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

6 YEAR GROWTH RESPONSE

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ABSTRACT

Tree and stand growth response to thinning and nitrogen (urea) fertilization of a 24-year-old Douglas-fir stand near Shawnigan Lake, B.C. is examined. Site specific growth response is reported in four ways: land area basis, individual tree basis, stand structure analysis, and crop tree analysis.

Fertilization alone and thinning, when accompanied by sufficient fertilization have, 6 years after treatment, increased standing volume (m^3/ha) and volume increment on a land area basis ($m^3/ha/a$). However, standing volume and volume increment on a land area basis at 6 years are still below control for thinning alone and thinning when not accompanied by sufficient fertilization. This follows from the effects of removing growing stock at the time of thinning. For all levels and combinations of thinning and fertilization that were applied, volume and diameter growth of the remaining trees have been increased over control.

Six-year gross volume increments (as % above control) of the 200 initially largest trees/ha are 20, 51 and 110 for heavy thinning alone, heavy fertilization alone and heavy thinning plus heavy fertilization, respectively. These volume increments, if adjusted by covariance analysis for differences in initial stocking and tree size distributions become 47, 76 and 139, respectively. Six-year mean stand diameter increments (as % above control) for all residual trees are, for these same treatments, 134, 205 and 362, respectively.

Based on volume growth of the remaining trees, thinning and fertilization still exhibit at 6 years a positive treatment interaction as was observed at 3 years. Growth response at 6 years is qualitatively similar to the response at 3 years. However, on a land area basis or on an individual tree basis, response, measured as gross volume periodic annual increment (PAI) in the first measurement period (0 to 3 years) and the second measurement period (3 to 6 years), is still increasing for thinning alone, but is tapering off and converging to control for fertilization alone and fertilization and thinning in combination.

Effects of treatment on tree mortality, crown development and diameter distribution are investigated. Probability of mortality is higher for the smaller more-suppressed trees and is increased by fertilization but decreased by thinning. Crown lift-off is reduced by thinning but, for a given level of thinning, is large-

ly unaffected by fertilization. All treatments have decreased the dispersion in the distribution of tree sizes, suggesting that thinning (as carried out here) and fertilization, alone or in combination, produce a more uniform stand in addition to exerting a direct effect on increment.

Stem form (form quotient) has not been significantly affected by treatment. However, height and diameter have shown characteristically different responses, indicating that height/diameter relations bear a complex relation to thinning and fertilization. In an attempt to illustrate a variety of characteristics and trends in growth response, response is shown by contour representations of response surfaces for a variety of indicators or measures of response.

RÉSUMÉ

Les auteurs examinent l'effet produit par une éclaircie et par la fertilisation à l'azote (urée), sur la croissance des arbres et d'un peuplement de Douglas taxifoliés âgés de 24 ans près de Shawnigan Lake, en C.-B. La réaction de croissance spécifique d'une station est notée de quatre façons: sur la base de superficie du terrain, sur la base des arbres pris isolément, d'après l'analyse de la structure du peuplement et d'après l'analyse de la production ligneuse.

La fertilisation seule, de même que l'éclaircie accompagnée d'une fertilisation suffisante, ont provoqué, 6 ans après l'accroissement du volume sur pied (m^3/ha) et amélioré l'accroissement de volume fondé sur la superficie du terrain ($m^3/ha/a$). Cependant le volume du matériel sur pied et l'accroissement de volume fondé sur la superficie du terrain aux 6 ans sont encore sous observation tant pour l'éclaircie seule que pour l'éclaircie non accompagnée de fertilisation suffisante. Cela résulte des effets de l'enlèvement de matériel sur pied au moment de l'éclaircie. A tous les niveaux et dans toutes les combinaisons d'éclaircie et de fertilisation appliqués, l'accroissement en volume et en diamètre des arbres résiduels a augmenté par rapport aux témoins.

Les accroissements du volume brut après 6 ans (en % au-dessus des témoins) des 200 arbres les plus grands au départ/ha, sont de 20, 51 et 110 lors d'une importante éclaircie seule, d'une forte fertilisation seule et d'une importante éclaircie accompagnée d'une forte fertilisation, respectivement. Ces accroissements de volume, si on les corrige par l'analyse de

covariance en raison des différences de densité initiale et de la distribution des tailles des arbres, deviennent 47, 76 et 139 respectivement. Les accroissements en diamètre dans le peuplement après 6 ans (en % au-dessus des témoins) chez tous les arbres résiduels sont, avec ces mêmes traitements, de 134, 205 et 362, respectivement.

Sur la base de l'accroissement en volume des arbres résiduels, l'éclaircie et la fertilisation présentent encore, après 6 ans, une interaction positive semblable à celle observée après 3 ans. La réaction de croissance après 6 ans s'avère qualitativement similaire à celle observée après 3 ans. Cependant, sur la base de la superficie du terrain et sur la base des arbres pris isolément, la réaction, mesurée en termes d'accroissement périodique annuel (APA) durant la première période de mesurage (0 à 3 ans) et la seconde, (3 à 6 ans), augmente encore avec l'éclaircie seule, mais décline et converge vers les témoins lors d'une fertilisation seule et d'une fertilisation combinée à une éclaircie.

Les effets des traitements sur la mortalité des arbres, sur le développement de la cime et sur le

diamètre font l'objet d'une étude. La probabilité de mortalité est plus forte chez les petits arbres, plus étouffés, et elle augmente avec la fertilisation mais diminue avec l'éclaircie. Le "soulèvement" des cimes est réduit par l'éclaircie mais, pour un niveau donné d'éclaircie, est très peu affecté par la fertilisation. Tous les traitements ont réduit la dispersion de la distribution des tailles d'arbres, ce qui suppose que l'éclaircie (telle qu'effectuée ici), et la fertilisation, seule ou combinée, produisent un peuplement plus uniforme en outre d'exercer une influence directe sur l'accroissement.

La forme de la tige (coefficient de décroissance) n'a pas été significativement affectée par le traitement. Cependant, la hauteur et le diamètre ont accusé des réactions caractéristiquement différentes, indiquant que les rapports hauteur/diamètre sont assujettis à une relation complexe avec l'éclaircie et la fertilisation. Pour essayer d'illustrer une variété de caractéristiques et de tendances aux réactions de croissance, la réaction est indiquée par des représentations du périmètre des aires de réaction pour toute une gamme d'indicateurs ou de mesures de la réaction.

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1.0 INTRODUCTION

Thinning and nitrogen fertilization of Pacific Northwest second growth Douglas-fir are being increasingly used as management practices to increase yields and to shorten the time for these immature trees to grow to merchantable sizes. Implementation of these practices, however, is made difficult by:

- 1) The inherent uncertainty, from an operations and future products standpoint, in how to manage stands for their possible developments over time of total land area yield (mean annual increment, MAI), piece size (mean stand diameter) and various tree characteristics (stem taper, number and size of branches, etc.). This, in turn, means inherent uncertainty in knowing what specific tree and stand responses to regard as feasible or optimal.
- 2) The inherent site - stand - treatment specific nature of tree and stand growth response to thinning and fertilization. This variability of growth response, in conjunction with the difficulties in specifying a most desired response, thwarts attempts to document growth response for all or even an adequate sample of management situations.
- 3) The long duration of the growth response and, consequently, the incomplete coverage of the response by current installation measurements. In contrast to the 1-year response period enjoyed by agricultural crop managers, forest managers have long had to contend with crop response periods which can be longer than the period of constancy or applicability of the management objectives which initiated the management practice. Where treatment is considered to remain effective for a definite period of time, response periods have been observed to be up to about 10 years for nitrogen fertilization (Leaf 1974), and longer still for the many spacing and thinning trials that have been carried out. Where treatment is viewed as a systems disturbance that initiates (in theory if not in practice) permanently different developments for the treated and untreated stand, the response period is then the period between treatment and harvest; a period that can range from a few years to many decades.

Formulation of operational thinning and fertilization guidelines, therefore, requires procedures to extrapolate, generalize and synthesize information derived from current sets of direct observations. Formulation of these guidelines can benefit from both an improved data base

and an improved framework of understanding of tree and stand response to thinning and nitrogen fertilization.

This report is based on measurements of 6 years of growth response to thinning and nitrogen (urea) fertilization of a 24-year-old, burned (1924), salvage logged (1927), reburned (1942) and planted (1948) Douglas-fir stand on a poor site (site index 21 m at 50 years, B.C. Min. of For., 1970, unpublished graphs) near Shawnigan Lake, B.C. Nine treatments were carried out as a 3 x 3 completely randomized factorial design, consisting of three levels of fertilization (F₀ - no fertilization, F₁ - 224 kg N/ha and F₂ - 448 kg N/ha) for each of three levels of thinning (T₀ - no thinning, T₁ - 1/3 basal area removed and T₂ - 2/3 basal area removed). Each treatment was carried out on two plots (0.1 acre = 0.0405 ha, surrounded by an 18 m buffer strip) in each of two successive years (1971 and 1972) for a total of four replications per treatment. Details of the site, experimental design and multidisciplinary nature of the project are described in the project's establishment report (Crown *et al.* 1975). Details of the tree-growth data base are described in the project's first measurement of growth response at 3 years (Crown *et al.* 1977). The 3-year report largely refrained from extrapolating response or examining effects of treatment on stand structure and future stand development, concentrating instead on developing methodology of reporting growth response.

This report:

- 1) gives 6-year growth response, following closely the methodology set out in the 3-year report in order to maintain continuity, and
- 2) discusses, from the vantage point of a longer response period, some characteristics of response and some effects of treatment on tree mortality, crown development and stand structure (distribution of tree sizes).

2.0 PRELIMINARY ANALYSES

The tree growth data base, including plot layout, kind and frequency of measurements and treatments is described in the 3-year report. As explained there, measurements include two distinct strategies:

- 1) a plot basis where, mostly at 3-year intervals, dbh, height, height to live crown and plot coordinants of all plot and some buffer trees were measured to evaluate initial plot conditions and to monitor changes at fixed time intervals

- through the course of the experiment, and
- 2) an individual tree basis where, at 1-year intervals, for a set of 464 trees called volume sample trees, dbh, height and upper stem diameters at selected taper steps were measured to provide yearly trends in increment, estimates of tree volume and stem form changes and to provide a data base for related investigations. These volume sample trees were selected 3 years after plot establishment according to a four-level stratification scheme based on level of fertilization, dbh, competitive position in the stand as defined by a Competitive Stress Index or CSI (Arney 1973) and change in CSI.

Differences between 6-year response for the 1971 and 1972 plots were not significant and, as was done at 3 years, data were again pooled to give nine treatments (3 levels of fertilization for each of 3 levels of thinning) each with four replications.

2.1 STEM FORM

Taper measurements, of the volume sample trees at 6 years, provided the data base for analysis of stem form. By using absolute form quotient (Husch *et al.* 1972) as a measure of stem form, analysis of

variance and multiple range tests (Newman 1939) showed no significant differences (to the 5% level) in form quotient among the nine treatments. On this basis, a single volume equation was derived for all subsequent volume calculations.

2.2 VOLUME EQUATION

A new local volume equation, determined similarly as for the 3-year analysis (Crown *et al.* 1977), but based upon the volume sample trees at 6 years in addition to 105 trees originally selected for this purpose, was derived for this analysis. The new volume equation is:

$$\log V = -4.21248 + 1.95836 \log (D) + 0.882447 \log (H)$$

where V = gross volume in m^3

D = dbh in cm

H = total height in m

with $R^2 = 0.998$ SEE = $9.31 \times 10^{-4} m^3$.

This new equation has been used to recalculate all volumes (0, 3 and 6 year). Hence, initial and 3-year volumes used in this report are numerically different from those same volumes as calculated in the 3-year

Table 1. Merchantable volume factors (B.C. Min. of For., close utilization limit).

| SPECIES | Regression Coefficients | | | | R^2 | SEE |
|--|-------------------------|--------|--------|--------|--------|-------|
| | a_1 | a_2 | a_3 | a_4 | | |
| Douglas-fir (coast, immature) | 0.9769 | 0.9063 | 3.8121 | 0.6708 | 0.9990 | 0.006 |
| Western Red Cedar (coast, immature) | 0.9301 | 1.0515 | 3.6683 | 0.6608 | 0.9995 | 0.003 |
| Western Hemlock (coast, immature) | 0.9695 | 1.1610 | 3.8598 | 0.5818 | 0.9997 | 0.003 |
| Balsam species (coast) | 0.9704 | 0.5923 | 2.0938 | 0.8408 | 0.9996 | 0.002 |
| Western White Pine | 0.9701 | 1.1221 | 3.8335 | 0.6190 | 0.9998 | 0.002 |
| Lodgepole Pine | 0.9607 | 1.1723 | 3.8140 | 0.6316 | 0.9998 | 0.003 |

Table 2. Gross volume response by treatment - land area basis.

| | | T ₀ | | | Treatment 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 |
| Increment - | (0 to 3 - m ³ /ha | 48 | 65 | 69 | 34 | 56 | 70 | 22 | 41 | 48 |
| | years) - % initial* | 33 | 48 | 68 | 39 | 64 | 79 | 48 | 83 | 103 |
| | (3 to 6 - m ³ /ha | 31 | 45 | 56 | 35 | 42 | 61 | 25 | 34 | 43 |
| | years) - % initial | 22 | 34 | 56 | 39 | 48 | 69 | 56 | 69 | 93 |
| | (0 to 6 - m ³ /ha | 79 | 111 | 125 | 69 | 98 | 131 | 48 | 74 | 91 |
| | years) - % initial | 55 | 82 | 124 | 78 | 112 | 148 | 104 | 152 | 196 |
| PAI - | (0 to 3 - m ³ /ha/a | 15.9 | 21.8 | 23.0 | 11.4 | 18.6 | 23.4 | 7.4 | 13.5 | 15.9 |
| | years) | | | | | | | | | |
| | (3 to 6 - m ³ /ha/a | 10.4 | 15.1 | 18.6 | 11.7 | 13.9 | 20.2 | 8.4 | 11.2 | 14.4 |
| | years) | | | | | | | | | |
| | (0 to 6 - m ³ /ha/a | 13.2 | 18.4 | 20.8 | 11.6 | 16.2 | 21.8 | 7.9 | 12.4 | 15.2 |
| | years) | | | | | | | | | |

* % of initial volume after treatment.

report. Plot measurements at 6 years were carried out in English units, with breast height at 4.5 feet (1.37 m). Complete metrification of the installation is in progress.

2.3 MERCHANTABLE VOLUME FACTORS

Merchantable tree volumes (by species and utilization limit) were determined as function of dbh by fitting curves to tabulated merchantable volume factors (MVF) developed by the B.C. Forest Service (Browne 1962). The form of the regression is:

$$\text{MVF} = \begin{cases} a_1 (1 - \exp(-a_2(\text{dbh} - a_3) a_4)) & \text{if } \text{dbh} > a_3 \\ 0 & \text{if } \text{dbh} \leq a_3 \end{cases}$$

Coefficients, for close utilization for those tree species found in these plots, are given in Table 1. Fitted curves were used rather than tabulated values because of the large step changes that occur in the tabulated values for dbh classes in the 5- to 15-cm diameter range, the range that includes the majority of the trees measured here.

3.0 6 - YEAR GROWTH RESPONSE

3.1 LAND AREA BASIS

Response on a land area basis, obtained directly from plot summaries, provides real measures of standing volume (m³/ha), volume increment

Table 3. Merchantable volume response by treatment - land area basis.

| | | T ₀ | | | Treatment 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 |
| Increment - | (0 to 3 - m ³ /ha | 34 | 53 | 52 | 29 | 49 | 64 | 22 | 41 | 48 |
| | years) - % initial* | 77 | 99 | 189 | 80 | 132 | 198 | 112 | 186 | 226 |
| | (3 to 6 - m ³ /ha | 31 | 46 | 56 | 33 | 41 | 61 | 26 | 35 | 45 |
| | years) - % initial | 72 | 86 | 205 | 90 | 110 | 188 | 134 | 160 | 212 |
| | (0 to 6 - m ³ /ha | 65 | 99 | 108 | 62 | 90 | 124 | 48 | 75 | 92 |
| | years) - % initial | 149 | 185 | 393 | 170 | 241 | 386 | 245 | 346 | 438 |
| PAI - | (0 to 3 - m ³ /ha/a | 11.2 | 17.7 | 17.3 | 9.7 | 16.4 | 21.2 | 7.4 | 13.5 | 15.8 |
| | years) | | | | | | | | | |
| | (3 to 6 - m ³ /ha/a | 10.4 | 15.2 | 18.7 | 10.9 | 13.7 | 20.2 | 8.8 | 11.6 | 14.9 |
| | years) | | | | | | | | | |
| | (0 to 6 - m ³ /ha/a | 10.8 | 16.4 | 18.0 | 10.3 | 15.1 | 20.7 | 8.1 | 12.6 | 15.4 |
| | years) | | | | | | | | | |

* % of initial volume after treatment.

(m³/ha/a), as well as diameter (cm) and diameter increment (cm/a).

3.1a VOLUME

Gross and merchantable volume (B.C. Min. of For. close utilization) 3- and 6-year responses, reported as mean response per plot (4 replications), are shown in Tables 2 and 3, and in Figure 1. Volume increment on a land area basis has responded positively to fertilization. For a given level of thinning, fertilization has increased 3- and 6-year gross and merchantable volume increments. For no thinning (T₀), 6-year gross volume increments for the three levels of fertilization (F₀, F₁ and F₂) are 79, 111 and 125 m³/ha, respectively. For light thinning (T₁) and heavy thinning (T₂), 6-year gross volume increments

for the three levels of fertilization are 69, 98 and 131 and 48, 74 and 91 m³/ha, respectively.

On the other hand, volume increment on a land area basis has generally responded negatively to thinning. For a given level of fertilization, thinning has decreased 3- and 6-year gross and merchantable volume increments (except in the case of T₁F₂). For no fertilization (F₀), 6-year gross volume increments for the levels of thinning (T₀, T₁, and T₂) are 79, 69 and 48 m³/ha, respectively. For light fertilization (F₁) and heavy fertilization (F₂), 6-year gross volume increments for the three levels of thinning are 111, 98 and 74 and 125, 131 and 91 m³/ha, respectively. This generally negative response to thinning (at 6 years) of volume increment on a land area basis is brought about by the removal of growing stock, 1/3 of the basal area for T₁ and 2/3 for T₂. The resulting

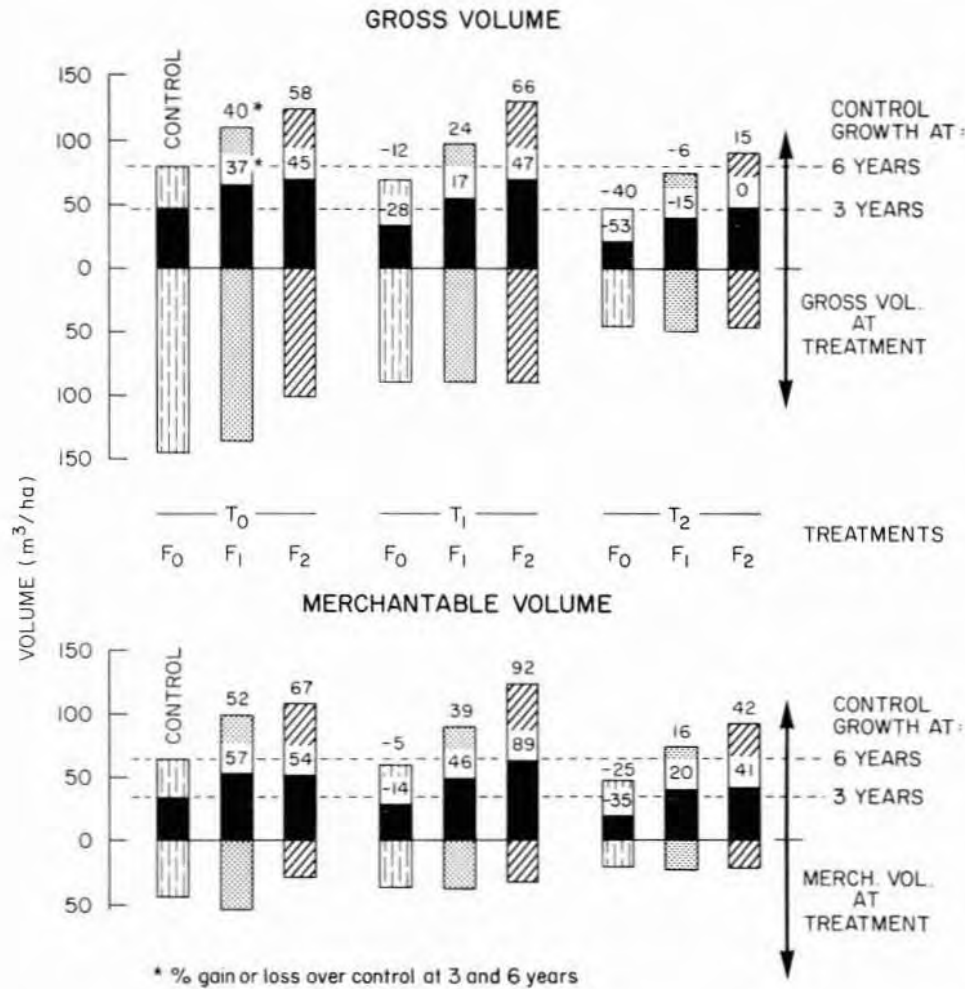


Fig. 1. Gross and merchantable volume response by treatment - land area basis.

growth, which accrues on a reduced growing stock, gives rise to a positive response of volume increment on an individual tree or a growing stock basis (Section 3.2). This growth is indicated in Tables 2 and 3 by volume increment shown as a % of the initial growing stock, which is lowest for the control and increases with either thinning or fertilization. For a given treatment, merchantable volume increment is less than volume increment on a land area basis (m^3/ha), but is greater than gross volume increment on a growing stock basis (% initial).

For the two thinning treatments (T_1F_0 and T_2F_0), gross volume PAIs ($m^3/ha/a$) are greater in the 3- to 6-year interval than is the 0- to 3-year interval. For all other treatments, including the control, the reverse is true. This indicates that at 6 years, gross volume increment on a land area basis is still increas-

ing relative to control for thinning alone, but has peaked and started to converge to control for fertilization alone and fertilization and thinning in combination. Thinning exhibits here a longer response period than fertilization.

3.1b DIAMETER

Tree size, reported as mean tree dbh per plot (or per hectare), is shown in Table 4. In contrast to volume increment on a land area basis, diameter increment (cm/a) has responded positively to both thinning and fertilization. Diameter increment has also responded positively on a growing stock basis (% initial) to both thinning and fertilization. Diameter response (as per cent over control) has been greatest for heavy thinning and heavy fertilization in combi-

Table 4. Mean stand diameter response by 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 |
| Increment - | (0 to 3 - cm | 0.73 | 1.24 | 1.54 | 1.24 | 1.93 | 2.31 | 1.81 | 2.65 | 3.51 |
| | years) - % initial* | 9 | 14 | 19 | 13 | 19 | 24 | 17 | 25 | 33 |
| | (3 to 6 - cm | 0.57 | 1.04 | 1.50 | 1.06 | 1.25 | 1.66 | 1.68 | 2.21 | 2.49 |
| | years) - % initial | 7 | 12 | 19 | 11 | 13 | 17 | 16 | 21 | 23 |
| | (0 to 6 - cm | 1.30 | 2.28 | 3.04 | 2.30 | 3.18 | 3.97 | 3.49 | 4.86 | 6.00 |
| | years) - % initial | 17 | 27 | 38 | 24 | 32 | 42 | 33 | 45 | 56 |
| PAI - | (0 to 3 - cm/a | 0.24 | 0.41 | 0.51 | 0.41 | 0.64 | 0.77 | 0.60 | 0.88 | 1.17 |
| | years) | | | | | | | | | |
| | (3 to 6 - cm/a | 0.19 | 0.35 | 0.50 | 0.35 | 0.42 | 0.55 | 0.56 | 0.74 | 0.83 |
| | years) | | | | | | | | | |
| | (0 to 6 - cm/a | 0.22 | 0.38 | 0.51 | 0.38 | 0.53 | 0.66 | 0.58 | 0.81 | 1.00 |
| | years) | | | | | | | | | |

* % of initial diameter after treatment

nation (T_2F_2), showing a 6-year increment of 6.0 cm compared to 1.3 cm for control, for a gain of 362 % over control.

3.2 INDIVIDUAL TREE BASIS

The effects of stand structure on individual tree and stand growth are complex and not fully understood. One way to account for these effects is to characterize the individual tree by its size, or dbh, and the stand by its dbh distribution and then analyze tree and stand response as functions of dbh and dbh distribution, respectively. A rationale for this approach is that growth (as measured by a variety of parameters) is generally observed to be closely correlated with diameter. Such was the case here, following an examination of correlations between growth

(measured as diameter, height, basal area, gross volume and merchantable volume increments) and various tree and stand descriptors, including initial diameter, initial diameter increment, initial height, initial CSI (Arney 1973) and change in CSI. This is the basis for choosing to analyse individual tree response (this section) and stand, or plot response (section 3.3) as functions of diameter and diameter distribution, respectively.

Six-year individual tree response, measured as individual tree PAI (0 to 6 years), is reported for diameter, basal area, height and gross volume per dbh class per treatment. Diameter classes were defined as 2.5 cm classes, ranging from class 1 with a mid-point of 3.75 cm to class 11 with a mid-point of 28.75 cm. These measured increments were regressed against initial dbh for the 2969 currently live undamaged

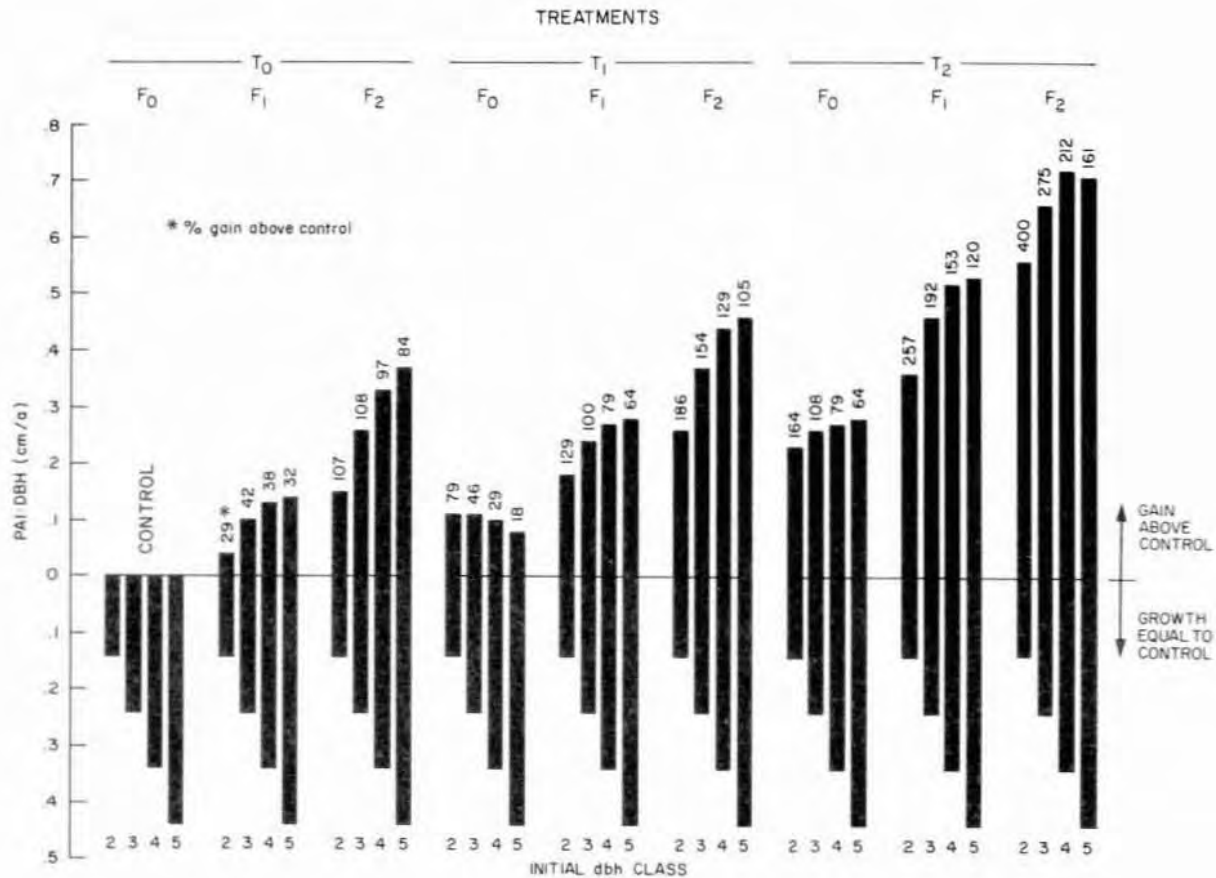


Fig. 2. PAI for dbh by dbh class and treatment - individual tree basis.

Douglas-fir plot trees (Table 5). Solutions to the regression equations for dbh classes 2 through 5 (the dbh classes containing the majority of the trees) are shown for dbh (Fig. 2), height (Fig. 3) and gross volume (Fig. 4).

Individual tree response at 6 years is generally similar to the response at 3 years (Crown *et al.* 1977). Diameter shows a positive response to both thinning and fertilization. The positive treatment interaction observed for diameter at 3 years is still present at 6 years. For dbh class 4 (10.0 to 12.5 cm), the gains above control for 6-year PAIs for T_0F_2 , T_2F_0 and T_2F_2 were 0.33, 0.25 and 0.72 cm/a, respectively, showing a positive interaction of 0.14 cm/a. As at 3 years, diameter increment at 6 years was larger for the initially larger diameters, except for the treatment T_1F_0 . Basal area, being proportional to the square of the diameter, responded similarly to diameter.

As at 3 years, height shows a positive response to fertilization for all levels of thinning, but a general-

ly negative response to thinning alone. This negative response, or "thinning shock", so pronounced at 3 years, is much reduced at 6 years. Dbh classes 2 and 3 for treatment T_1F_0 even show a slight positive response. If this trend were to continue, response at Shawnigan Lake could in time show an increase in height growth from thinning alone, in agreement with the Douglas-fir spacing trials carried out on a similarly poor site at Wind River, near Carson, Washington (Reukema 1970).

Gross volume measures diameter and height combined. On an individual tree basis, gross volume increment has responded positively to both thinning and fertilization, in contrast to gross volume increment on a land area basis (Section 3.1a). Except for treatment T_1F_0 , gross increment was larger for the initially larger diameters. Maximum gross volume increment (% over control) was observed for T_2F_2 , ranging from 151% for dbh class 5 to 408% for dbh class 2.

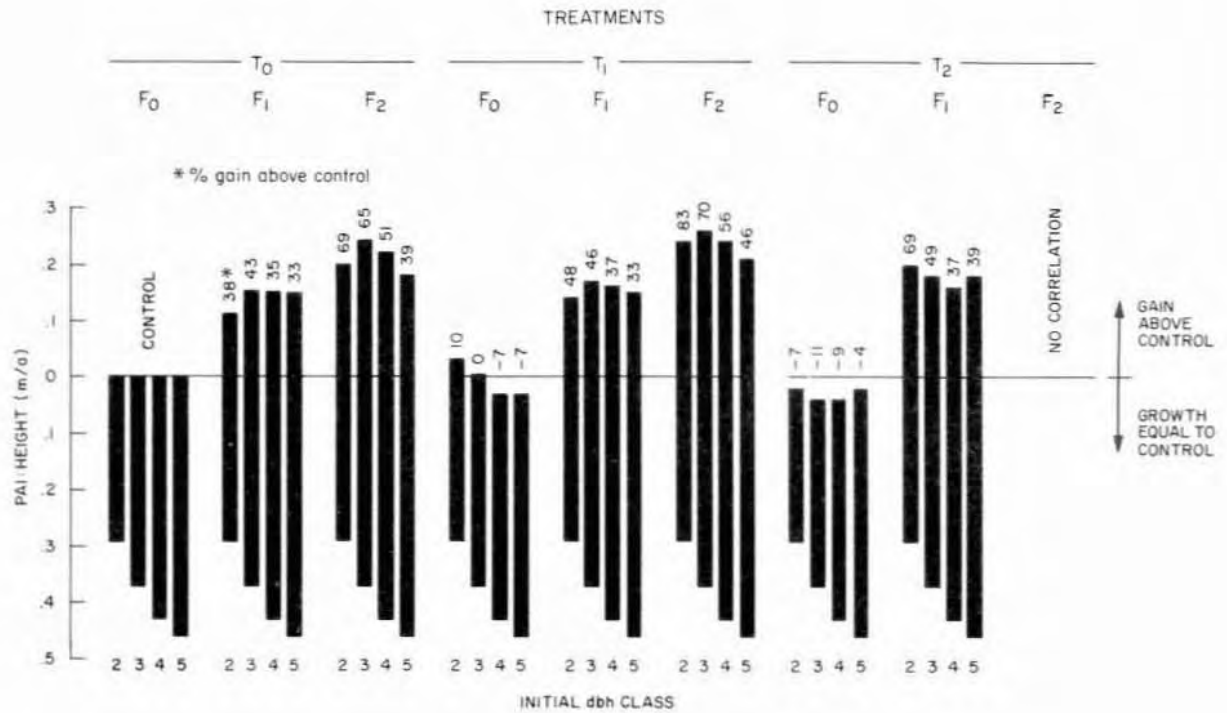


Fig. 3. PAI for height by dbh class and treatment - individual tree basis.

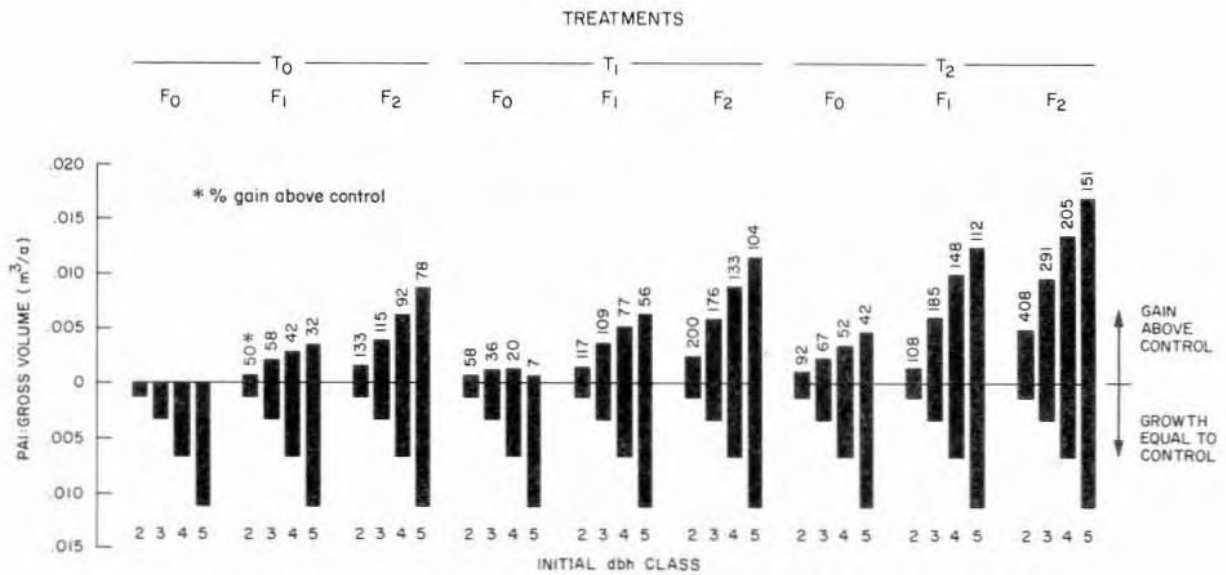


Fig. 4. PAI for gross volume by dbh class and treatment - individual tree basis.

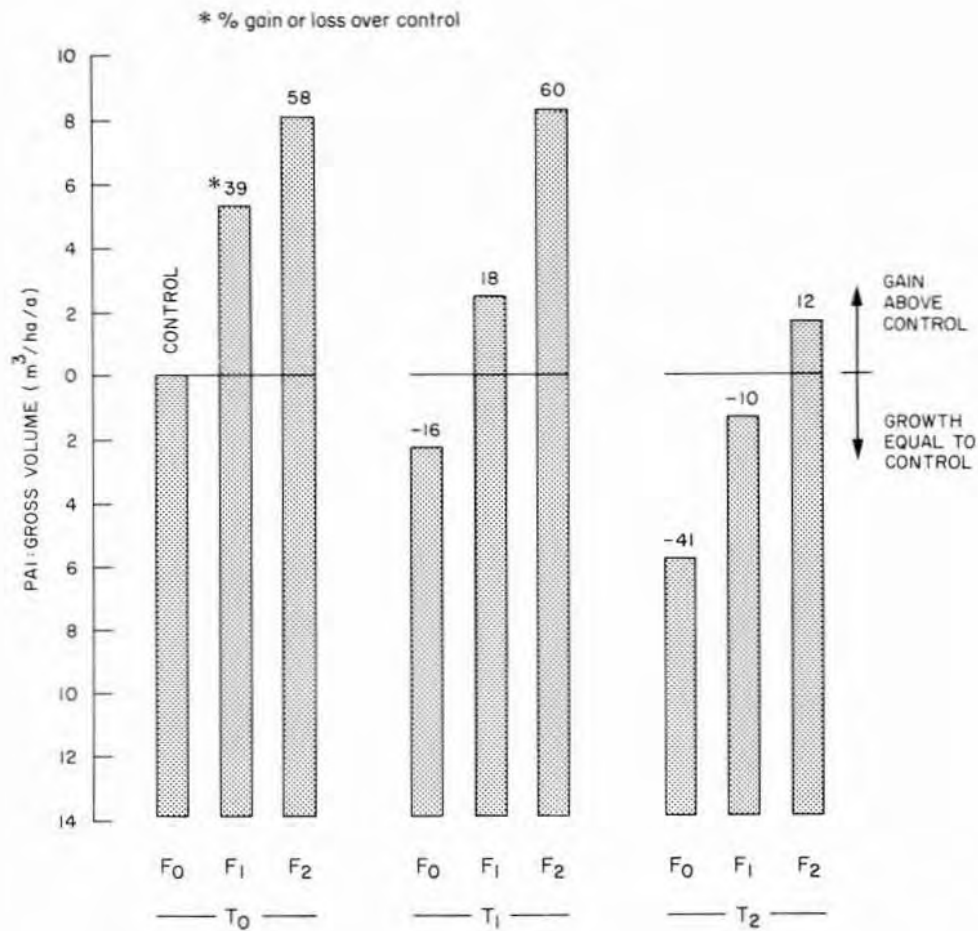


Fig. 5. Calculated gross volume PAI of the 2969 currently live undamaged Douglas-fir trees for comparison with stand structure analysis.

3.3 STAND STRUCTURE ANALYSIS

Volume response on a land area basis provides a real measure of how thinning and fertilizing a stand affect its resulting standing volume and volume increment per hectare. But thinning introduces large differences in initial stocking between thinning levels. These differences affect area basis volume measurements and are responsible for the negative response of volume increment per hectare to thinning, as discussed in Section 3.1. There are also lesser differences in stocking among fertilization levels within each thinning level, because of inherent plot-to-plot variation. In addition, for even-aged stands, such as the stand treated in this experiment, the initially larger trees show a higher volume increment (Fig. 4). Consequently, volume measurements on a land area basis are further affected by initial plot differences in stand structure (dbh distribution).

Stand structure analysis (Anon. 1975; Crown *et al.* 1977) is used here to account for these differences in initial stocking and initial diameter distribution among treatments. In this way, the analysis compares the effects of thinning and fertilization on growth after treatment by simulating treatment effect on volume increment in the absence of initial stand differences. This method grows the trees on each plot as if the plot had not been treated, by incrementing trees in each diameter class by the control increments for that diameter class. Response is then measured by comparing this "control image" for each plot with that plot's actual measured increment.

As was done in the 3-year analysis, gross volume increment/ha was determined as follows:

let i and j index treatment and dbh class, respectively,

let V_{ij} = gross volume increment of a tree of dbh equal to the mid-point of dbh class j , determined by solving the regression equation (Table 5) for treatment i for dbh classes 1 through 7, those classes represented in the initial stand condition in all treatments,

n_{ij} = number of trees in dbh class j for treatment i ,

then define:

$$\Delta V_i = \sum_j (V_{ij}) \times (n_{ij})$$

= total gross volume increment for treatment i and

$$\Delta V_i' = \sum_j (V_{1j}) \times (n_{ij})$$

where the V_{1j} are the control gross volume increments.

= total "control image" gross volume increment for treatment i .

Treatment response (% above control image) is then given by

$$\frac{\Delta V_i}{\Delta V_i'} \times 100.$$

By using the currently live undamaged Douglas-fir trees in dbh classes 1 through 7 to define dbh distributions per treatment (the n_{ij}), total gross volume increments per treatment (the V_i) can be determined (Fig. 5). Figure 5 is similar to (but not the same as) Figure 1. Both show gross volume increment on a land area basis. However, Figure 1 is derived from measured increments of all plot trees (3345 following treatment), whereas Figure 5 is derived from increments of trees of the mean of dbh classes 1 to 7, determined by the regressions in Table 5 applied to the currently live trees above. Figure 5 serves as a better reference to which results of stand structure analysis can be compared.

Stand structure analysis (Fig. 6) was carried out for three dbh distributions:

- the actual dbh distributions of the currently live trees above for each of the nine treatments (Table 6),
- the mean dbh distributions for the three thinning levels, to remove differences within thinning

levels and compare fertilization levels within thinning levels, and

- a single mean dbh distribution of the middle thinning level, T_1 , to compare thinning and fertilization on the same basis.

Figures 5 and 6 show that stand structure analysis has changed the qualitative nature of volume response, giving 6-year gross volume increment a positive response to both thinning and fertilization, as was found for gross volume increment expressed as a % of the initial growing stock in Table 2. Results of stand structure analysis at 6 years are similar to results at 3 years (Crown *et al.* 1977). By using Figure 6c for comparison, volume increment responded higher to fertilization alone (41 and 93% over control for T_0F_1 and T_0F_2 , respectively) than to thinning alone (20 and 53% over control for T_1F_0 and T_2F_0 , respectively). Maximum response was 210% over control for T_2F_2 .

3.4 CROP TREE ANALYSIS

This method of analysis focuses attention on those trees ear-marked for a final harvest - the crop trees. Analysis was carried out for 200 and 600 trees/ha, chosen on the basis of largest initial dbh. These numbers span the range of stocking levels currently being considered for managing stands similar to the stand studied here. Six-year gross volume increment for these selected numbers of crop trees was determined directly as a mean response per plot (4 replications), converted to a per hectare basis, and also adjusted for differences in initial dbh and height by covariance analysis, using dbh and height as covariates (Fig. 7).

Crop tree analysis gives 6-year gross volume increment a positive response to both thinning and fertilization. The measured response favors thinning over fertilization, giving responses (% over control) of 63 and 51 for T_0F_1 and T_0F_2 versus 6 and 20 for T_1F_0 and T_2F_0 . Maximum response was 110 for T_2F_2 . The covariance adjusted response, which accounts for the removal of growing stock by thinning, favors fertilization over thinning, giving responses of 3 and 37 for T_1F_0 and T_2F_0 versus 25 and 75 for T_0F_1 and T_0F_2 . Maximum response was 139 for T_2F_2 . The covariance adjusted response, which accounts for differences in stocking and stand structure in a different way than in the stand structure analysis, gives qualitatively similar but lower responses (% above control) than the stand structure analysis.

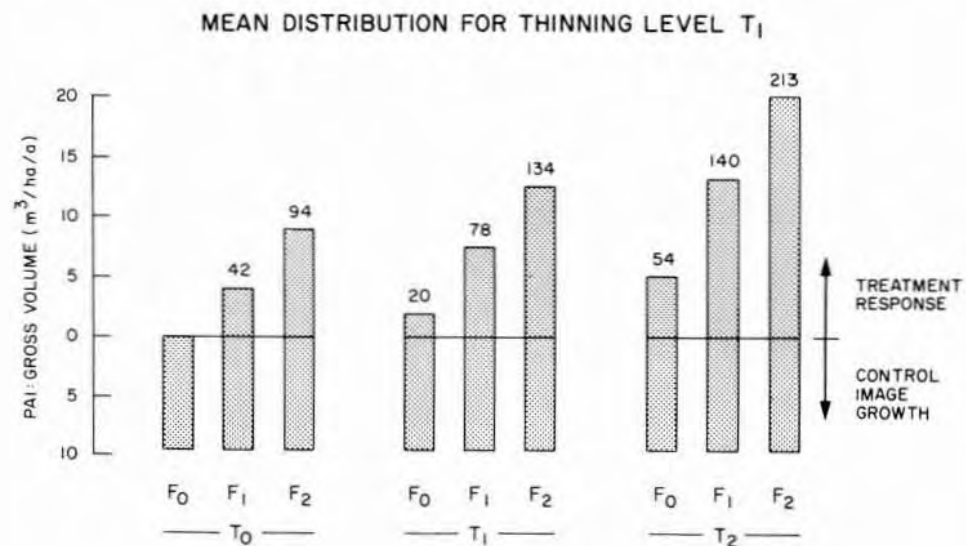
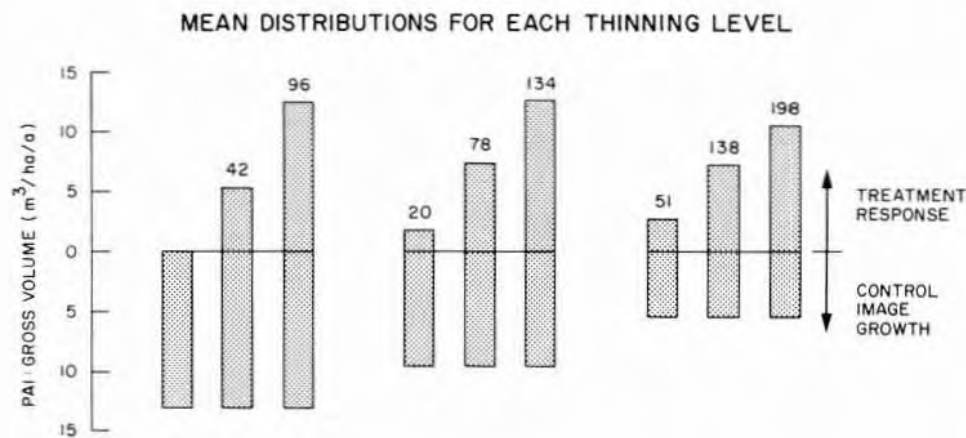
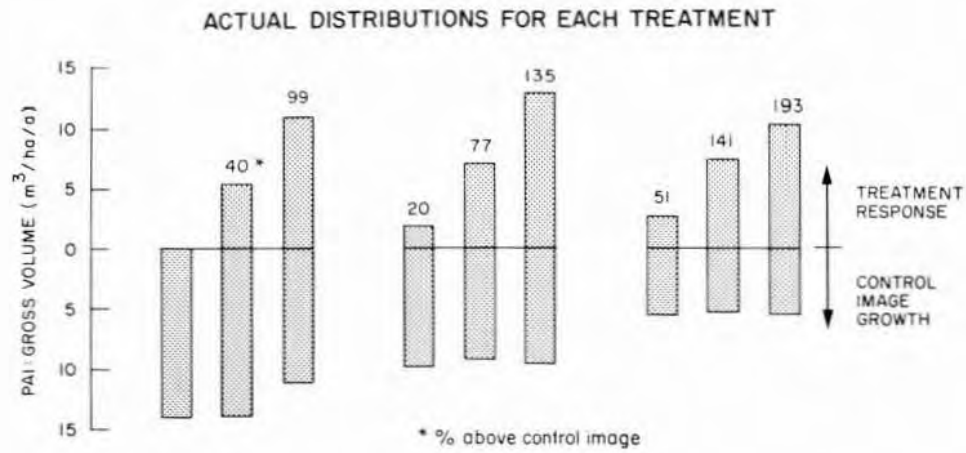


Fig. 6. Gross volume increment by treatment calculated by stand structure analysis.

Table 5. Regression equations for periodic annual increment (PAI)* for dbh, ba, height and gross volume by treatment.

dbh 6-year increment = $a_0 + a_1 D + a_2 D^2$

| Treatment | a_0 | a_1 | a_2 | R^2 | SEE (cm) |
|-------------------------------|-----------|----------|------------|--------|----------|
| T ₀ F ₀ | -0.630190 | 0.235364 | 0.0003255 | 0.8263 | 0.3206 |
| T ₁ F ₀ | -0.281838 | 0.323698 | -0.0055511 | 0.6420 | 0.4281 |
| T ₂ F ₀ | 0.274879 | 0.335250 | -0.0030851 | 0.5733 | 0.5115 |
| T ₀ F ₁ | -1.746340 | 0.514008 | -0.0096170 | 0.8113 | 0.4865 |
| T ₁ F ₁ | -1.106260 | 0.565804 | -0.0125670 | 0.7468 | 0.4828 |
| T ₂ F ₁ | -1.172610 | 0.804718 | -0.0215839 | 0.5583 | 0.6363 |
| T ₀ F ₂ | -2.061630 | 0.698603 | -0.0141064 | 0.7646 | 0.6380 |
| T ₁ F ₂ | -2.088460 | 0.858059 | -0.0227087 | 0.6533 | 0.7295 |
| T ₂ F ₂ | -0.373609 | 0.894818 | -0.0265223 | 0.5163 | 0.6845 |

ba 6-year increment = $a_0 + a_1 D + a_2 D^2$

| Treatment | a_0 | a_1 | a_2 | R^2 | SEE (cm ²) |
|-------------------------------|----------|---------|-----------|--------|------------------------|
| T ₀ F ₀ | -2.1518 | -0.6411 | 0.389970 | 0.9188 | 5.6299 |
| T ₁ F ₀ | -17.1145 | 4.3247 | 0.168160 | 0.8637 | 8.6679 |
| T ₂ F ₀ | -12.4724 | 3.7249 | 0.363685 | 0.8353 | 12.2644 |
| T ₀ F ₁ | -24.1102 | 4.2246 | 0.258231 | 0.9038 | 10.0901 |
| T ₁ F ₁ | -39.3105 | 9.0925 | 0.100922 | 0.9059 | 10.0103 |
| T ₂ F ₁ | -86.8659 | 20.0380 | -0.202675 | 0.8115 | 16.5897 |
| T ₀ F ₂ | -22.5013 | 3.9112 | 0.483342 | 0.8827 | 11.8952 |
| T ₁ F ₂ | -49.2367 | 11.4244 | 0.159632 | 0.8445 | 15.7352 |
| T ₂ F ₂ | -72.5572 | 21.0384 | -0.163590 | 0.8221 | 18.7876 |

height 6-year increment = $a_0 + a_1 D + a_2 \sqrt{D}$

| Treatment | a_0 | a_1 | a_2 | R^2 | SEE (m) |
|-----------|----------|-----------|---------|--------|---------|
| T_0F_0 | -3.70699 | -0.360774 | 3.07775 | 0.6220 | 0.4473 |
| T_1F_0 | -0.10186 | -0.073120 | 1.00073 | 0.2016 | 0.4807 |
| T_2F_0 | -0.14470 | 0.050376 | 0.57259 | 0.2666 | 0.5065 |
| T_0F_1 | -7.33135 | -0.758252 | 5.77610 | 0.7020 | 0.4588 |
| T_1F_1 | -5.97931 | -0.690099 | 5.15547 | 0.3839 | 0.5202 |
| T_2F_1 | 1.49938 | 0.038976 | 0.48433 | 0.1294 | 0.6494 |
| T_0F_2 | -9.06973 | -1.105440 | 7.57829 | 0.4976 | 0.6462 |
| T_1F_2 | -6.40311 | -0.850220 | 5.96475 | 0.3134 | 0.5284 |
| T_2F_2 | 3.53497 | -0.052276 | 0.30459 | 0.0006 | 0.6979 |

Gross volume 6-year increment = $a_0 + a_1 D + a_2 D^2$

| Treatment | a_0 | a_1 | a_2 | R^2 | SEE (m ³) |
|-----------|----------|-----------|-----------|--------|-----------------------|
| T_0F_0 | 0.00639 | -0.003444 | 0.0005679 | 0.9327 | 0.0056 |
| T_1F_0 | -0.01030 | 0.001331 | 0.0003353 | 0.9024 | 0.0078 |
| T_2F_0 | 0.00128 | -0.001948 | 0.0006370 | 0.8549 | 0.0121 |
| T_0F_1 | -0.01481 | 0.001374 | 0.0004404 | 0.9343 | 0.0092 |
| T_1F_1 | -0.03009 | 0.005352 | 0.0003187 | 0.9349 | 0.0090 |
| T_2F_1 | -0.08628 | 0.015990 | 0.0000395 | 0.8455 | 0.0162 |
| T_0F_2 | -0.01251 | 0.000571 | 0.0006515 | 0.9107 | 0.0101 |
| T_1F_2 | -0.03648 | 0.006672 | 0.0004237 | 0.8881 | 0.0137 |
| T_2F_2 | -0.05073 | 0.012460 | 0.0002463 | 0.8526 | 0.0175 |

* For the 2969 currently live undamaged Douglas-fir trees.
D = Initial dbh.

Table 6. Dbh frequency distributions* by dbh class by treatment used in stand structure analysis.

| Class | Initial dbh | Treatment | | | | | | | | |
|-------|----------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|
| | Mid-point (cm) | T ₀ F ₀ | T ₀ F ₁ | T ₀ F ₂ | T ₁ F ₀ | T ₁ F ₁ | T ₁ F ₂ | T ₂ F ₀ | T ₂ F ₁ | T ₂ F ₂ |
| 1 | 3.75 | 588 | 241 | 272 | 56 | 25 | 43 | 0 | 0 | 0 |
| 2 | 6.25 | 1238 | 699 | 817 | 340 | 322 | 322 | 25 | 56 | 68 |
| 3 | 8.75 | 1300 | 1015 | 1120 | 656 | 588 | 749 | 371 | 248 | 247 |
| 4 | 11.25 | 792 | 743 | 650 | 619 | 569 | 582 | 316 | 390 | 334 |
| 5 | 13.75 | 198 | 235 | 111 | 198 | 210 | 155 | 130 | 130 | 118 |
| 6 | 16.25 | 19 | 62 | 50 | 43 | 50 | 43 | 19 | 18 | 56 |
| 7 | 18.75 | 12 | 43 | 0 | 6 | 0 | 12 | 12 | 0 | 0 |
| Total | | 4147 | 3038 | 3020 | 1918 | 1764 | 1906 | 873 | 842 | 823 |

* of the 2969 currently live undamaged Douglas-fir trees, converted to a per hectare basis.

4.0 SOME EFFECTS OF TREATMENT ON STAND STRUCTURE

4.1 MORTALITY

Tree mortality over the 6-year period since treatment has been slight, totalling 135 out of 3343 initially live plot trees or 0.67%/year. Per cent mortality (for 1971 plot trees) was examined with respect to:

- 1) treatment (Table 7a),
- 2) tree size (dbh class) and competitive status (CSI class) (Table 7b),
- 3) canopy position (individual tree height relative to mean tree height per plot) (Fig. 8), and
- 4) years since treatment (Fig. 9).

There was insufficient mortality to enable a detailed analysis of it with respect to each of the above strata. However, observed mortality suggests that probability of mortality is:

- 1) increased by fertilization and decreased by thinning (Lee 1974),
- 2) higher in trees of smaller dbh and larger CSI (Arney 1973),

- 3) higher in trees in intermediate and suppressed crown classes, and
- 4) increasing with time since treatment (Lee 1974).

4.2 CROWN DEVELOPMENT

Measurements were taken of total tree height (H) and height to live crown (HLC) initially and at 6 years for all plot trees. These measurements enable analysis of:

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

$$\text{changes in LCR: } \Delta \text{LCR} = \text{LCR (6 years)} - \text{LCR (initial)}$$

$$\text{crown lift-off: } \Delta \text{HLC} = \text{HLC (6 years)} - \text{HLC (initial)}$$

Results by treatment (Table 8) for the 200 and 600 initially largest trees/ha (Section 3.4) show that crown lift-off (ΔHLC) has been greatest for the control (2.7 m over 6 years), is relatively unaffected by

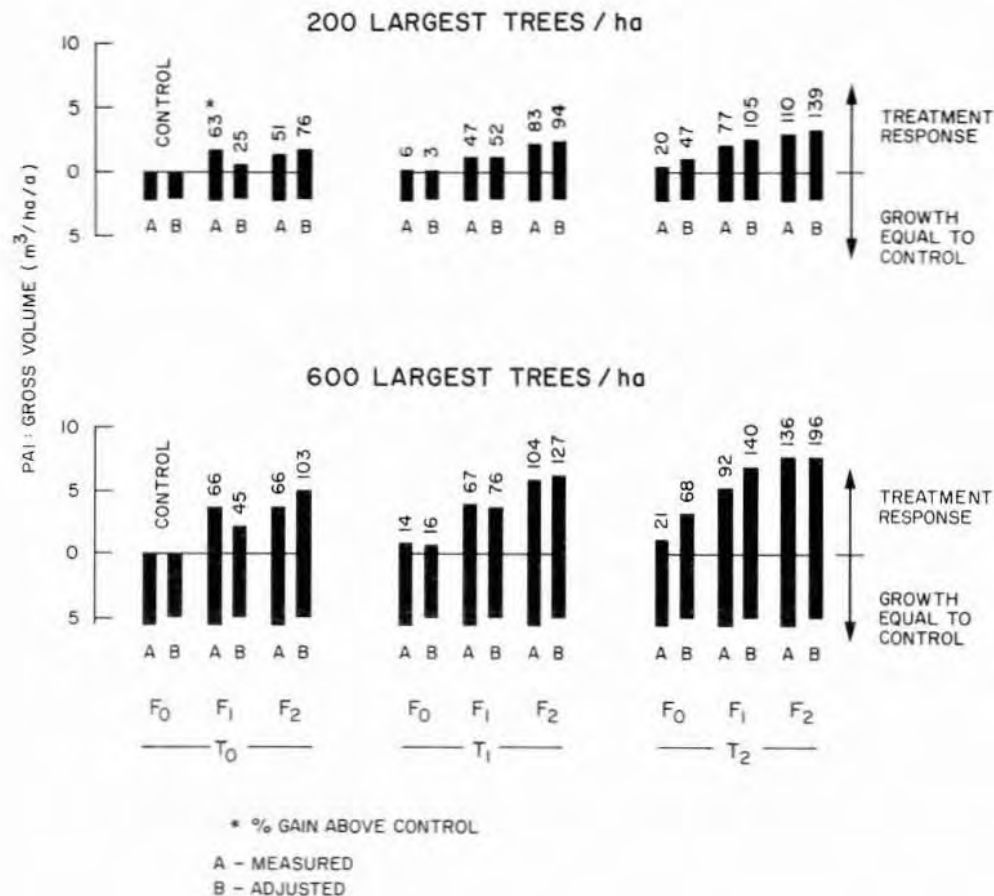


Fig. 7. Gross volume increment (unadjusted and adjusted by covariance analysis) by treatment for the 200 and 600 initially largest trees/ha.

fertilization, but is reduced by thinning (to about 1/3 of the control for heavy thinning). Live crown ratios (Δ LCR) have been reduced for the control (by 0.14). This reduction has been slowed slightly by fertilization, but slowed considerably more by thinning, being almost halted for heavy thinning. The unthinned plots, therefore, appear to be severely suppressed, as shown by their rapid crown lift-off and reduction over time of live crown ratio. Fertilization, for a given level of thinning, does not markedly affect crown development as assessed by these measures.

4.3 DIAMETER DISTRIBUTION

Initial and 6-year dbh distributions for four treatments (control, T₀F₂, T₂F₀ and T₂F₂) were fitted to the Weibull function. All distributions were unimodal. Two measures of dispersion of dbh distribution are considered:

- 1) The shape parameter, C_1 of the Weibull distribution (Bailey and Dell 1973). A larger value of this parameter, once its value is large enough (> 1.0) to give a unimodal distribution, can be interpreted to mean less dispersion in the dbh distribution.
- 2) The full width at half height (FWHH) divided by the location of the peak of the unimodal distribution. This measure, which is relatively unaffected by the tails of skewed but otherwise approximately normal distributions, is analogous to coefficient of variation for the normal distribution.

Changes in these two parameters are used to indicate changes between initial and 6-year dbh distributions by treatment, where an increase in the Weibull shape parameter, C_1 , and a decrease in FWHH/peak location indicate a decrease in dispersion of dbh distribution and therefore an evolution toward greater stand uniformity. For the control and treatments

Table 7. Tree mortality by treatment and by tree size (dbh class) and competitive stress (CSI class).^a

By Treatment

| Level of thinning \ Level of fert. | 2 | 1 | 0 | mean (total) |
|--|------------------------------------|----------|----------|-------------------------------------|
| 0 | 9.7 ^b (57) ^c | 7.7 (45) | 2.4 (19) | 7.8 ^d (121) ^e |
| 1 | 2.4 (8) | 0.3 (1) | 0.9 (3) | 1.8 (12) |
| 2 | 0.7 (1) | 0.7 (1) | 0.0 (0) | 0.7 (2) |
| mean (total) | 8.7 ^d (66) ^e | 7.4 (47) | 2.2 (22) | |

By Tree Size and Competitive Stress

| dbh class \ CSI class | Open | Dominant | Co-dominant | Intermediate | Suppressed | Mean (total) |
|-----------------------------|------------------------------------|-----------|-------------|--------------|------------|-------------------------------------|
| 1 | 42.9 ^b (3) ^c | 28.6 (8) | 40.0 (28) | 42.4 (25) | 67.6 (23) | 47.0 ^d (87) ^e |
| 2 | 2.0 (1) | 4.3 (6) | 5.4 (11) | 5.7 (9) | 6.6 (5) | 5.4 (32) |
| 3 | 0.5 (1) | 1.7 (5) | 1.9 (6) | 1.2 (2) | 0.0 (0) | 1.6 (14) |
| 4 | 0.0 (0) | 0.0 (0) | 0.9 (2) | 0.0 (0) | 0.0 (0) | 0.9 (2) |
| mean (total) | 26.2 ^d (5) ^e | 13.8 (19) | 25.4 (47) | 30.9 (36) | 56.7 (28) | |

a). As defined by Arney, 1973

b). % mortality over 6 years since treatment defined as (number dead / number initial) X 100.

c). Number of trees that died over 6 years since treatment.

d). Mean % (weighted by number of dead).

e). Total number.

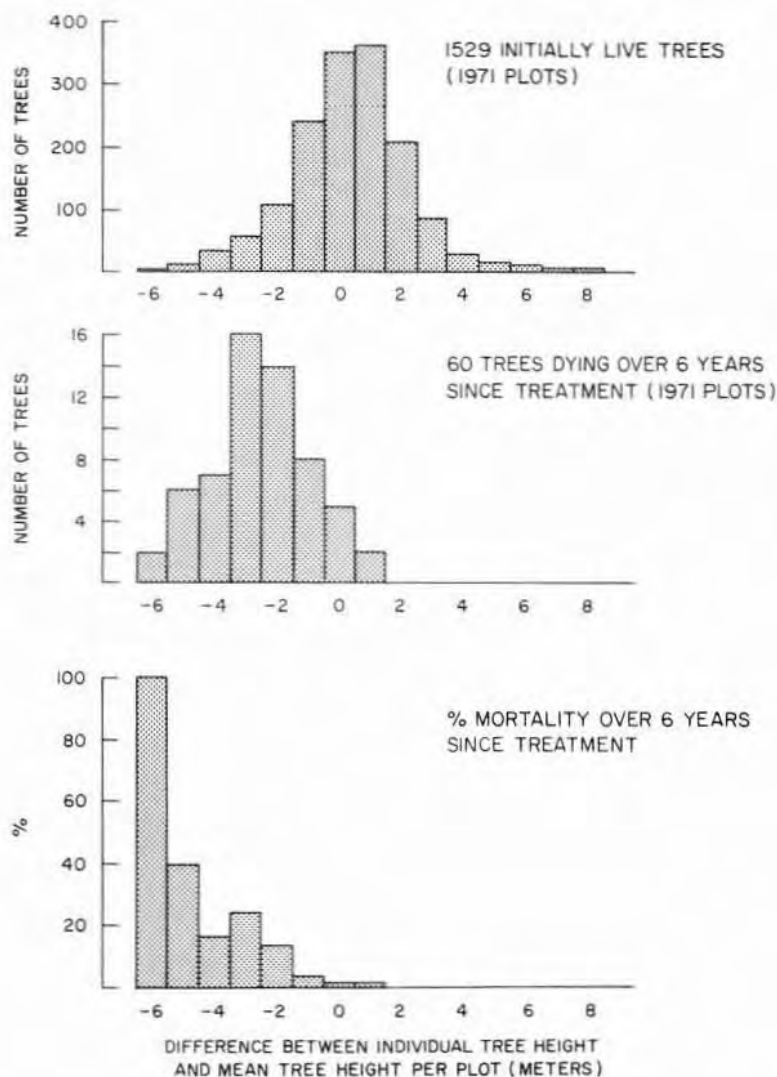


Fig. 8. Tree mortality with respect to canopy position.

T₂F₂, T₂F₀ and T₂F₂, changes in the Weibull shape parameter were -0.01, 0.21, 0.32 and 1.40 and changes in the FWHH/peak location were 0.12, -0.03, -0.02 and -0.15, respectively. Relative to control, these three treatments have, by these measures, led to increased stand uniformity, especially for the combined treatment, T₂F₂.

5.0 SOME CHARACTERISTICS OF GROWTH RESPONSE

One way to characterize growth response to thinning and fertilization is to show how each of a variety of measures of growth, or indicators, varies

with and depends upon the level and combination of thinning and fertilization. Such a characterization of growth response has already been suggested (Tables 7 and 8), where discrete, calculated values for various indicators (probability of tree mortality, height to live crown, and live crown ratio) are tabulated with respect to level of thinning and fertilization.

If thinning and fertilization are viewed as independent variables and each indicator as a dependent variable, tabulated values such as those in Tables 7 and 8 can be fitted to obtain a contour representation of a "response surface" analogously to the fitting of a set of data points by a line or curve. This fitting can be done to as many or as few tabulated values as

Table 8. Live crown ratio and height to live crown by treatment for the 200 and 600 initially largest trees / ha.

| | 600 Largest | | | | 200 Largest | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|-------------------|---|-------|------|---|-------------|---|------|------|------|---|------|------|------|---|------|------|-----|--|--|--|--|-------|---|---|---|---|------|------|------|---|------|------|------|---|------|------|------|--|--|--|
| HLC (initial) - m | <table><tr><td>T \ F</td><td>0</td><td>1</td><td>2</td></tr><tr><td>0</td><td>2.8</td><td>2.5</td><td>2.2</td></tr><tr><td>1</td><td>2.5</td><td>2.4</td><td>2.6</td></tr><tr><td>2</td><td>2.3</td><td>2.3</td><td>2.2</td></tr></table> | T \ F | 0 | 1 | 2 | 0 | 2.8 | 2.5 | 2.2 | 1 | 2.5 | 2.4 | 2.6 | 2 | 2.3 | 2.3 | 2.2 | | | | <table><tr><td>T \ F</td><td>0</td><td>1</td><td>2</td></tr><tr><td>0</td><td>2.6</td><td>2.4</td><td>2.2</td></tr><tr><td>1</td><td>2.5</td><td>2.2</td><td>2.3</td></tr><tr><td>2</td><td>2.1</td><td>2.1</td><td>2.1</td></tr></table> | T \ F | 0 | 1 | 2 | 0 | 2.6 | 2.4 | 2.2 | 1 | 2.5 | 2.2 | 2.3 | 2 | 2.1 | 2.1 | 2.1 | | | |
| T \ F | 0 | 1 | 2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 0 | 2.8 | 2.5 | 2.2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1 | 2.5 | 2.4 | 2.6 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 2 | 2.3 | 2.3 | 2.2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| T \ F | 0 | 1 | 2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 0 | 2.6 | 2.4 | 2.2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1 | 2.5 | 2.2 | 2.3 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 2 | 2.1 | 2.1 | 2.1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| HLC (6-year) - m | <table><tr><td>T \ F</td><td>0</td><td>1</td><td>2</td></tr><tr><td>0</td><td>5.5</td><td>5.5</td><td>4.6</td></tr><tr><td>1</td><td>4.8</td><td>4.4</td><td>4.9</td></tr><tr><td>2</td><td>3.2</td><td>3.5</td><td>3.0</td></tr></table> | T \ F | 0 | 1 | 2 | 0 | 5.5 | 5.5 | 4.6 | 1 | 4.8 | 4.4 | 4.9 | 2 | 3.2 | 3.5 | 3.0 | | | | <table><tr><td>T \ F</td><td>0</td><td>1</td><td>2</td></tr><tr><td>0</td><td>5.3</td><td>5.4</td><td>5.3</td></tr><tr><td>1</td><td>4.8</td><td>4.2</td><td>4.8</td></tr><tr><td>2</td><td>2.9</td><td>3.2</td><td>2.9</td></tr></table> | T \ F | 0 | 1 | 2 | 0 | 5.3 | 5.4 | 5.3 | 1 | 4.8 | 4.2 | 4.8 | 2 | 2.9 | 3.2 | 2.9 | | | |
| T \ F | 0 | 1 | 2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 0 | 5.5 | 5.5 | 4.6 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1 | 4.8 | 4.4 | 4.9 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 2 | 3.2 | 3.5 | 3.0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| T \ F | 0 | 1 | 2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 0 | 5.3 | 5.4 | 5.3 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1 | 4.8 | 4.2 | 4.8 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 2 | 2.9 | 3.2 | 2.9 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Δ HLC - m | <table><tr><td>T \ F</td><td>0</td><td>1</td><td>2</td></tr><tr><td>0</td><td>2.7</td><td>3.0</td><td>2.4</td></tr><tr><td>1</td><td>2.2</td><td>2.0</td><td>2.3</td></tr><tr><td>2</td><td>1.0</td><td>1.2</td><td>0.8</td></tr></table> | T \ F | 0 | 1 | 2 | 0 | 2.7 | 3.0 | 2.4 | 1 | 2.2 | 2.0 | 2.3 | 2 | 1.0 | 1.2 | 0.8 | | | | <table><tr><td>T \ F</td><td>0</td><td>1</td><td>2</td></tr><tr><td>0</td><td>2.7</td><td>3.0</td><td>2.1</td></tr><tr><td>1</td><td>2.4</td><td>2.0</td><td>2.4</td></tr><tr><td>2</td><td>0.8</td><td>1.2</td><td>0.9</td></tr></table> | T \ F | 0 | 1 | 2 | 0 | 2.7 | 3.0 | 2.1 | 1 | 2.4 | 2.0 | 2.4 | 2 | 0.8 | 1.2 | 0.9 | | | |
| T \ F | 0 | 1 | 2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 0 | 2.7 | 3.0 | 2.4 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1 | 2.2 | 2.0 | 2.3 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 2 | 1.0 | 1.2 | 0.8 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| T \ F | 0 | 1 | 2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 0 | 2.7 | 3.0 | 2.1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1 | 2.4 | 2.0 | 2.4 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 2 | 0.8 | 1.2 | 0.9 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| LCR (initial) | <table><tr><td>T \ F</td><td>0</td><td>1</td><td>2</td></tr><tr><td>0</td><td>.75</td><td>.79</td><td>.79</td></tr><tr><td>1</td><td>.78</td><td>.79</td><td>.77</td></tr><tr><td>2</td><td>.78</td><td>.79</td><td>.79</td></tr></table> | T \ F | 0 | 1 | 2 | 0 | .75 | .79 | .79 | 1 | .78 | .79 | .77 | 2 | .78 | .79 | .79 | | | | <table><tr><td>T \ F</td><td>0</td><td>1</td><td>2</td></tr><tr><td>0</td><td>.79</td><td>.81</td><td>.81</td></tr><tr><td>1</td><td>.80</td><td>.82</td><td>.81</td></tr><tr><td>2</td><td>.82</td><td>.82</td><td>.82</td></tr></table> | T \ F | 0 | 1 | 2 | 0 | .79 | .81 | .81 | 1 | .80 | .82 | .81 | 2 | .82 | .82 | .82 | | | |
| T \ F | 0 | 1 | 2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 0 | .75 | .79 | .79 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1 | .78 | .79 | .77 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 2 | .78 | .79 | .79 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| T \ F | 0 | 1 | 2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 0 | .79 | .81 | .81 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1 | .80 | .82 | .81 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 2 | .82 | .82 | .82 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| LCR (6-year) | <table><tr><td>T \ F</td><td>0</td><td>1</td><td>2</td></tr><tr><td>0</td><td>.61</td><td>.64</td><td>.68</td></tr><tr><td>1</td><td>.66</td><td>.71</td><td>.68</td></tr><tr><td>2</td><td>.75</td><td>.76</td><td>.79</td></tr></table> | T \ F | 0 | 1 | 2 | 0 | .61 | .64 | .68 | 1 | .66 | .71 | .68 | 2 | .75 | .76 | .79 | | | | <table><tr><td>T \ F</td><td>0</td><td>1</td><td>2</td></tr><tr><td>0</td><td>.65</td><td>.67</td><td>.72</td></tr><tr><td>1</td><td>.68</td><td>.73</td><td>.71</td></tr><tr><td>2</td><td>.79</td><td>.79</td><td>.81</td></tr></table> | T \ F | 0 | 1 | 2 | 0 | .65 | .67 | .72 | 1 | .68 | .73 | .71 | 2 | .79 | .79 | .81 | | | |
| T \ F | 0 | 1 | 2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 0 | .61 | .64 | .68 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1 | .66 | .71 | .68 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 2 | .75 | .76 | .79 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| T \ F | 0 | 1 | 2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 0 | .65 | .67 | .72 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1 | .68 | .73 | .71 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 2 | .79 | .79 | .81 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Δ LCR | <table><tr><td>T \ F</td><td>0</td><td>1</td><td>2</td></tr><tr><td>0</td><td>-.14</td><td>-.15</td><td>-.11</td></tr><tr><td>1</td><td>-.12</td><td>-.08</td><td>-.09</td></tr><tr><td>2</td><td>-.04</td><td>-.03</td><td>.00</td></tr></table> | T \ F | 0 | 1 | 2 | 0 | -.14 | -.15 | -.11 | 1 | -.12 | -.08 | -.09 | 2 | -.04 | -.03 | .00 | | | | <table><tr><td>T \ F</td><td>0</td><td>1</td><td>2</td></tr><tr><td>0</td><td>-.14</td><td>-.14</td><td>-.09</td></tr><tr><td>1</td><td>-.12</td><td>-.08</td><td>-.10</td></tr><tr><td>2</td><td>-.02</td><td>-.03</td><td>-.01</td></tr></table> | T \ F | 0 | 1 | 2 | 0 | -.14 | -.14 | -.09 | 1 | -.12 | -.08 | -.10 | 2 | -.02 | -.03 | -.01 | | | |
| T \ F | 0 | 1 | 2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 0 | -.14 | -.15 | -.11 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1 | -.12 | -.08 | -.09 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 2 | -.04 | -.03 | .00 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| T \ F | 0 | 1 | 2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 0 | -.14 | -.14 | -.09 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1 | -.12 | -.08 | -.10 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 2 | -.02 | -.03 | -.01 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |

there may be and done by as simple or as sophisticated a fitting procedure as may be warranted.

Growth response is examined below by displaying, as response surfaces, a variety of growth indicators. These response surfaces, collectively, indicate qualitative shapes and trends in response. The contour representations of the response surfaces below are generated, for each indicator considered, by fitting, according to a linear interpolation routine called CNTOUR (Mair 1978), the nine treatment values tabulated as equally spaced points into a 3×3 array. Equally spaced tabulations are used since thinning and fertilization were applied in equal sized increments - 0, 1/3 and 2/3 basal area removed for T₀, T₁ and T₂ and 0, 224 and 448 kg N/ha added for F₀, F₁ and F₂, respectively. To interpret these response surfaces:

- the response surface is represented by contour lines; lines connecting points of equal response,
- the value of the response surface at a point is the fitted value of the response for that level of thinning and fertilization, and
- the slope (magnitude and direction) of the response surface at a point expresses the sensitivity of the response to thinning and fertilization for that level of thinning and fertilization.

5.1 LAND AREA BASIS

Three-year and 6-year volume and diameter increment on a land area basis calculated for the nine treatments carried out have been shown in Tables 2, 3 and 4. These calculated values, some displayed as bar graphs (Fig. 1), can also be displayed as response surfaces (Fig. 10). In Figure 10, the solid lines show contours of equal response, generated by fitting the nine tabulated values. The dotted lines show the general directions of maximum change in the response. Figure 10 shows that on a land area basis:

- 1) Volume increment and diameter increment have qualitatively different response surfaces. Volume increment is maximized by heavy fertilization but light and no thinning. Diameter growth is maximized by heavy fertilization and heavy thinning.
- 2) Gross volume and merchantable volume response are qualitatively similar.
- 3) 3- and 6-year responses are qualitatively similar.

5.2 INDIVIDUAL TREE BASIS

Diameter and height measurements of the

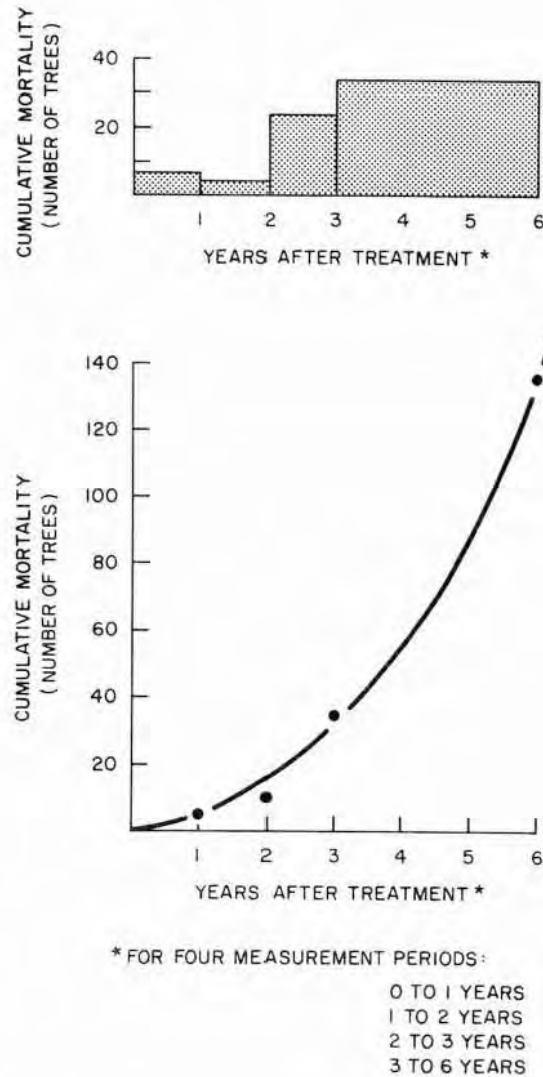


Fig. 9. Tree mortality with respect to years after treatment.

volume sample trees, taken yearly since treatment, provide a data base for a closer look at shapes and trends in individual tree response. Current annual increment, CAI, reported as treatment minus control (mean for all volume sample trees), is shown by treatment for dbh (Fig. 11) and height (Fig. 12). Various indicators can be derived from these curves. The dependence of these indicators on thinning and fertilization can then be looked at by displaying the indicator response surfaces. Therefore, response surfaces of dbh (Fig. 13) and height (Fig. 14) for all 464 volume sample trees, as well as for the 228 which are below 10-cm initial dbh (representing the small tree component) and the 236 above 10-cm initial dbh (representing the crop tree component), are shown for the

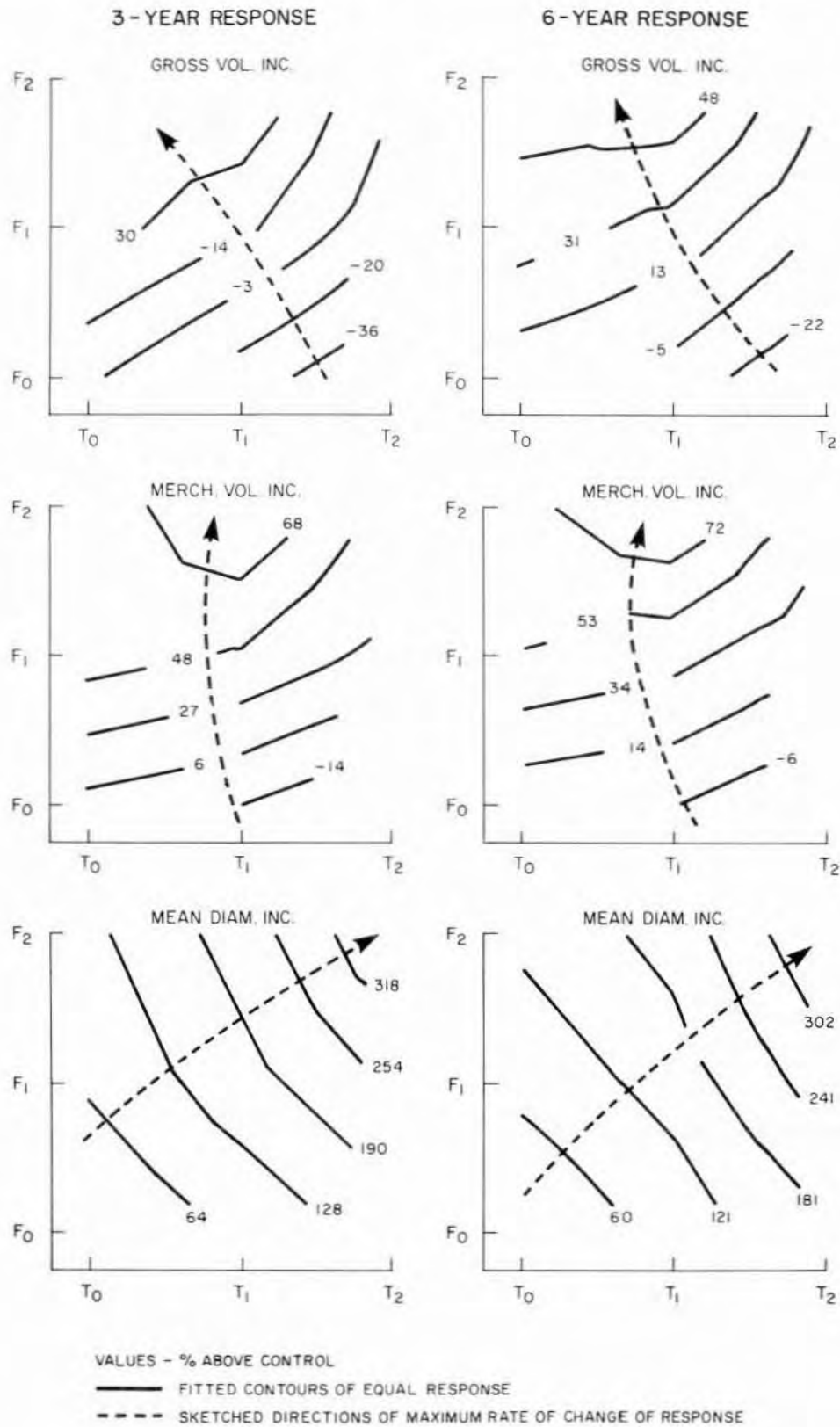


Fig. 10. Response surfaces of gross and merchantable volume increment (land area basis) and mean stand diameter 3-year and 6-year response.

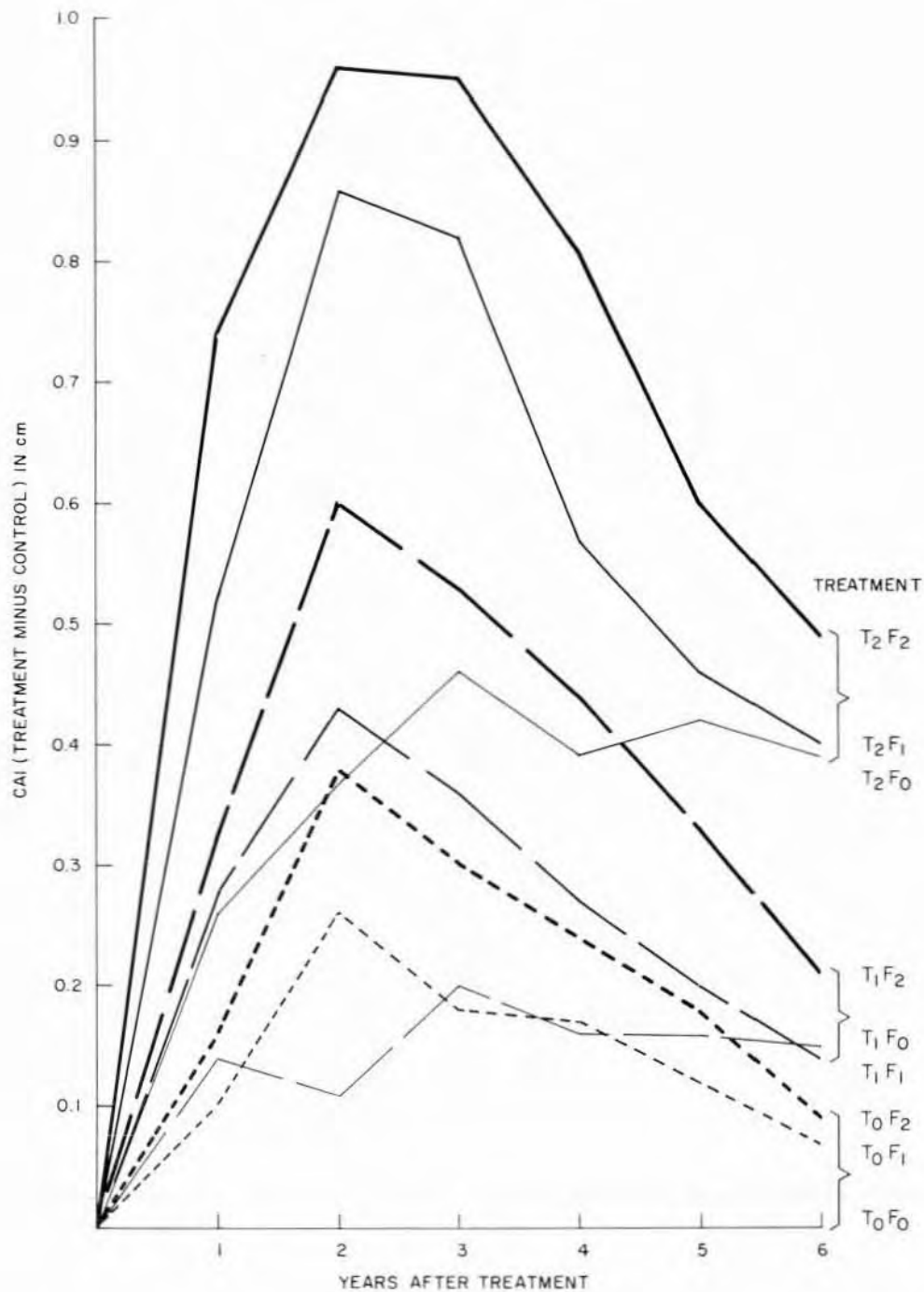


Fig. 11. CAI for diameter for all volume sample trees by treatment.

following indicators:

- 1) maximum CAI - as a measure of the amplitude (or difference in any one year between treated and control) of the response,
- 2) time to maximum CAI - as a measure of the

quickness of the response,

- 3) a forecasted duration, determined from Figures 11 and 12 as a linearly extrapolated return to control based on the value of each curve at 6 years and its slope determined by its maximum value and value at 6 years - as a measure of the

longevity of the response, and

- 4) cumulative increment at 1 year, 6 years and forecasted end as determined above - as a measure of the magnitude (or cumulative difference between treated and control) and time dependence of this magnitude, of the response.

Examination of Figures 11 and 12 and the response surfaces in Figures 13 and 14 suggests that:

- 1) Over the 6 years of observation, diameter has responded more in amplitude than has height. If maximum CAI, shown in Figures 11 and 12 as treatment minus control to better illustrate response shapes and trends, is expressed instead as % above control, response in diameter increment has ranged to a maximum of 380% (for T₂F₂ at 3 years), whereas height increment has ranged to a maximum of only 124% (for T₂F₂ at 6 years).
- 2) Diameter has responded more quickly than has height:
 - times to maximum CAI are shorter for diameter (Fig. 13, response surface # 2) than for height (Fig. 14, response surface # 2) and
 - height response (Fig. 12) but not diameter response (Fig. 11), for thinning alone, exhibits a delayed response (thinning shock).
- 3) Relatively, diameter (Fig. 13) has responded a little more to thinning, whereas height (Fig. 14) has responded a little more to fertilization, both in amplitude (# 1) and magnitude of response at 1 year (# 4) and 6 years (# 5). This follows from the directions of the dotted lines which are, relatively, more nearly horizontal (no response to fertilization) for diameter and more nearly vertical (no response to thinning) for height.
- 4) Cumulative diameter response to forecasted end (Fig. 13, # 6) is different for the small tree versus the crop tree component.
- 5) Fertilization shows a faster - but shorter-lived response in diameter and especially in height than does thinning. This follows (Figs. 13 and 14, # 4, 5 and 6), again, from the directions of the dotted lines which shift progressively more parallel to the thinning axis with time after treatment.

6.0

CONCLUSIONS

Site specific 6-year growth response to thinning and nitrogen (urea) fertilization of a 24-year-old Douglas-fir stand has been reported by four methods: land area basis, individual tree basis, stand structure

analysis and crop tree analysis. Each of these methods offers certain attractive features (Crown *et al.* 1977). Some characteristics of response have been examined and discussed by means of contour representations of response surfaces which have been derived for a variety of growth indicators.

Thinning involves the removal of growing stock. Used as a stand management tool, thinning changes the standing volume (and therefore the residual stand MAI) and the tree size distribution of the stand at the time of thinning, in addition to changing the growth of the remaining trees after thinning. Thinning "response" can, therefore, refer to changes brought about at thinning, after thinning or both. Fertilization, on the other hand, changes only growth after treatment.

Fertilization has increased volume (gross and merchantable) and diameter growth on whatever basis these are considered. Thinning, carried out here so as to increase mean stand diameter at the time of thinning, has increased diameter growth after thinning on whatever basis it is considered. The effect of thinning on volume has been to decrease volume wherever the measure of volume includes the effect of removing growing stock as well as growth thereafter (land area basis) and to increase volume wherever the measure considers only growth after thinning (individual tree basis, stand structure analysis and crop tree analysis).

Fertilization and thinning, used in combination, have increased diameter and diameter increment in all cases (Table 4) and have increased or decreased volume or volume increment, depending upon the particular combination of fertilization and thinning level and the particular measure of volume considered (Tables 2 and 3). For example, considering merchantable volume at 6 years (Table 3), standing volumes are still below control (108 m³/ha) for three treatments, T₂F₀ (68 m³/ha), T₂F₁, (97 m³/ha) and T₁F₀ (98 m³/ha). Merchantable volume PAIs on a land area basis are below control (10.8 m³/ha/a) for two treatments, T₂F₀ (8.1 m³/ha/a) and T₁F₀ (10.3 m³/ha/a). However, for all treatments, including the above, mean stand diameter, diameter increment and volume increment of the remaining trees are all increased over control. Considering growth of the remaining trees, fertilization and thinning continue to show a positive interaction. (Sect. 3.2).

The response surfaces in Figure 10 show how diameter and gross volume increment on a land area basis respond at 3 and 6 years, with respect to thin-

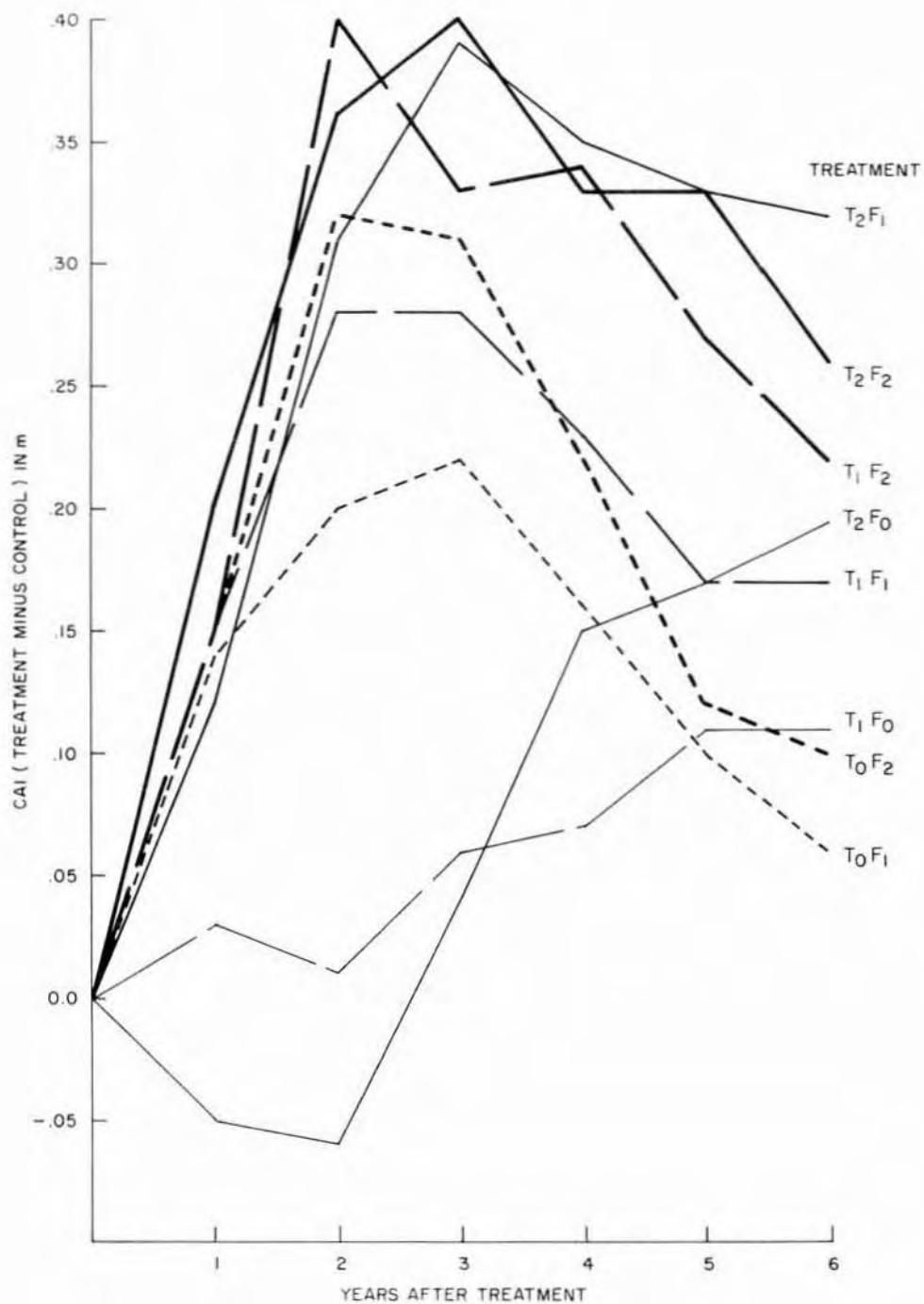


Fig. 12. CAI for height for all volume sample trees by treatment.

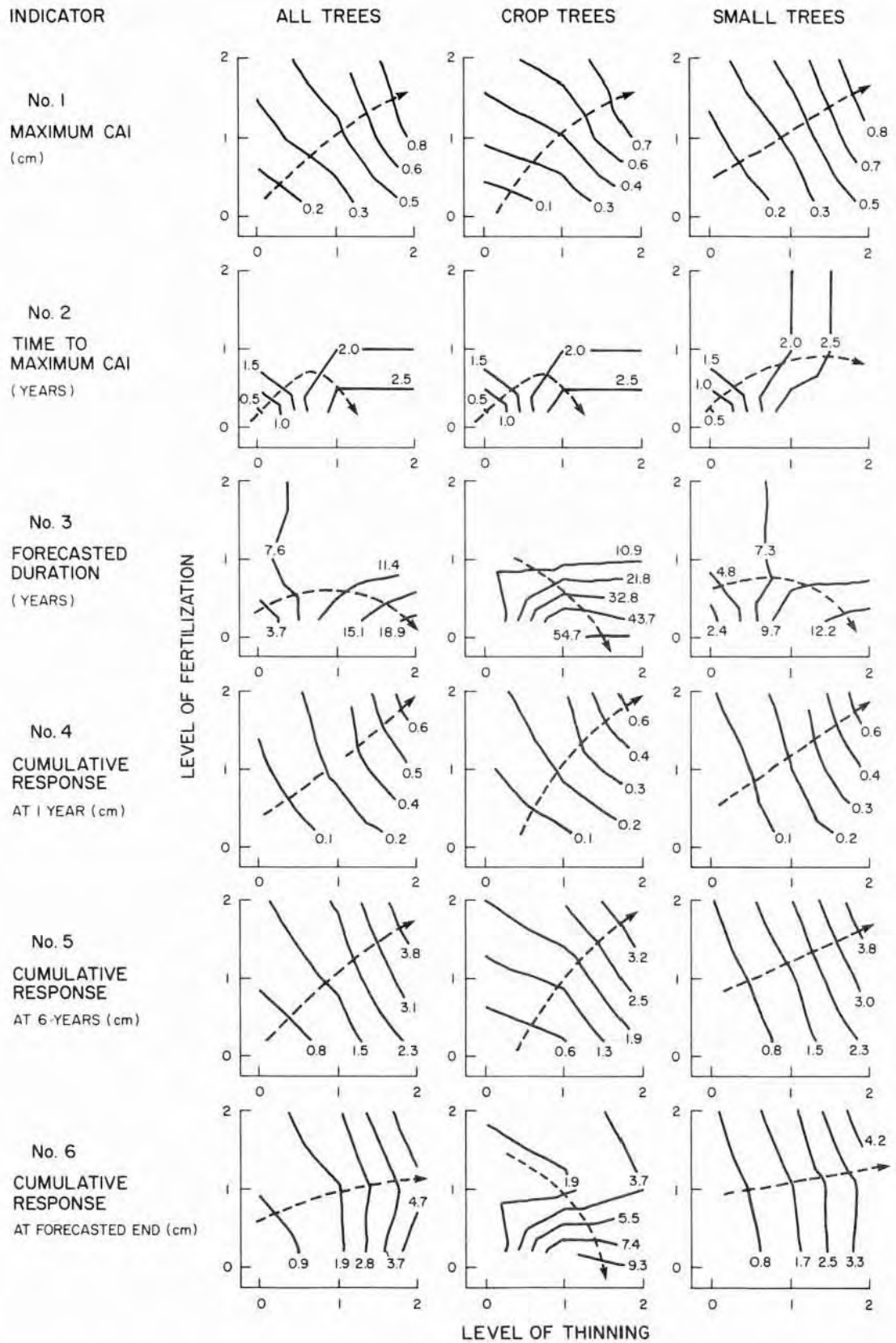


Fig. 13. Response surfaces of indicators of diameter growth response for the volume sample trees.

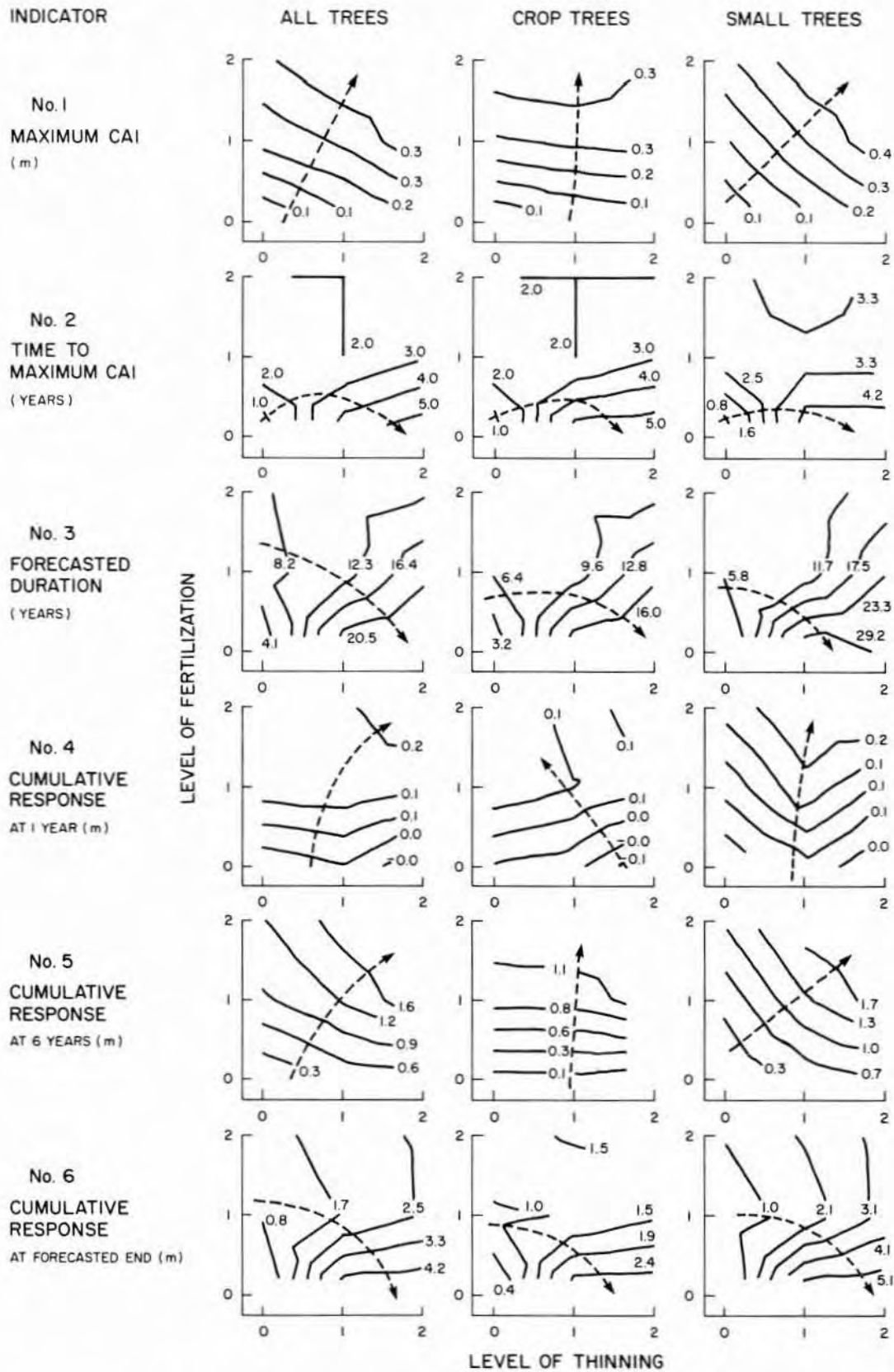


Fig. 14. Response surfaces of indicators of height growth response for the volume sample trees.

ning and fertilization. By viewing level and combination of thinning and fertilization as options within a stand management regime, Figure 10 can indicate (for this site-specific situation) what management options would meet particular management objectives; the objectives, in this case, being stated in terms of desired values of volume (or MAI, since stand age is known) versus tree size (dbh) versus intended time of utilization (years after treatment). This use of Figure 10 would apply to response surfaces generated for more or different indicators and can be expanded to include statistical weighting or summing of different indicator surfaces into composite surfaces (Peterman 1975).

On a land area basis (Fig. 1 and Tables 2, 3 and 4) or on an individual tree basis (Figs. 11 and 12), response at 6 years is generally tapering off; PAI (gain above control) is generally less for the second measurement period (3 to 6 years) than for the first period (0 to 3 years). This, however, is not the case for individual tree height increment for thinning with no fertilization (Fig. 12). The apparently longer response period of volume to thinning than to fertilization (Sects. 3.1 and 3.2), based on a comparison of volume PAIs in the 0 - 3 and 3 - 6 measurement period, is a result of the delayed height growth response to thinning alone. If the present trends in height response to thinning alone persist, it could lead to:

- an increase in height growth for thinning alone, as has been observed elsewhere (Reukema 1970), and
- a volume response for thinning alone which could "catch up" to the volume response for thinning and fertilization in combination.

The faster and larger but shorter-lived response of tree diameter compared to tree height suggests a complex relation between treatment and height/diameter relationships. Stem form has not been observed to change significantly with treatment (Sect. 2.1). Crown development and tree mortality have both behaved as might be expected, showing a more rapid crown base lift-off, greater reduction in live crown ratio and greater probability of mortality for the smaller, more suppressed trees, which are subjected to the more dense (in terms of number of stems/ha or amount of foliage) stand condition.

Forecasting and generalizing response, observed here for only a part of its duration and for a parti-

cular site-stand-treatment situation, is a particularly difficult, yet important, issue. Only forecasting of the observed response has been attempted here. Doing so raises the question of whether response is transient or permanent. Developmental changes with respect to treatment, as detected by various measures of stand structure (mortality, crown development, diameter distribution), indicate that treatment does alter underlying stand structure, in addition to producing the more readily observed changes in increment. To the extent that stand structure affects stand development, treating a stand can be expected to send the stand along a permanently different development trajectory. The view that response lasts for a definite, measurable time and that after this time the treated stand resumes development similar to the untreated stand should be regarded as an assumption and an approximation.

It is very difficult to quantify this aspect of response. A useful way to view response, however, may be as the summation of two components:

- 1) a shorter-lived component which affects increment directly by directly affecting tree growth environment: in this case, the nutrient and moisture regimes (and to a lesser extent the light regime) by fertilization, and the light regime (and to a lesser extent the nutrient and moisture regimes) by thinning, and
- 2) a longer-lived component which will continue to affect increment through the different stand structures which are produced by the shorter component.

Both of these components, in theory, are always present and operative. Their relative importance, however, is a function of the particular site-stand-treatment situation and how long after treatment is the intended use of the treated stand. This view of response suggests that information about such a longer component, about which we possess relatively less information, is necessary to understand and evaluate response to treatments carried out in juvenile, young and immature stands.

Whatever ways are devised (or chosen) to measure stand response to stand management regimes, an evaluation of response, and therefore a development of management guidelines, is dependent upon what measures of response are chosen (volume per hectare, tree size, MAI, a measure of stem form or stand uniformity, etc.) and when the response is evaluated.

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