84	9.58	10.89	11.84	11.84	12.44	13.63	14.20
– (6-year) – cm	9.11	10.88	11.08	11.95	13.09	13.50	14.12	15.57	16.69
– (9-year) – cm	10.06	12.11	12.46	13.01	14.31	14.90	15.65	17.28	18.53
Increment									
– (0 to 3 years) – cm	0.73	1.24	1.54	1.24	1.93	2.31	1.81	2.65	3.51
– % initial*	9	14	19	13	19	24	17	25	33
– (3 to 6 years) – cm	0.57	1.04	1.50	1.06	1.25	1.66	1.68	2.21	2.49
– % initial	7	12	19	11	13	17	16	21	23
– (6 to 9 years) – cm	0.53	0.67	0.82	1.02	1.15	1.14	1.56	1.73	1.83
– % initial	7	8	10	11	12	12	15	16	17
– (0 to 9 years) – cm	1.83	2.95	3.86	3.32	4.33	5.11	5.05	6.95	7.83
– % initial	23	34	48	34	44	54	48	62	73
PAI									
– (0 to 3 years) – cm/a	0.24	0.41	0.51	0.41	0.64	0.77	0.60	0.88	1.17
– (3 to 6 years) – cm/a	0.19	0.35	0.50	0.35	0.42	0.55	0.56	0.74	0.83
– (6 to 9 years) – cm/a	0.18	0.22	0.27	0.34	0.38	0.38	0.52	0.58	0.61
– (0 to 9 years) – cm/a	0.20	0.33	0.43	0.37	0.49	0.57	0.56	0.77	0.87

* % of initial diameter after treatment

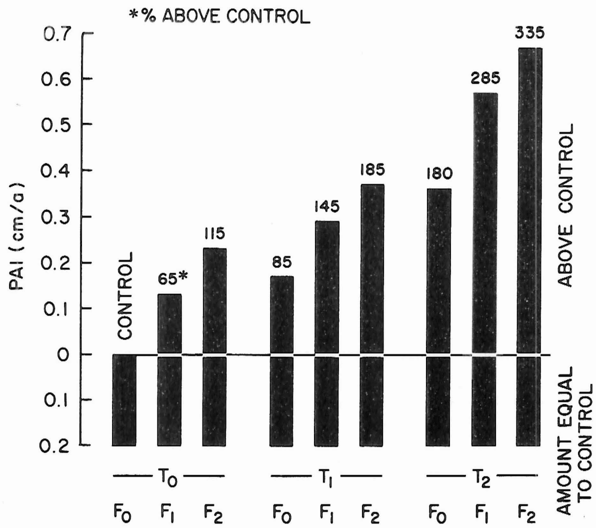


Fig. 2. Diameter—mean annual increments (0 to 9 years) above control are graphed above the solid line for each treatment and numbers indicate percentage gain above control; increments equal to control are shown below the solid line.

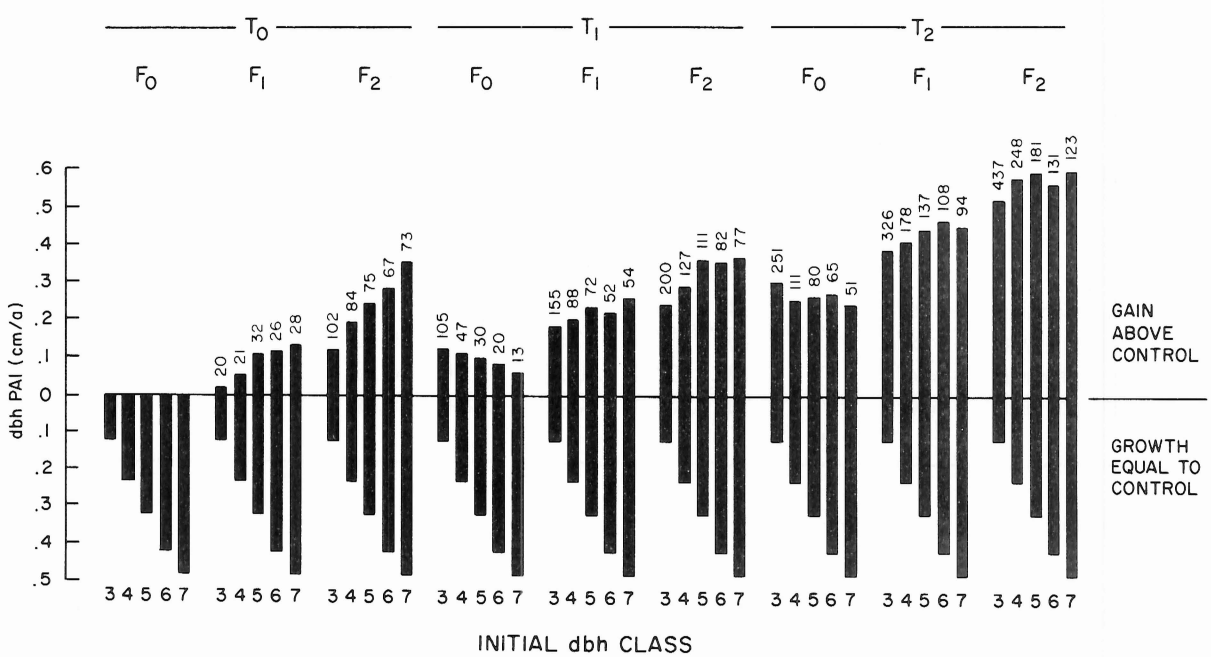


Fig. 3. Individual tree analysis for dbh PAI (0 to 9 years). The growth is graphed by treatment and by dbh classes within each treatment. Actual amounts of growth (cm/a per mean tree) are graphed while the percent gain over control is shown above the bars.

especially thinning, it appears clear that mean dbh and dbh increments have increased substantially in response to both thinning and fertilization, since the differences are too great to be accounted for on the basis of differing initial mean dbh. Again, diameter response was greatest in T_2F_2, the 9-year increment being more than four times that for the control. Fertilization had considerably less effect on diameter increment in the 6 to 9 years than in previous years but thinning maintained its effect.

INDIVIDUAL TREE BASIS

The analysis here characterizes a tree by its dbh and a stand by its dbh distribution. Trees of different initial dbh would be expected to grow at different rates, even in the absence of differences in other factors relevant to growth. A comparison of trees of similar dbh across treatments is therefore more informative than overall comparisons, as was done in the previous sections, especially with differing initial dbh distributions. Figs. 3, 4, 5, and 6 compare growth on an individual tree basis (PAI, 0 to 9 years) across treatments and dbh classes. Only those dbh classes common to all treatments were used. These classes are 2.5 cm wide; the lowest dbh class is 5.0 cm to 7.5 cm and the highest class (No. 7) is 15.0 cm to 17.5 cm.

The 9-year individual tree response, measured as individual tree PAI (0 to 9 years), is given for diameter, basal area, height, and gross volume for each dbh class and each treatment (Figs. 3 to 6). Regressions were not used here to generate Figs. 3 to 6, as was done in the 6-year report; rather, these figures were based on the original data from the 2946 currently live, undamaged Douglas-fir plot trees.

The general trend for diameter, basal area, and gross volume was for an increase in the absolute amounts with increasing diameter classes but a decrease in the PAI as a percent of initial amounts present with increasing dbh. The situation for height increments was less clear (Fig. 5) with respect to both absolute and percentage increases, although the lowest dbh class still generally yielded the highest percent increase in PAI.

The 9-year individual tree response is generally similar to those of 3-years (Crown *et al.* 1977) and 6-years (Hall *et al.* 1980). Diameter, basal area, height, and volume all show a positive response to both thinning and fertilization, although the response of height to thinning is only marginal. It is evident that the thinning shock apparent at both the 3- and 6-year analyses has been overcome and it seems likely that height will show an increasingly positive response to thinning in future. The responses of diameter, basal area, height, and volume were all significant (Tables A3 to A6 in the Appendix). In addition, most of the interactions were also significant; specifically, there was a positive interaction between thinning and fertilization, except for height, such that the effects of the two in combination are usually greater than the sum of their effects alone.

STAND STRUCTURE ANALYSIS

Gross volume response on a land area basis, as analyzed above, can give biased results if the initial dbh distribution and plot volumes are not the same for all plots. This is often the case and it is certainly the case where thinning is involved, since thinning alters gross volume and likely the dbh distribution within a plot. One way of handling this problem of comparing growth rates amongst plots of heterogenous dbh distribution is stand structure analysis (Anon. 1975), as was used in the 3- and 6-year reports. In this method, volume increments are accumulated for each dbh class of each treatment, based on the individual tree analysis data. The control volume increments are then used to calculate the mean growth per tree for each dbh class in the control group. These means are then weighted by multiplying by the numbers of trees in each dbh class in each treatment to obtain "control images" which represent the growth expected if the treatment had no effect. A quotient is then formed of the sum over dbh classes of the actual growth obtained for a given treatment divided by the corresponding sum of the control images for that treatment. These values are graphed in Fig. 7; the percentages growth over the control images generally reflect the trends seen in Fig. 6 for the individual tree analysis and also the percentages over control given in Table 4 where the percent growth over initial stock from Tables 1 and 2 have been converted to a comparison with control. In both analyses, an increase in volume increments is seen with both fertilization and thinning. The major disadvantage of both these analyses is that they do not include all dbh classes present in any given treatment. The stand structure analysis presented here was done using only the actual dbh distributions of the various treatments, since this yielded similar results to the other two methods used in the 3- and 6-year reports. The original dbh distribution used for the stand structure analysis is shown in the Appendix in Table A7.

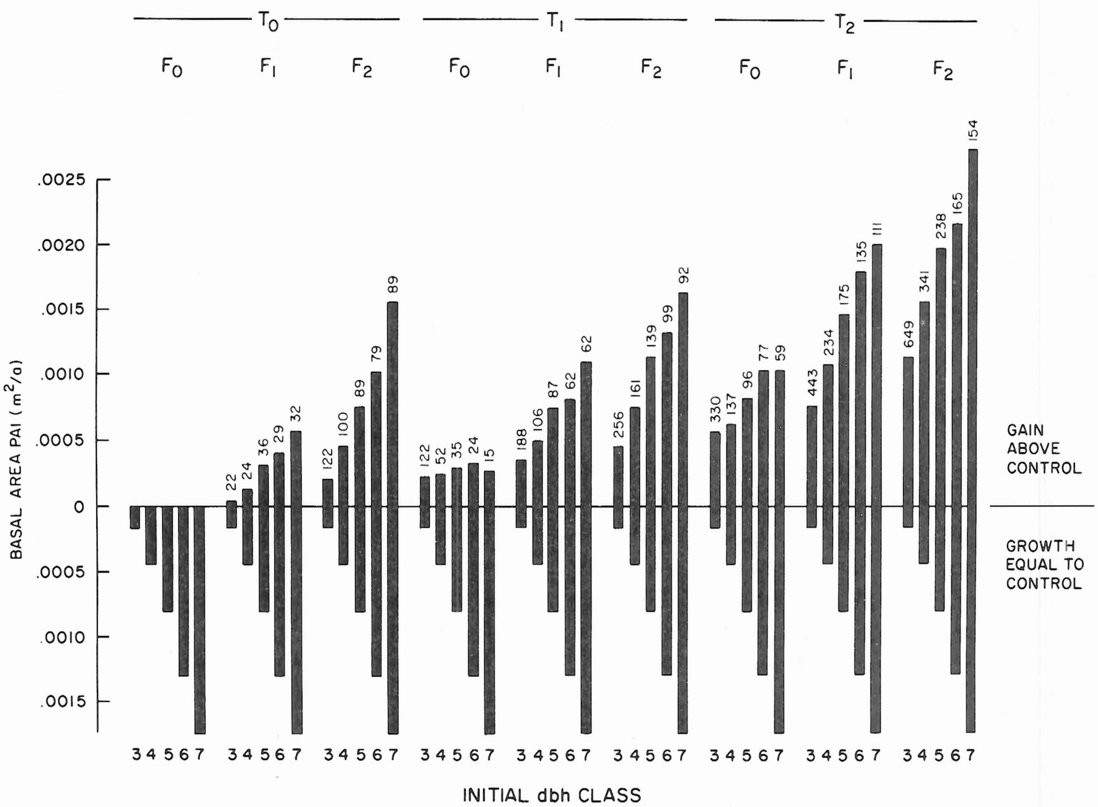


Fig. 4. Individual tree analysis for basal area PAI (0 to 9 years) by treatment and dbh class. Actual growth (m^2/a per mean tree) and percent gain over control are shown.

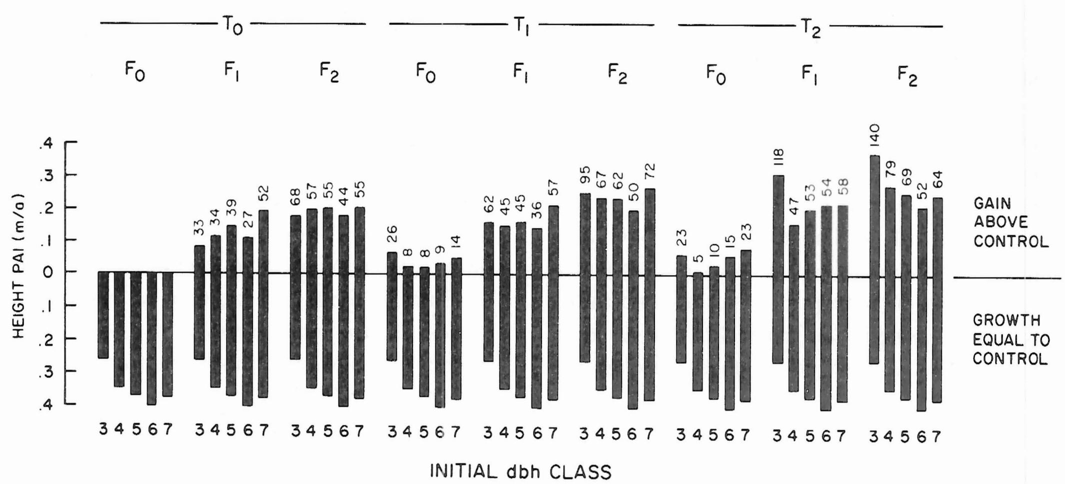


Fig. 5. Individual tree analysis for height PAI (0 to 9 years) by treatment and dbh class. Actual growth (m/a per mean tree) and percent gain over control are shown.

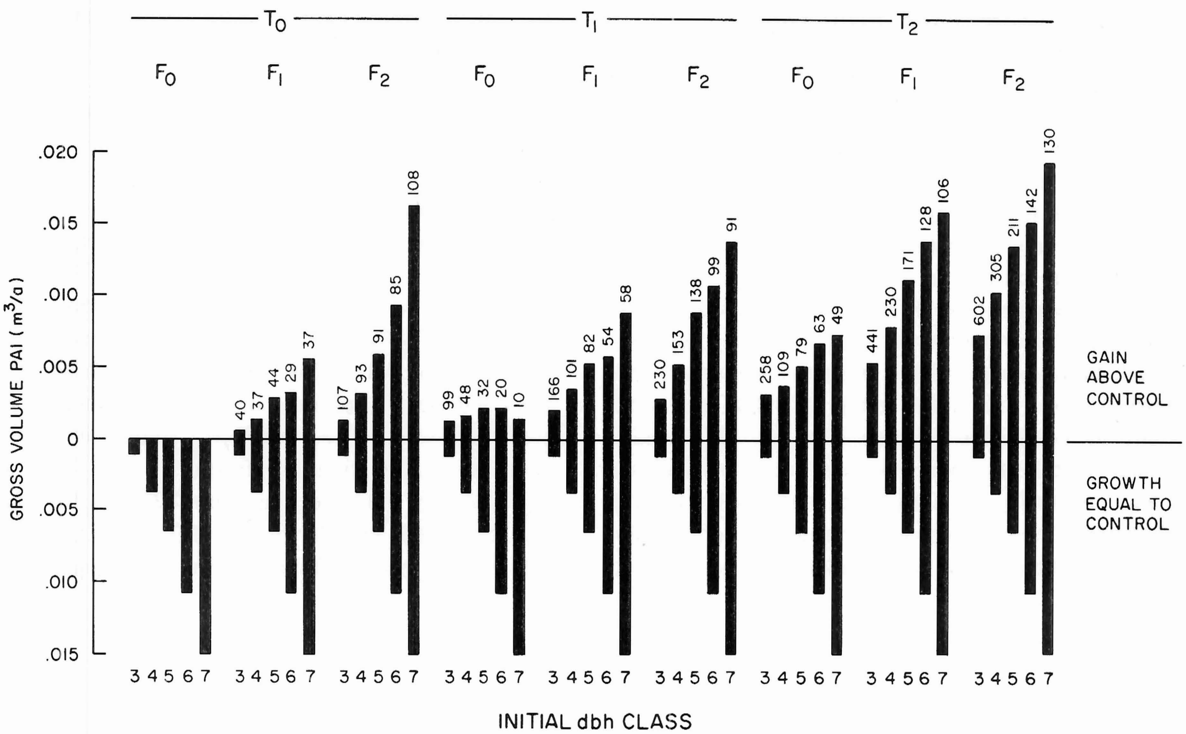


Fig. 6. Individual tree analysis for gross volume PAI (0 to 9 years) by treatment and dbh class. Actual growth (m^3/a per mean tree) and percent gain over control are shown.

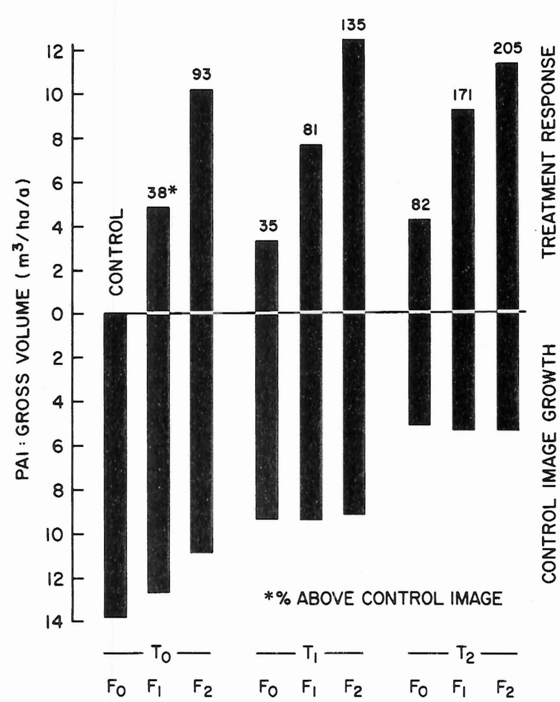


Fig. 7. Gross volume PAI (0 to 9 years) analyzed by stand structure analysis. The control images (i.e., the growth expected in the absence of treatment effects) appear below the solid line; growth above the line is taken as treatment response.

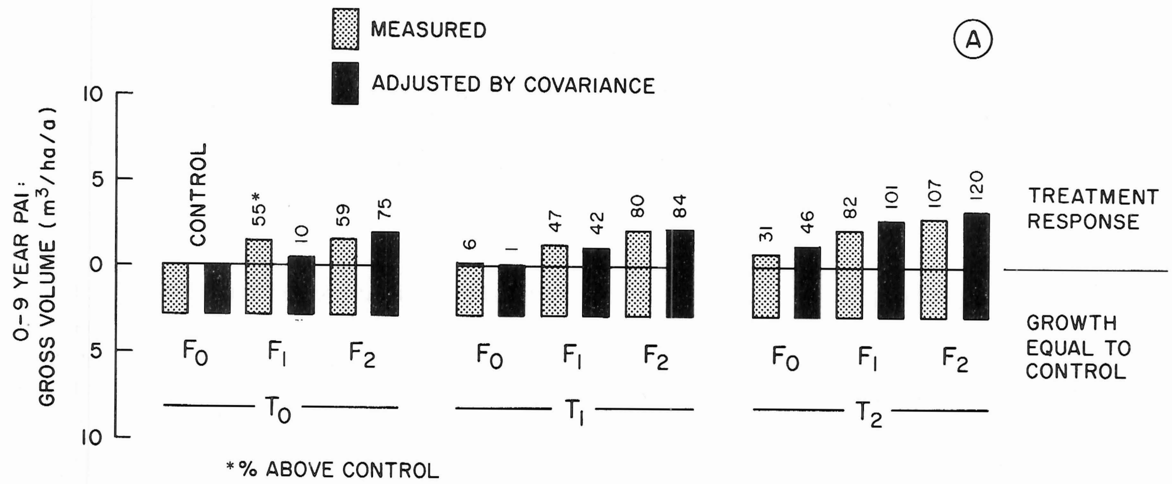
CROP TREE ANALYSIS

In the following analysis, the trees of largest initial dbh from each plot were used for calculating gross volume increments; equal numbers were used from each plot. These trees represent the largest 200 and 600 trees per hectare; they correspond to those trees which will likely constitute the final harvest and span the range of currently normal stocking levels for managed stands similar to the Shawnigan stand. The gross volume increments per plot, converted to a per hectare basis, are presented both in unadjusted and adjusted form, for differences in initial dbh and height by covariance analysis (Fig. 8). Since equal numbers of trees per plot were used here, this analysis is also in reality an individual tree analysis. The adjustments made by covariance analysis are formally similar to those made by stand structure analysis, so that one would expect similar results from the two types of analysis, and in fact they are.

The 9-year gross volume increment for the 200 largest trees per hectare increases with thinning and to a greater extent with fertilization for both the unadjusted and adjusted means (Fig. 8a); the measured (unadjusted) response for thinning (percent over control) is 6 and 31 for T_1F_0 and T_2F_0, respectively, versus the effect for fertilization of 55 and 59 for T_0F_1 and T_0F_2. The maximum response was 107 for T_2F_2. The response adjusted for initial dbh and height (percent over control) for thinning was 1 and 46 for T_1F_0 and T_2F_0, respectively, versus that for fertilization of 10 and 75 for T_0F_1 and T_0F_2. Again, the largest response, 120, was for T_2F_2. The treatment effects for the 600 largest trees (Fig. 8b) closely parallel those of the 200 largest trees.

Table 4. Relative gain over control of the 9-year Gross and Merchantable volume increments, calculated as percent over initial stocking from Tables 1 and 2.

	F_0	F_1	F_2	Mean
(a) Gross volume:				
– T_0	0	41	110	50.3
– T_1	52	107	159	106
– T_2	120	210	266	198.7
– Mean	57.3	119.3	178.3	118.3
(b) Merchantable volume:				
– T_0	0	14	154	56
– T_1	19	61	141	73.7
– T_2	76	142	183	133.7
– Mean	31.7	72.3	159.3	87.8



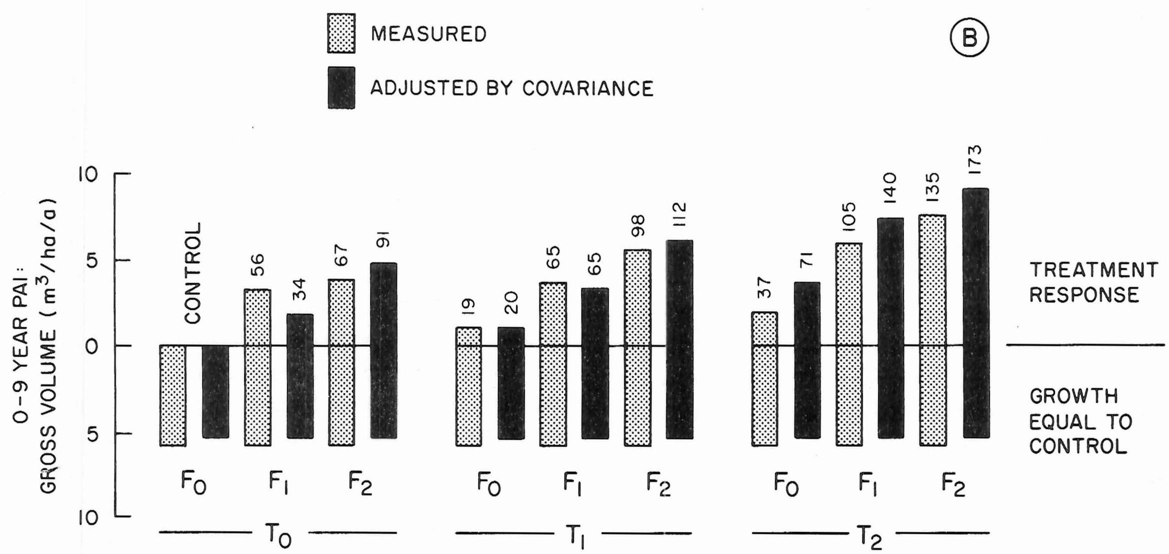


Fig. 8. Crop tree analysis—gross volume increments by treatment, unadjusted and adjusted by covariance for initial dbh. Treatment responses on an individual tree basis are graphed together with percent gain above control.

(a) 200 largest trees per hectare.

(b) 600 largest trees per hectare.

Some Effects of Treatments on Stand Structure

MORTALITY

Tree mortality for the first 9 years has been light, totalling 226 out of 3343 initially live plot trees, or 0.75% per year. Total percent mortality for the combined 1971 and 1972 plots is presented with respect to:

(a) treatment—Table A9

(b) tree size (dbh class)—Fig. 9

Three trends in the 6-year data are somewhat stronger here; mortality is increased by fertilization (in agreement with Miller and Pienaar 1973 and with Lee 1974) and decreased by thinning (Table A9) and trees of smaller dbh are more likely to die than trees of larger dbh (Fig. 9).

CROWN DEVELOPMENT

The crop trees were used in the analysis of changes of crown length and its relation to total tree height with treatment. Total tree height (H), height to live crown (HLC), and live crown length (LCL) were measured initially and at 9 years. From these, we obtain:

Live crown ratio:

$$\text{LCR} = \frac{\text{crown length}}{\text{tree height}} = \frac{\text{H} - \text{HLC}}{\text{H}}$$

Changes in LCR:

$$\Delta\ \text{LCR} = \text{LCR (9 years)} - \text{LCR (initial)}$$

Crown lift-off:

$$\Delta\ \text{HLC} = \text{HLC (9 years)} - \text{HLC (initial)}$$

These indices are shown by treatment in Table A8 for the 200 and 600 initially largest trees per hectare. Crown lift-off (ΔHLC) was relatively unaffected by fertilization but decreased markedly with thinning to about one third (for T_2) of the unthinned (T_0) condition. Live crown length increased slightly with fertilization but increased markedly with thinning, as a result of reduced crown lift-off with thinning. Live crown ratios decrease over time; the decrease is greatest for T_0 and least for T_2 but is unaffected by fertilization (Table A8). Evidently, competition for light is an important factor in unthinned plots but it greatly reduced in heavily thinned plots.

DIAMETER DISTRIBUTION

Initial and 9-year diameter distributions in 2.5 cm classes and by treatments are shown in Table A7. It is evident that differences existed initially across treatments, especially with respect to thinning; these differences were even more pronounced 9 years later, as a result of differential growth rates. In addition, the spread of the dbh distribution for each treatment has increased with time; there are more dbh classes occupied for each treatment at 9 years than initially. Also, the modes of the 9 distributions at 9 years are all lower than the corresponding modes initially; the dbh distributions become flatter and wider with time. This implies that the trees were more uniform with respect to dbh initially than at 9 years. This behavior of the distribution shapes conflicts somewhat with the behavior of the shape parameters of the Weibull distribution which have been calculated for each of the 18 distributions (Table A10). These were calculated for each distribution after eliminating all leading empty classes, since these alter both the shape and the scale parameters, unless the estimation procedure includes a location parameter (Bailey and Dell 1973). In most cases, the Weibull shape parameter (C) decreased with time for T_0 and T_1 but increased for T_2. This could have various explanations but since each of the mean and variance of the Weibull distribution depends on both the scale and shape parameters, it appears that no simple relationship exists between the shape parameter and the uniformity of the dbh distribution that it describes (Mood *et al.* 1974).

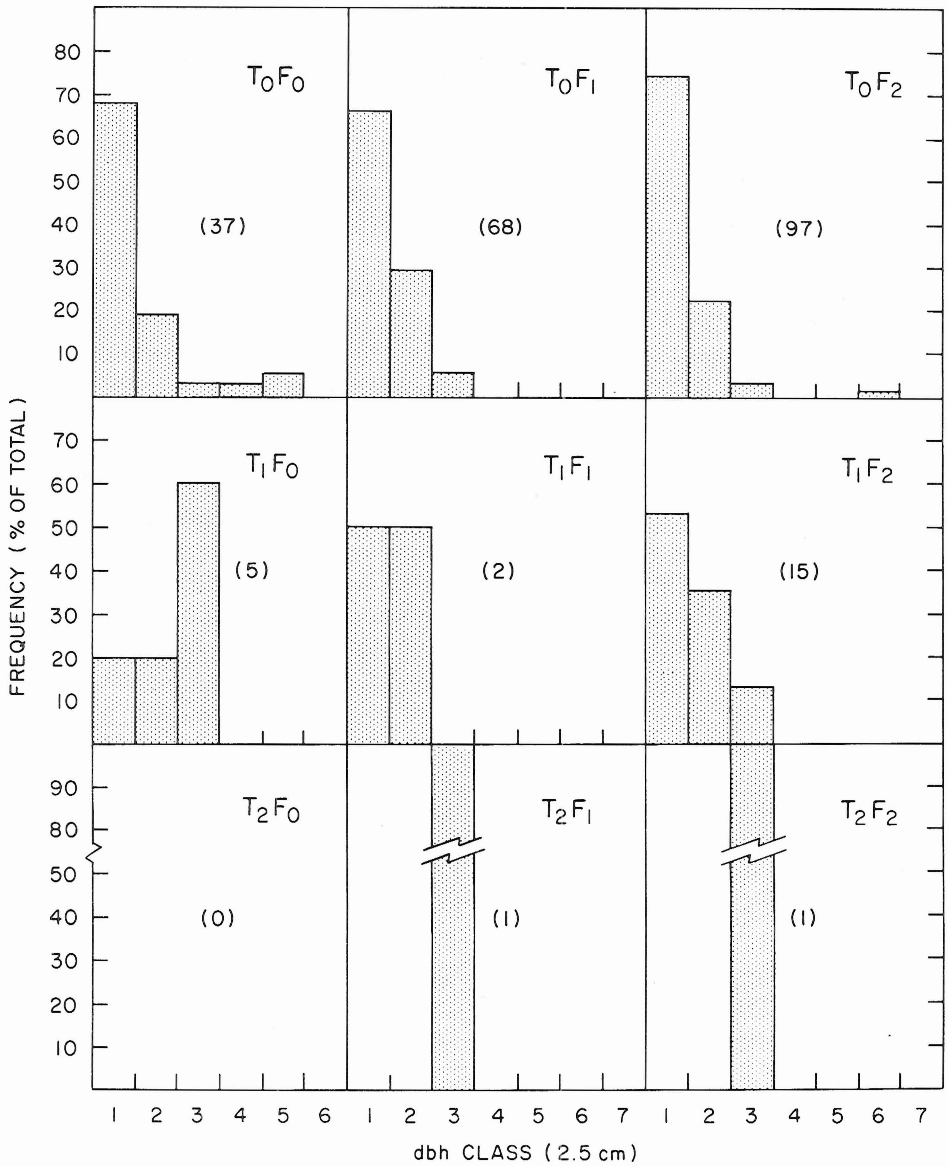


Fig. 9. Mortality graphed by treatment and dbh classes. Each bar represents the percentage of all the dead trees of a given treatment that fall within the given dbh class. The numbers in parentheses are the number of trees that died in that treatment.

Volume Tree Response

The trees used for volume determination were a subset of the plot trees and were initially chosen to be representative of the plot trees. They were chosen on the basis of initial dbh and competitive stress index (Arney 1973) with an attempt to span the range of both of these variables found at Shawnigan. The volume trees were specifically considered with respect to diameter and height CAI response in the 6-year report, as they have been measured annually since 1970. Extrapolation from the 6-year curves (Hall *et al.* 1980) suggested that the response of both diameter and height to fertilization would approach control near 12 years after treatment. Measurements taken since then have changed this picture and at first glance, they appear anomalous over time (Figs. 10 to 11). For diameter and, more drastically, height, the control group declines after year 4, reaches a low point at year 6 to 7, and then increases back towards the values of control initially. These troughs in the control graphs are coincident (within one year) with the troughs of the graphs of all the other treatments. The most plausible explanation is that a change of weather occurred around these troughs. Local weather data support this idea (Fig. 12). Since the diameter and height data consist of an amalgamation of the 1971 and 1972 trees, these have been separated in an attempt to clarify this pattern; the controls of each year are graphed over time, together with the rainfall in June (when height growth occurs in Shawnigan (Brix and Mitchell 1980)) and the total rainfall from April to July (Fig. 12). Since height growth of Douglas-fir at Shawnigan occurs over a much shorter period of time than does diameter growth (May to August inclusive), height would be expected to be more sensitive to short-term variations in rainfall, since these variations would tend to average out to some extent over an entire growing season for diameter. As Figs. 10 to 11 show, height increments have changed more drastically than diameter increments; the diameter increments for the control group in Fig. 10 decreased by about 40% from the earlier average to the 6th year after treatment, while the height increments for the control group decreased by 55% over the same period (Fig. 11). The other treatment groups show even greater fluctuations, indicating that treatment response was affected by weather patterns. Fig. 12 shows that the rainfall patterns reflect this behavior; June rainfall was lowest in 1977 (9.1 mm), while the average monthly rainfall for April to July was lowest in 1978 (27.2 mm). In both cases, however, the rainfall in 1977 differed little from that in 1978. For both the 1971 and 1972 plot data, height increments were lowest in 1977—the year with least June rainfall. Diameter increments were lowest in 1976 for 1971 plot data and in 1978 for the 1972 plot data. The reason for the low point in the 1971 data is not readily apparent from the rainfall patterns. The close conformity of the other major changes in the increments with the weather changes, however, indicates that weather must be considered in any analysis of growth responses to stand treatments. So far, this has not been done in the Shawnigan reports.

In light of the variation in control increments, changes in the treatment increments for both diameter and height were calculated as percent of control (Figs. 13 and 14). In this way, we hoped to better separate the effects of the treatments from those of weather, though interactions would still be present. The effects of the treatments on diameter increments peaked after 2 or 3 years with fertilizer and about year 6 with thinning and then decreased, while the effects of all treatments on height were considerably protracted (Figs. 13 and 14); the T_1 and T_2 plot trees kept increasing in height increments until the 7th year after treatment.

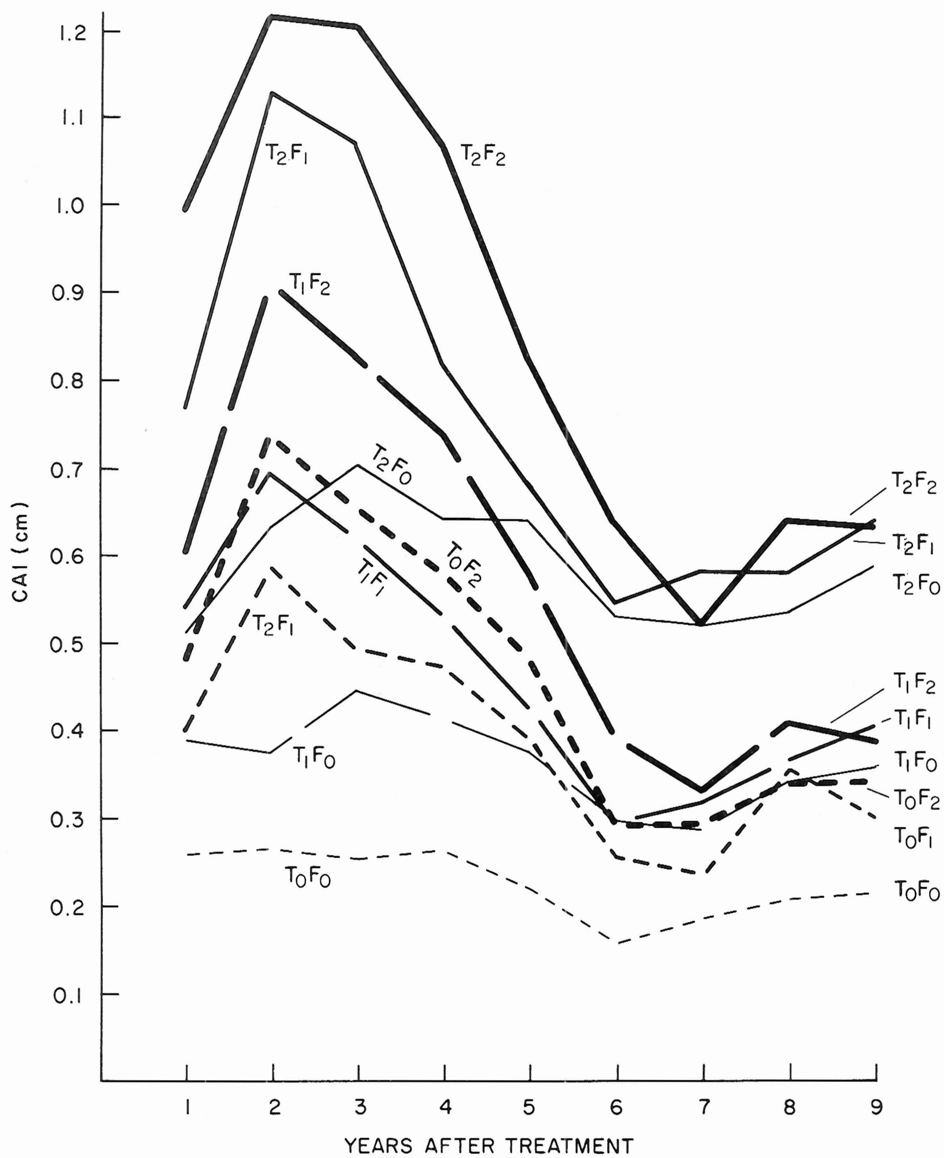


Fig. 10. CAI for diameter for all volume sample trees by treatment and time. Treatments are not adjusted for control.

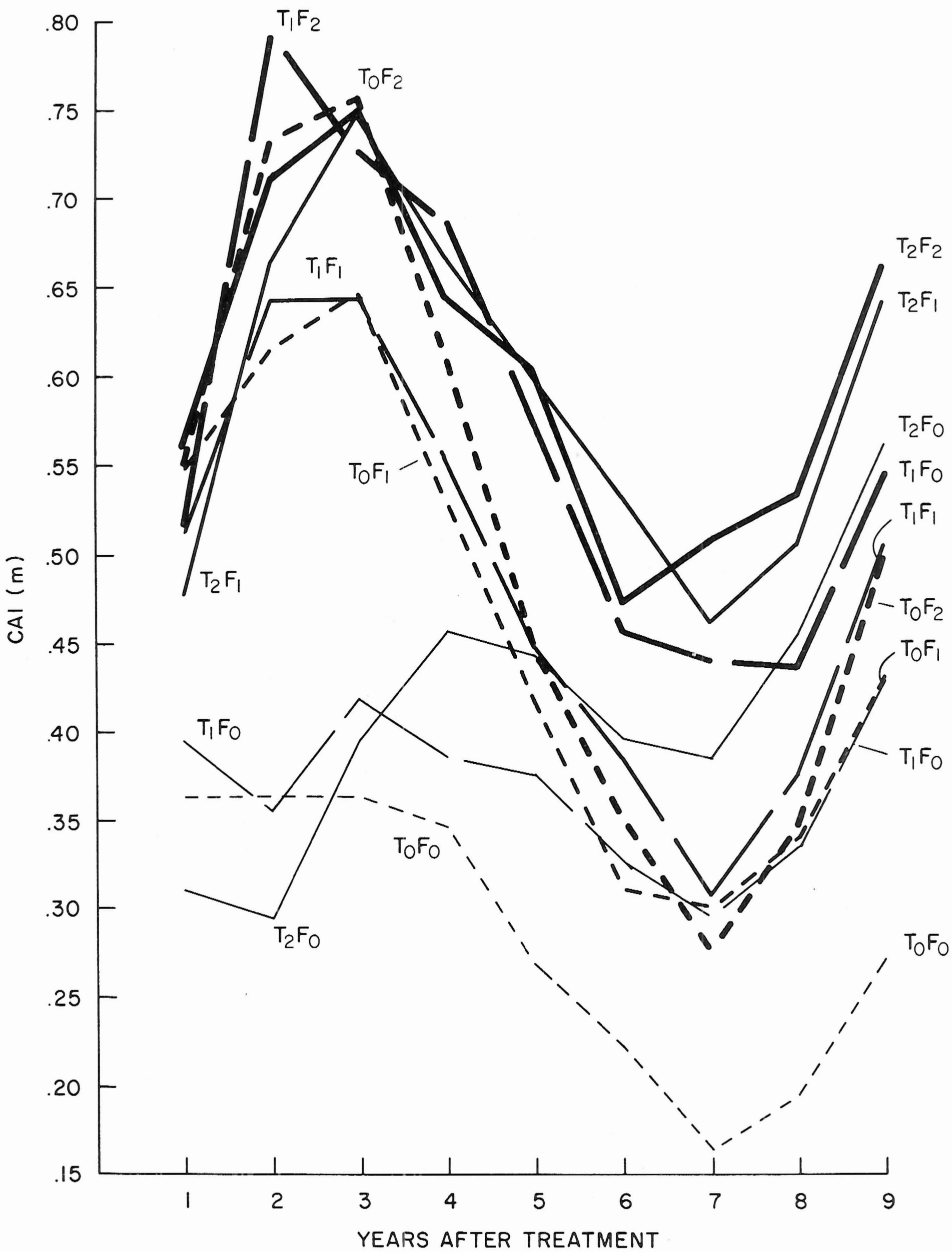


Fig. 11. CAI for height for all volume sample trees by treatment and time. Treatments are not adjusted for control.

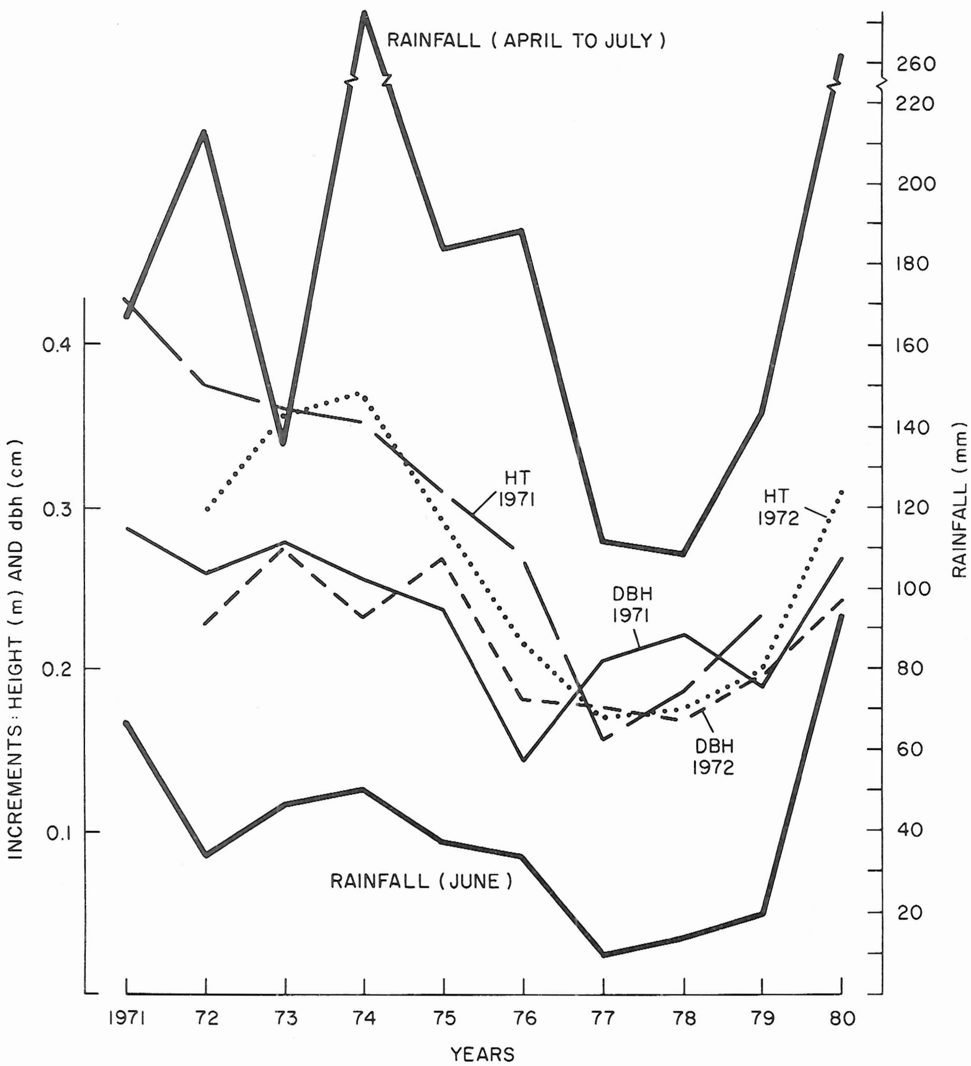


Fig. 12. Summer rainfall together with control increments for diameter and height. The 1971 and 1972 data are graphed separately.

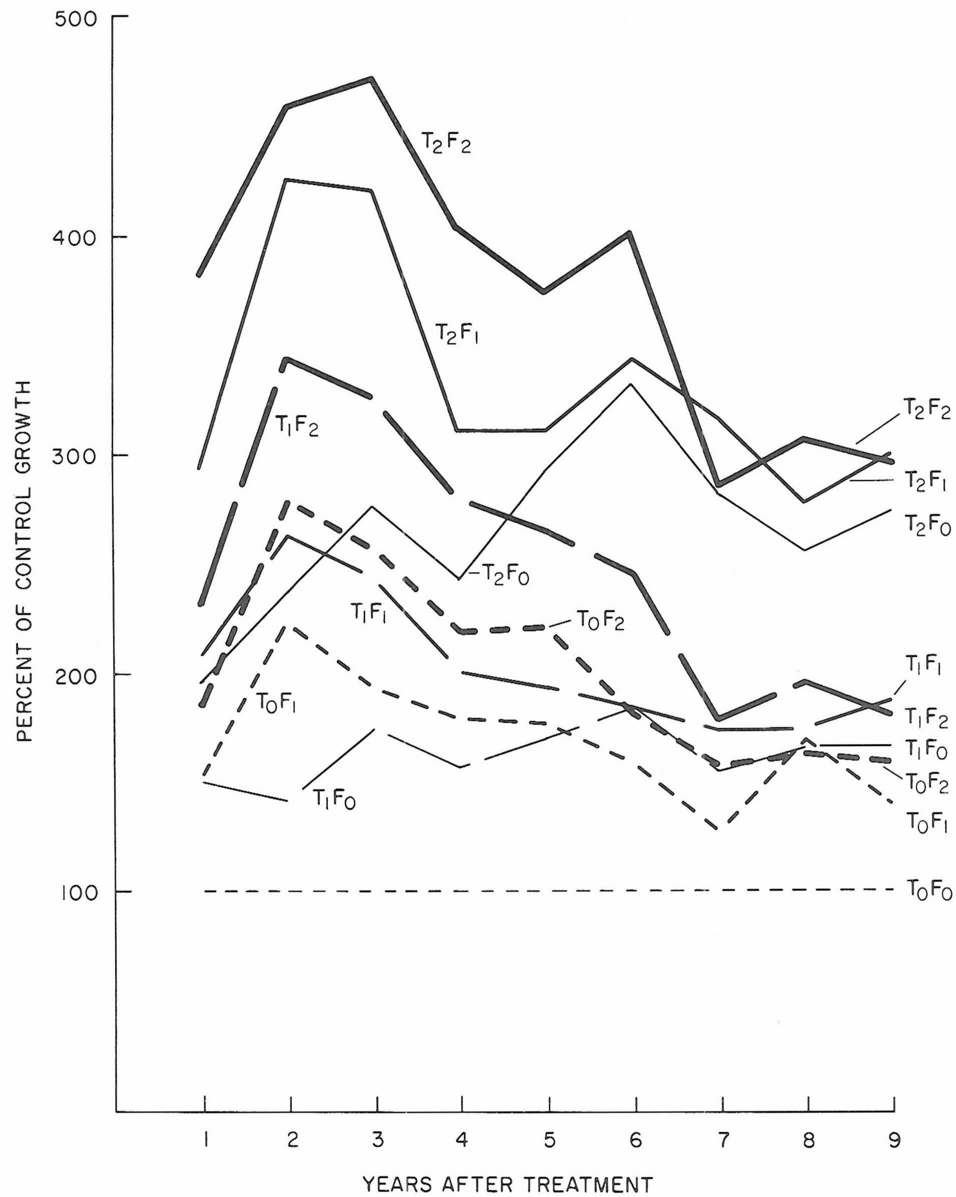


Fig. 13. CAI for diameter of the volume sample trees represented as a percentage of control CAI.

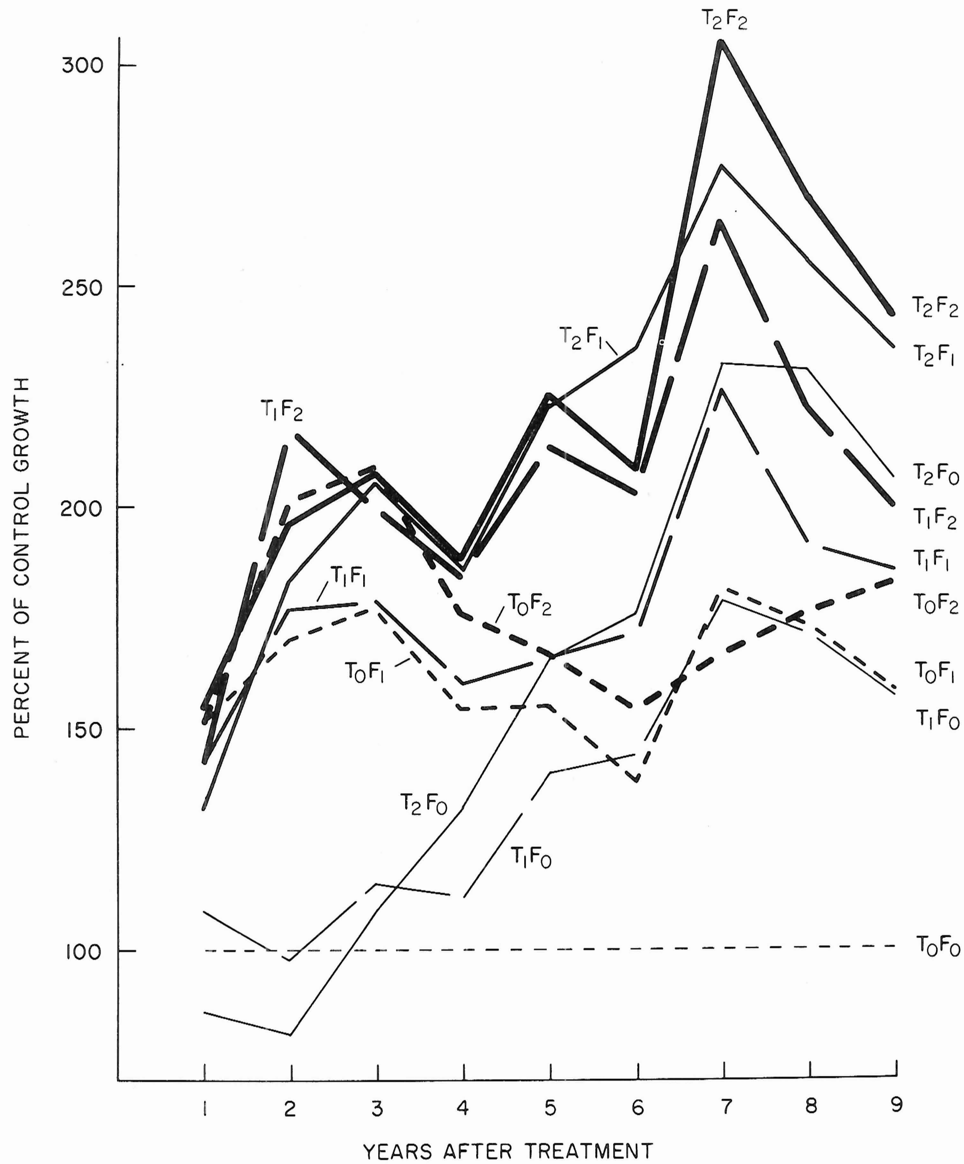


Fig. 14. CAI for height of the volume sample trees represented as a percentage of control CAI.

Conclusions

This report has described the 9-year growth response of a 24-year-old Douglas-fir stand to thinning and fertilization with urea. Four different methods of analysis were used: the response on a land area basis, individual tree analysis, stand structure analysis, and crop tree analysis. Certain of these methods are interrelated; i.e., stand structure analysis and crop tree analysis are both modified individual tree analyses but with the focus not specifically on the individual trees. As pointed out by Hall *et al.* (1980), the response to thinning may result from changes brought about by the act of thinning or by changes occurring after thinning, while the response to fertilization occurs only as a result of changes in growth after treatment.

The responses on an individual tree basis are the most fundamental since they are accomplished solely from altered physiological conditions of individual trees. The land area response consists of an accumulation of individual tree responses and also depends directly on thinning due to the removal of trees; it is thus a secondary response but is often of more interest to the forest manager. On an individual tree basis, both fertilization and thinning have increased diameter, basal area, and volume growth. Fertilization has also increased height growth but thinning caused an initial shock for 2 years and depressed total height growth for the first six years or so. By 9 years, however, the response of height to thinning was slightly positive. The positive effects of both fertilization and thinning are still evident at 9 years in all four measures.

On a land area basis, gross and merchantable volume have both increased with fertilization, and this increase appears likely to continue for some time. The response to thinning is less direct since thinning was done in such a way that the average dbh was slightly increased by thinning. In addition, the removal of trees results in a lower growing stock. Thus the response to thinning on a land area basis results in decreased gross merchantable volume and volume increments which are still evident for T_2, but not for T_1, in the 6- to 9-year period. The effects of differing initial dbh distributions are more subtle. The stand structure and crop tree analyses using covariance attempt to remove the confounding introduced between inital dbh and treatment. When the degree of heterogeneity of dbh distributions over treatments is relatively small, then both techniques will yield valid results. Two factors, however, reduce the validity of these two techniques for this type of analysis, if heterogeneity of initial dbh distributions across treatments is great: (a) covariance analysis is very sensitive to departures from homogeneity of the covariate across treatments (Kirk 1968) and (b) the number of dbh classes common to all treatments will be considerably reduced for the stand structure analysis and thus these common classes will not be representative of any given treatment. For some treatments (i.e., thinned), they constitute the smaller trees, while for other treatments (i.e., unthinned), they constitute the larger trees. Thus, competitive relationships become confounded with dbh class. In the Shawnigan experiment, it is unlikely that either of these objections will be important since initial (after thinning) heterogeneity of the dbh classes across treatments was slight (Table A7).

The major advantages of thinning appear to be: (a) the production of larger trees and (b) the reduction of the rotation period until harvest. These responses are compatible with long-term objectives and their effects are expected to last longer than those of fertilization for diameter and volume. On the other hand, fertilization provides a quick response but probably not a long-lasting one. Any conclusions regarding the length of time of the responses, based on the Shawnigan data, are premature in view of the recent increase in height responses apparently as a result of weather changes. At this point, it would appear useful to incorporate weather data into the analyses of future responses.

LITERATURE CITED

Anon. 1975. State Univ., Seattle, Wash. College of For. Res., Regional Forest Nutrition Research Project. Biennial Report 1972-1974, 39 pp.

Arney, J.D. 1973. Tables for quantifying competitive stress on individual trees. Can. For. Serv., Pac. For. Res. Cent., Inf. Rep. BC-X-78, 15 pp.

Bailey, R.L. and T.R. Dell. 1973. Quantifying diameter distributions with the Weibull function. For. Sci. 19:97-104.

Brix, H. and A.V. Mitchell. 1980. Effects of thinning and nitrogen fertilization on xylem development in Douglas-fir. Can. J. For. Res. 10:121-128.

Browne, J.E. 1962. Standard cubic-foot volume tables for the commercial tree species of B.C., B.C. For. Serv., Forest Surveys and Inventory Div., 107 pp.

Crown, M. and C.P. Brett. 1975. Fertilization and thinning effects on a Douglas-fir ecosystem at Shawnigan Lake: an establishment report. Can. For. Serv., Pac. For. Res. Cent., Inf. Rep. BC-X-110, 45 pp.

Crown, M., R.V. Quenet, and C.R. Layton. 1977. Fertilization and thinning effects on a Douglas-fir ecosystem at Shawnigan Lake: 3-year growth response. Can. For. Serv., Pac. For. Res. Cent., Inf. Rep. BC-X-152, 36 pp.

Hall, T.H., R.V. Quenet, C.R. Layton, and R.J. Robertson. 1980. Fertilization and thinning effects on a Douglas-fir ecosystem: 6-year growth response. Can. For. Serv., Pac. For. Res. Cent., Inf. Rep. BC-X-202, 31 pp.

Husch, B., C.I. Miller, and T.W. Beers. 1972. Forest Mensuration. Ronald Press Co., N.Y., 410 pp.

Kirk, R.E. 1968. Experimental Design: Procedures for the Behavioral sciences. Brooks-Cole, Belmont, California, 577 pp.

Lee, Y.J. 1974. Four-year basal area growth response of a 25-year-old Douglas-fir stand to thinning and urea fertilization. Can. J. For. Res. 4:568-571.

Miller, R.E. and L.V. Pienaar. 1973. Seven-year response of 35-year-old Douglas-fir to nitrogen fertilizer. USDA For. Serv., Pac. Nor. For. Range Exp. Stn., Portland, Oregon. Res. Paper PNW-165, 24 pp.

Miller, R.E. and S.R. Webster. 1979. Fertilizer response in mature stands of Douglas-fir. *In* Proc. For. Fertil. Cont. (S.P. Gessel, R.M. Kenady, and W.A. Atkinson, eds.) Union, Wash., Sept. 25-27, 1979. Univ. Wash., Coll. Fer. Resources, Inst. For. Res., Cont. No. 40, pp. 126-132.

Mood, A.M., F.A. Graybill, and D.C. Boes. 1974. Introduction to the Theory of Statistics. McGraw-Hill, N.Y., 564 pp.

Table A1. Form quotients at different stem heights for the 9 treatments. Each form quotient is the diameter at that height divided by dbh.

Treatment	% of Total Height Above Breast Height				
	10	30	50	70	90
T_0F_0	93.2	80.6	64.0	38.8	13.0
T_0F_1	93.1	79.9	63.1	38.2	12.8
T_0F_2	93.3	81.1	63.2	38.0	12.7
T_1F_0	93.0	80.6	63.2	38.1	12.7
T_1F_1	92.9	80.3	61.1	37.4	12.5
T_1F_2	93.1	80.9	62.7	37.7	12.6
T_2F_0	92.7	80.1	61.9	37.2	12.4
T_2F_1	89.9	77.8	60.3	36.3	12.1
T_2F_2	92.3	79.3	61.1	36.7	12.2
Thinning*	>0.05	<0.05	<0.01	<0.01	<0.01
Fertilization*	>0.05	>0.05	>0.05	>0.05	>0.05

* These numbers are probabilities obtained from analysis of variance which test for differences in form quotients resulting from each treatment.

Table A2. Volume equation coefficients by treatment for $\log(V) = a_1 + a_2 \log(D) + a_3 \log(H)$.

Treatment	Regression Coefficients				
	a_1	a_2	a_3	R^2	SEE
T_0F_0	–4.19250	1.98176	0.84475	0.996	0.043
T_0F_1	–3.73647	0.90851	0.87408	0.997	0.033
T_0F_2	–3.75575	2.41669	0.03804	0.996	0.038
T_1F_0	–4.51040	1.51688	1.59692	0.990	0.046
T_1F_1	–4.25441	1.83665	1.03941	0.997	0.023
T_1F_2	–4.42212	1.88198	1.13413	0.986	0.052
T_2F_0	–3.98343	1.94962	0.70757	0.986	0.029
T_2F_1	–3.55880	2.16555	0.13521	0.966	0.047
T_2F_2	–4.28230	1.78500	1.12813	0.988	0.025

Table A3. Analysis of variance for diameter increments by treatments and initial dbh class (D).

Source	DF	MS	F	P	
T	2	4.913	621.976	0.000	***
F	2	3.768	477.039	0.000	***
D	4	4.982	630.757	0.000	***
TxF	4	0.048	6.137	0.000	***
TxD	8	0.016	2.097	0.033	*
FxD	8	0.061	7.800	0.000	***
TxFxD	16	0.009	1.127	0.323	NS
Error	2732	0.008			

Two-way tables of means (cm):

	Fertilization		
	F_0	F_1	F_2
T_0	0.23	0.32	0.43
T_1	0.37	0.48	0.58
T_2	0.56	0.73	0.87

	dbh				
	1	2	3	4	5
T_0	0.16	0.31	0.43	0.53	0.67
T_1	0.30	0.44	0.55	0.63	0.71
T_2	0.55	0.62	0.76	0.85	0.97
F_0	0.15	0.30	0.41	0.52	0.57
F_1	0.21	0.38	0.55	0.65	0.71
F_2	0.30	0.51	0.69	0.81	0.93

Table A4. Analysis of variance for basal area increments by treatments and initial dbh class (D).

Source	DF	MS $\times 10^{-4}$	F	P	
T	2	0.3167	627.773	0.000	***
F	2	0.2868	568.546	0.000	***
D	4	0.8412	1667.401	0.000	***
TxF	4	0.0044	8.703	0.000	***
TxD	8	0.0043	8.483	0.000	***
FxD	8	0.0139	27.630	0.000	***
TxFxD	16	0.0006	1.232	0.234	NS
Error	2732	0.0005			

Two-way tables of means ($m^2 \times 10^{-2}$)

	Fertilization		
	F_0	F_1	F_2
T_0	0.04	0.06	0.08
T_1	0.07	0.10	0.12
T_2	0.17	0.16	0.21

	dbh				
	1	2	3	4	5
T_0	0.02	0.05	0.09	0.13	0.20
T_1	0.04	0.07	0.12	0.16	0.22
T_2	0.08	0.12	0.17	0.23	0.31
F_0	0.02	0.05	0.08	0.13	0.17
F_1	0.03	0.06	0.12	0.17	0.21
F_2	0.04	0.09	0.16	0.22	0.30

Table A5. Analysis of variance for height increments by treatments and initial dbh class (D).

Source	DF	MS	F	P	
T	2	0.299	52.177	0.000	***
F	2	2.335	407.382	0.000	***
D	4	0.371	64.714	0.000	***
TxF	4	0.007	1.311	0.263	NS
TxD	8	0.045	7.859	0.000	***
FxD	8	0.020	3.491	0.000	***
TxFxD	16	0.008	1.510	0.087	NS
Error	2732	0.006			

Two-way tables of means (m):

	dbh				
	1	2	3	4	5
T_0	0.34	0.45	0.48	0.49	0.54
T_1	0.42	0.49	0.51	0.53	0.56
T_2	0.56	0.48	0.54	0.56	0.58
F_0	0.28	0.36	0.39	0.43	0.42
F_1	0.39	0.48	0.54	0.55	0.60
F_2	0.48	0.57	0.60	0.60	0.61

Table A6. Analysis of variance for volume increments by treatments and initial dbh class (D).

Source	DF	MS	F $\times 10^{-2}$	P	
T	2	0.215	417.702	0.000	***
F	2	0.301	585.329	0.000	***
D	4	1.008	1960.663	0.000	***
TxF	4	0.004	8.809	0.000	***
TxD	8	0.004	7.513	0.000	***
FxD	8	0.018	36.511	0.000	***
TxFxD	16	0.001	3.280	0.000	***
Error	2732	0.001			

Two-way tables of means ($m^3 \times 10^{-1}$):

	Fertilization		
	F_0	F_1	F_2
T_0	0.04	0.06	0.08
T_1	0.07	0.10	0.12
T_2	0.11	0.16	0.19

	dbh				
	1	2	3	4	5
T_0	0.02	0.05	0.09	0.14	0.23
T_1	0.03	0.07	0.12	0.17	0.23
T_2	0.07	0.10	0.17	0.23	0.31
F_0	0.02	0.04	0.08	0.13	0.18
F_1	0.02	0.06	0.12	0.17	0.23
F_2	0.03	0.08	0.15	0.23	0.32

Table A7(a). Treatment versus 2.5 cm diameter class table: Initial diameter distribution (numbers per hectare).

Diam. Class	T_0			T_1			T_2		
	F_0	F_1	F_2	F_0	F_1	F_2	F_0	F_1	F_2
1	519.80	148.51	136.14	55.69	18.56	37.13	0.00	0.00	0.00
2	1219.06	668.32	730.20	340.35	327.97	303.22	24.75	61.88	68.07
3	1330.44	1027.23	1126.24	649.74	600.25	761.14	383.66	278.47	284.65
4	823.02	754.95	655.94	625.00	587.87	594.06	327.97	414.60	352.72
5	204.21	235.15	117.57	191.83	216.58	160.89	129.95	129.95	117.57
6	18.56	61.88	43.32	43.32	55.69	43.32	18.56	18.56	55.69
7	12.38	43.32	0.00	6.19	0.00	12.38	12.38	0.00	0.00
8	0.00	12.38	0.00	0.00	0.00	0.00	0.00	6.19	0.00
9	6.19	6.19	0.00	6.19	6.19	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	4133.66	2957.92	2809.40	1918.32	1813.12	1912.13	897.28	909.65	878.71

Table A7(b). Treatment versus 2.5 cm diameter class table: 9-year diameter distribution (numbers per hectare).

Diam. Class	T_0			T_1			T_2		
	F_0	F_1	F_2	F_0	F_1	F_2	F_0	F_1	F_2
1	377.48	92.82	18.56	0.00	0.00	0.00	0.00	0.00	0.00
2	792.08	346.53	297.03	99.01	80.45	43.32	0.00	0.00	0.00
3	928.22	556.93	507.43	290.84	173.27	142.33	6.19	6.19	6.19
4	928.22	680.69	649.75	495.05	383.66	340.35	129.95	74.26	24.75
5	705.45	606.44	581.68	495.05	402.23	451.73	272.28	185.64	99.01
6	272.28	358.91	501.24	321.78	377.48	426.98	278.47	222.77	210.40
7	105.20	167.08	179.46	154.70	272.28	346.53	142.33	259.90	235.15
8	6.19	74.26	43.32	49.50	86.63	111.39	37.13	92.82	210.40
9	12.38	37.13	18.56	6.19	30.94	24.75	24.75	61.88	61.88
10	0.00	24.75	12.38	0.00	0.00	18.56	6.19	0.00	24.75
11	0.00	6.19	0.00	6.19	0.00	6.19	0.00	6.19	6.19
12	6.19	6.19	0.00	0.00	6.19	0.00	0.00	0.00	0.00
Total	4133.66	2957.92	2809.41	1918.32	1813.12	1912.13	897.28	909.65	878.71

Table A8. Height to Live Crown (HLC), Live Crown Ratio (LCR), and Live Crown Length (LCL) (initial, at year 9, and increment) by treatment for the 200 and 600 initially largest trees per hectare.

		600 Largest			200 Largest		
		F_0	F_1	F_2	F_0	F_1	F_2
HLC (m)							
– initial	– T_0	2.8	2.5	2.2	2.6	2.4	2.2
	– T_1	2.6	2.4	2.6	2.5	2.2	2.3
	– T_2	2.3	2.3	2.2	2.1	2.1	2.1
– 9-year	– T_0	6.9	7.1	6.5	6.7	7.0	6.1
	– T_1	5.9	5.8	6.5	5.7	5.6	6.5
	– T_2	3.5	4.0	3.7	3.3	4.0	3.7
– Δ	– T_0	4.1	4.6	4.3	4.1	4.6	3.9
	– T_1	3.3	3.4	3.9	3.2	3.4	4.2
	– T_2	1.2	1.7	1.5	1.2	1.9	1.6
LCR							
– initial	– T_0	0.75	0.79	0.79	0.79	0.82	0.81
	– T_1	0.78	0.79	0.77	0.80	0.82	0.81
	– T_2	0.78	0.78	0.79	0.82	0.82	0.82
– 9-year	– T_0	0.54	0.57	0.59	0.59	0.61	0.63
	– T_1	0.61	0.64	0.62	0.64	0.67	0.63
	– T_2	0.75	0.75	0.77	0.79	0.77	0.78
– Δ	– T_0	–0.21	–0.22	–0.20	–0.20	–0.21	–0.18
	– T_1	–0.17	–0.15	–0.15	–0.16	–0.15	–0.18
	– T_2	–0.03	–0.03	–0.02	–0.03	–0.05	–0.04
LCL							
– initial	– T_0	8.8	9.4	8.5	9.8	10.6	9.3
	– T_1	8.9	9.1	8.9	9.8	9.9	9.8
	– T_2	8.3	8.6	8.3	9.4	9.7	9.4
– 9-year	– T_0	8.2	9.6	9.5	9.5	10.8	10.6
	– T_1	9.4	10.6	10.4	10.5	11.5	11.1
	– T_2	10.7	12.2	12.5	12.2	13.4	13.3
– Δ	– T_0	–0.6	0.2	1.0	–0.3	0.2	1.3
	– T_1	0.5	1.5	1.5	0.7	1.6	1.3
	– T_2	2.4	3.6	4.2	2.8	3.7	3.9

Table A9. Tree mortality by treatment for the combined 1971 and 1972 plots over the 9-year treatment period.

	F_0		F_1		F_2	
	%	No.	%	No.	%	No.
T_0	4.7	(37)	11.6	(68)	16.6	(97)
T_1	1.6	(5)	0.7	(2)	4.5	(15)
T_2	0.0	(0)	0.7	(1)	0.7	(1)

Table A10. Weibull shape parameters for initial and final dbh distributions by treatments.

	Initial	Final
T_0		
$- F_0$	2.11	2.01
$- F_1$	2.32	2.24
$- F_2$	2.69	2.70
T_1		
$- F_0$	2.75	2.32
$- F_1$	2.88	2.42
$- F_2$	2.99	2.71
T_2		
$- F_0$	2.61	2.77
$- F_1$	2.58	2.98
$- F_2$	2.46	3.49