

Volume Growth Trends in a Douglas-Fir Levels-of-Growing-Stock Study

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ABSTRACT: Mean curves of increment and yield in gross total cubic volume and net merchantable cubic volume were derived from seven installations of the regional cooperative Levels-of-Growing-Stock Study (LOGS) in Douglas-fir. The technique used reduces the seven curves for each treatment for each variable of interest to a single set of readily interpretable mean curves. To a top height of 100 ft and corresponding average age of 45 years, volume growth and yield are strongly related to stocking level, being highest at the highest stocking levels. At that point, current annual increment is still far greater than mean annual increment. Thinning has accelerated diameter growth of the largest 40 trees per acre as well as of the stand average. Maximum volume production would be obtained at stand relative densities approaching the zone of competition-related mortality, although in practice considerations of feasibility of frequent entries and wildlife and amenity considerations would make somewhat lower average levels necessary. *West. J. Appl. For.* 21(2):79–86.

Key Words: Thinning, stocking, growth, yield, *Pseudotsuga menziesii*.

The Levels-of-Growing-Stock Study (LOGS) is a long-term cooperative study of the relationship between stocking level and increment in coast Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) that began in 1961. The cooperators are the USDA Forest Service, the Weyerhaeuser Company, Oregon State University, the Washington Department of Natural Resources, the Canadian Forest Service, and the British Columbia Ministry of Forests. The stated objective was “to determine how the amount of growing stock retained in repeatedly thinned stands of Douglas-fir affects cumulative wood production, tree size, and growth-growing stock ratios” (Staeble and Williamson 1962). The study was stimulated in part by questions about the then commonly held belief that essentially the same production could be obtained over a wide range of stand densities, and that thinning merely redistributed a constant gross increment among varying numbers of trees (Staeble 1960).

Of nine LOGS installations established from 1961 to 1970 in western Washington, western Oregon, and on Vancouver Island, seven have completed the planned course of treatment; five of these are on good sites (II) and two are on medium sites (III). The two remaining installations are on poor sites (IV) and are still incomplete; one of these has been so severely damaged by root disease and windfall as to raise doubts about its usefulness in any analysis.

Reports have been published on the seven completed installations (Beddows 2002, Curtis and Clendenen 1994,

Curtis and Marshall 2002, Hoyer et al. 1996, King et al. 2002, Marshall et al. 1992, Marshall and Curtis 2002). Until now there has been no combined analysis across installations, beyond that of Curtis and Marshall (1986) based on incomplete data. With seven installations and eight density control treatments, there are 56 different growth trends for each variable of interest. These are cumbersome and difficult to grasp, although there are general similarities in trends observed and conclusions drawn to date for the individual installations (Curtis et al. 1997).

This report reduces the information on volume growth trends to a more compact and more readily understandable form. The initial analysis was in terms of gross growth in total stem cubic volume (CVTS). This measures biological productivity in bolewood volume and was selected in part because of the expectation that this would be less influenced by erratic values arising from mortality than would be the case with net volume. A parallel analysis was made for net growth in merchantable cubic volume to a 6-in. top (CV6), which is probably of more interest to management-oriented foresters. Trends in yield, mean annual increment (MAI), and current annual increment (CAI) were expected to differ somewhat for the two volume measures.

Study Design

The seven LOGS installations used in this analysis (Clemons, Francis, Hoskins, Iron Creek, Sayward, Skykomish, and Stampede Creek) included both plantations and naturally seeded stands. Each installation consisted of 27 one-fifth-acre plots selected to meet stringent standards of

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uniformity and of comparability in site and stocking. Each included three replications of eight thinning treatments and unthinned control, with treatment allocation completely randomized. All plots except the controls received an initial calibration thinning to adjust them to as nearly identical density and structure as possible, with residual density defined by the spacing rule:

$$\text{Spacing} = 0.6167 \cdot \text{QMD} + 8,$$

where spacing is in feet and QMD is quadratic mean diameter in inches. Sixteen crop trees were selected on each plot on the basis of spacing and apparent vigor, to be favored in thinning and used as the basis for mean stand top height. Loss of some trees and changes in vigor during the course of the experiment later led to substitution of the nearly equivalent 40 trees per acre (eight per plot) of largest diameter as the basis for top height, hereafter referred to as H40.

After an initial 10 ft of height growth and at intervals of ~10 ft thereafter, five treatment thinnings were made. Some trees were removed from all crown classes, with average diameter of cut trees approximating the average diameter of noncrop trees. d:D ratios (ratios of average diameter of trees cut to average diameter of all trees before cutting) were usually in the range of 0.90 to 0.95. Residual growing stock levels were defined by retention of specified percentages of the gross basal area growth observed on the control during the previous period (Table 1), thereby defining levels in terms of productive capacity of the site and providing eight treatments that increased in basal area at very different rates. Treatments 1, 3, 5, and 7 will be referred to as "fixed" treatments; treatments 2 and 4 as "increasing" treatments; and treatments 6 and 8 as "decreasing" treatments, corresponding to the direction of change in retention of growing stock (Table 1).

Analysis

Methods

The original study plan called for analysis of variance (ANOVA) as the primary analysis method for individual installations. A repeated measures ANOVA was applied to each individual installation. The results are given in the publications cited above and show a general similarity in results among installations. Namely:

- There were no significant differences between fixed versus variable treatments in periodic annual increment in volume, basal area, or diameter.

Table 1. Levels-of-growing-stock study treatment schedule showing percentages of gross basal area increment of control retained at each thinning (after calibration thinning).

Thinning	T-1	T-2	T-3	T-4	T-5	T-6	T-7	T-8
First	10	10	30	30	50	50	70	70
Second	10	20	30	40	50	40	70	60
Third	10	30	30	50	50	30	70	50
Fourth	10	40	30	60	50	20	70	40
Fifth	10	50	30	70	50	10	70	30

- Differences between increasing versus decreasing treatments and those between increasing treatments were consistently significant.
- Differences among increasing treatments were consistently significant for volume and basal area, and were significant for diameter in some but not all installations.
- Differences among decreasing treatments were significant in some but not all installations.

Associated graphical and regression analyses provided much additional information about the nature of the differences. A combined analysis of all data is less straightforward than analyses for individual installations. The data consist of sequences of repeated measurements for each treatment within each installation, where installations differ considerably in productivity and additional variation is introduced by differences in the age and height at which each installation was established.

It was hypothesized that the seven installation growth curves for an individual treatment could be reduced to a single interpretable average curve or equation for a given characteristic. The most common approach to similar problems is to express growth or yield as a function of site index and age. However, in LOGS, rate of development and hence years between measurements and between treatment thinnings vary with site quality. Any expression in site index and age must involve some (possibly complicated) interactions, not readily estimable when only seven installations are available. And, the hierarchical nature of the data makes regressions fit to the pooled data questionable from a statistical standpoint; significance tests and conventional measures of fit are clearly invalid.

The procedure here adopted for analysis of volume relationships consisted of the following steps:

1. For each treatment within each installation, fit a function, cumulative volume = $f(\text{H40})$, where H40 is defined as mean height of the largest (by diameter) 40 trees per acre.
2. Use (1) to interpolate estimates, for each treatment within each installation, of cumulative volume production corresponding to 5-foot intervals of H40.
3. Calculate mean volume production of each treatment across installations for each 5-foot interval of H40.
4. Derive an equation estimating age from H40 and site index, and use this to convert the estimates of (3) to an age basis.
5. For each treatment, the values obtained in (4) then define the volume production curve for the mean site productivity.
6. The estimates of (5) can then be converted to estimates of CAI by differencing the volume production curves.

Site Productivity Classification

Comparisons of curves of height over age in LOGS show that although five installations track King's (1966) height

growth curves closely, one (Skykomish) is somewhat different and one (Stampede, in southwest Oregon) is considerably different. And, one installation (Skykomish) has a major hemlock component, which makes interpretation of a Douglas-fir site index somewhat problematic.

The LOGS study plan (Staebler and Williamson 1962) specified thinning interval by a fixed amount (10 ft) of height growth, and amount of growing stock to be retained at each thinning was specified as percentages of the gross basal area growth observed on the untreated control plots. It was assumed that gross basal area production of the controls represented potential productivity of the site, which may or may not be adequately expressed by site index (S). [The existence of differing production potentials within classes defined by height development (site index) is well established in some European work (Assmann 1959, 1970, Hummel and Christie 1957), and is suggested by some anomalies in the LOGS data, discussed later.]

These considerations suggested that for a given treatment and installation, thinned plot production could be expressed as a function of top height. This could then be converted to an age basis using an equation, $age = f(H40, S)$, derived either from existing site index curves or by direct fitting to the LOGS data. Other values such as MAI and CAI could then be derived from the volume production equation.

The above general procedure, based on Eichhorn's rule, has long been used in Europe in preparation of yield tables (Assmann 1970, Hummel and Christie 1957; and has been applied to Douglas-fir in British Columbia as explained by Mitchell and Cameron (1985). The Hummel and Christie publication was contemporaneous with Staebler's (1960) development of the ideas in the LOGS study plan and very likely influenced his thinking.

Data used are from Marshall (2003). Values of site index (S) and top height (H40) were calculated individually by treatments within installations. Site index is from King (1966) using observed top height nearest to age 50 at breast height. Age in the following discussion is total age. CVTS is cubic volume of total stem, inside bark, and including stump. CV6 is merchantable cubic volume to a 6-in. top inside bark.

Production as a Function of Top Height

Plots by installation of cumulative gross CVTS production of controls over H40 show considerable differences in elevation of the curves (Figure 1), which have little relationship to site index. Thus, the two installations with the highest site indices (Hoskins and Skykomish) are at the opposite margins of the sheaf of curves. Relationships for basal area are similar. Some means of accounting for differences in productivity is clearly needed, though conventional site index is not very effective in these data (which represent a fairly limited range in site indices).

An alternative measure of site productivity that appears to be more effective, and consistent with Staebler's (1960) thinking as shown by the study plan, is cumulative gross CVTS production of controls at a standard H40, here taken as 100 ft (corresponding approximately to completion of the

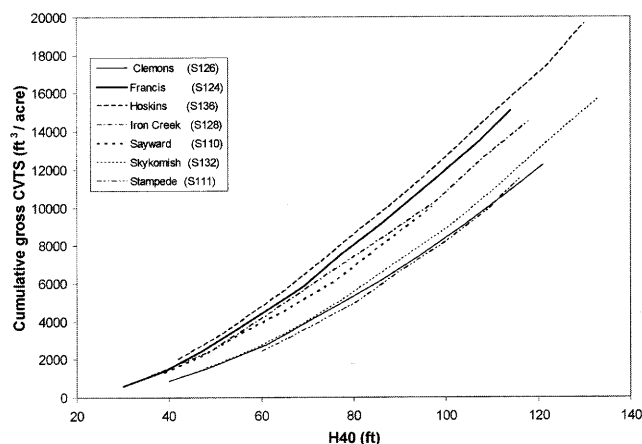


Figure 1. Gross CVTS yield of controls in relation to top height, by installation.

sequence of thinnings). These values (P) are shown in Table 2, by installation. Mean P was 10,196. Mean site index of thinned plots was 124. Similar data plots for each of the thinning treatments show a more or less similar ordering of gross volume production by installation, with Clemons, Skykomish, and Stampede consistently low for a given H40.

Calibration Cut Volumes

Appreciable CVTS volumes were removed at the calibration cut, and some estimate of these removals should be included as part of total production. Volumes removed at calibration were estimated as differences between volume of controls at the time of initial entry and mean volume of thinned plots on the same installation after the calibration cut (Table 3).

When plotted over initial H40, values for five installations fall in a virtual straight line, whereas Hoskins is considerably higher and Skykomish is somewhat lower. The high value for Hoskins probably reflects dense regeneration that presumably would not influence development after calibration.

The regression

calibration cut removal =

$$-146.07 + 17.8086 \cdot (\text{initial H40}) \quad (1)$$

was used to estimate a calibration removal to be added to postcalibration volume in the computation of cumulative

Table 2. Gross cumulative production in CVTS of controls at H40 = 100 ft (P) and corresponding site indices, by installation.

Installation	P (cumulative CVTS at H40 = 100 ft) (ft³/acre)	Site index (mean of thinned plots) (ft)
Clemons	8,412	126
Francis	11,970	124
Hoskins	12,605	136
Iron Creek	10,778	128
Sayward	10,555	110
Skykomish	8,854	132
Stampede Creek	8,195	111

Table 3. Estimates of total cubic volumes (CVTS) removed in calibration cut.

Installation	Volume removed (ft ³ /acre)
Clemons	373
Francis	234
Hoskins	1,249
Iron Creek	446
Sayward	557
Skykomish	329
Stampede Creek	954

gross CVTS production. (Because calibration removal in CV6 was near zero, this step was omitted in later analysis of CV6 relationships.)

Conversion from Height to Age

The basic Eichhorn procedure involves a conversion from a height basis to an age basis. This analysis used a regression fit directly to the pooled individual period measurements from the seven installations:

$$\begin{aligned} \text{Age} = & b_0 + b_1 \cdot \text{H40} + b_2 \cdot \text{H40}^2 + b_3 \cdot \text{H40}^3 \\ & + b_4 \cdot S \cdot \text{H40} + b_5 \cdot S \cdot \text{H40}^2 + b_6 \cdot S^2 \cdot \text{H40} \\ & + b_7 \cdot S^2 \cdot \text{H40}^2, \quad (2) \end{aligned}$$

with

$$\text{RSQ} = 0.99 \quad \text{and} \quad \text{RMSE} = 1.09.$$

This equation was used in all subsequent conversions from a height to an age basis.

Gross CVTS Production

Cumulative Gross CVTS Production in Relation to H

Interpolation equations were fit separately to data for each treatment within each installation, using all available data. The equation form used was:

$$\begin{aligned} \ln(\text{cumulative CVTS}) = & b_0 + b_1 \cdot (1/\text{H40}) + b_2 \cdot \text{H40} \\ & + b_3 \cdot \ln \text{H40} + b_4 \cdot (\ln \text{H40})^2. \quad (3) \end{aligned}$$

In all cases this gave very close fits to the data (RSQ = 0.99+).

Plotting of the seven installation curves for each treatment showed that with the possible exception of the very lowest stocking treatments (1, 2, 3) there was a fairly consistent ranking by installation among the various treatments. The curves for a given treatment were similar in shape and strongly suggest that a single average curve would be a good representation for the mean productivity condition.

Estimates from these curves were tabulated by 5-ft intervals of H40. Means were calculated for the seven installation estimates for each treatment, and these when plotted gave the curves of mean gross CVTS production over H40 shown in Figure 2. Means were not calculated for H40 greater than 100 ft, the greatest common height in the data. Equation 2 and the overall mean site index of 124 were then used to convert H40 values to corresponding estimated ages,

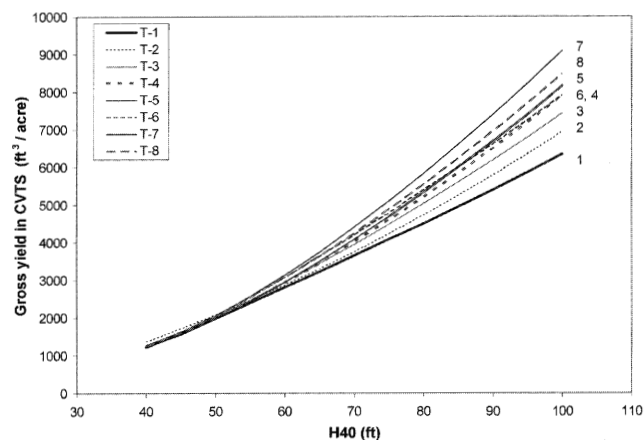


Figure 2. Treatment means of cumulative gross CVTS yields in relation to top height.

producing the curves of mean gross CVTS production over age shown in Figure 3.

Mean Annual Increment (MAI)

Values of MAI, shown in Figure 4, were calculated by dividing the estimated yields by the corresponding ages.

Current Annual Increment (CAI)

CAI in gross CVTS was approximated as $(\text{CVTS}_2 - \text{CVTS}_1) / (A_2 - A_1)$, using ages corresponding to 5-ft increments in height. These values are plotted over the corresponding mid-period ages in Figure 5.

Net CV6 Production

The above curves of cumulative gross CVTS represent biological production of stem wood. Up to height 100 ft, mortality losses have been slight although increasing with height, and there is not much difference between gross and net CVTS. However, practically oriented foresters are generally more interested in net production of harvestable material. Therefore, a parallel analysis was done in terms of net merchantable cubic volume production to a 6-in. top (CV6), which can be expected to differ somewhat from values for gross CVTS production. The origin of the system is necessarily different, and curve

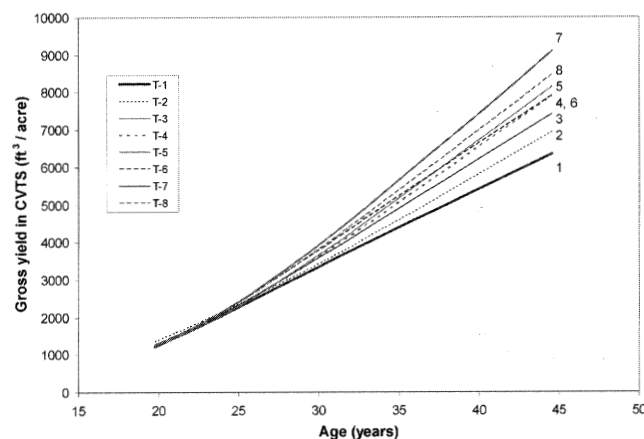


Figure 3. Treatment means of cumulative gross yields in CVTS in relation to age.

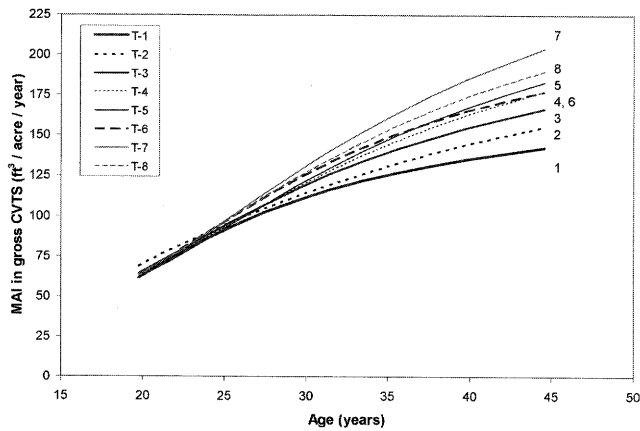


Figure 4. Treatment means of MAIs in gross CVTS in relation to age.

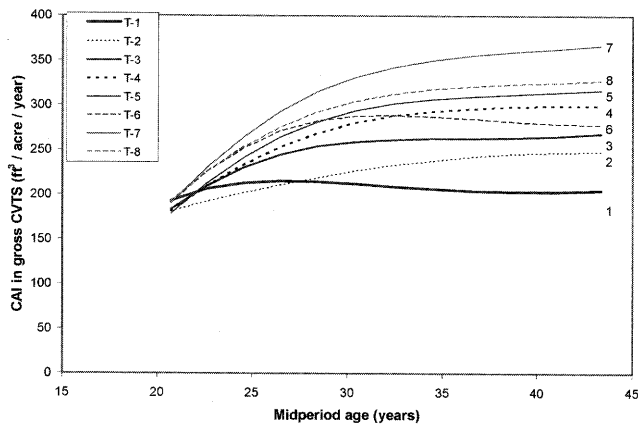


Figure 5. Treatment means of CAIs in gross CVT in relation to age.

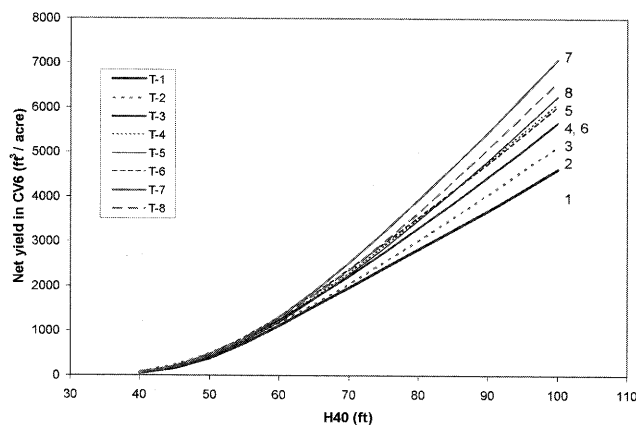


Figure 6. Treatment means of net yields in CV6 in relation to top height.

shapes will also differ somewhat because of the changing ratio of merchantable to total volume with increase in tree size.

Cumulative Net CV6 in Relation to H40

The procedure used paralleled that for gross CVTS, using the initial equation form:

$$\ln(\text{cumulative net CV6}) = a + b_1 + b_2 \cdot (1/X) + b_3 \cdot X + b_4 \cdot \ln X + b_5 \cdot (\ln X)^2 + b_6 \cdot (\ln X)^3, \quad (4)$$

where $X = H40 - 30$. This was fit separately to data for each treatment within each installation, and terms making negligible contribution were deleted. This gave very close fits to the data points. Estimates for each treatment at intervals of 5 ft in height were averaged overall installations for H40 values up to 100 ft (Figure 6). These were then converted to curves of volume production over age (Figure 7), using Equation 2.

MAI in Net CV6

This was obtained by dividing the mean net CV6 for successive ages by the corresponding ages (Figure 8).

CAI in Net CV6

CAI values were estimated as $(V_2 - V_1)/(age_2 - age_1)$, and are shown in Figure 9.

Attained Diameters

Although the primary analysis here is in terms of cubic volume, the effects of treatment on diameter are also important. Means of quadratic mean diameter (QMD) of all trees and mean diameters of the largest 40 trees per acre (D40) corresponding to $H40 = 100$ ft were calculated and are compared in Figure 10. Corresponding standard errors and coefficients of variation (CVs) are shown in Table 4.

Discussion

The LOGS study plan specified that installation initial heights should be in the range of 20 to 40 ft. Thinnings were to be made at intervals of 10 ft of height growth. Thinning removals were specified as percentages of gross basal area increment of the untreated controls.

Actual installation means of initial heights ranged from 28 ft (Francis) to 59 ft (Stampede), with a mean of 41 ft. Thus, a given height does not represent an identical stage in the treatment sequence in different installations, and differences must have some effect on the relations of volume and basal area to H40. To whatever extent gross basal area

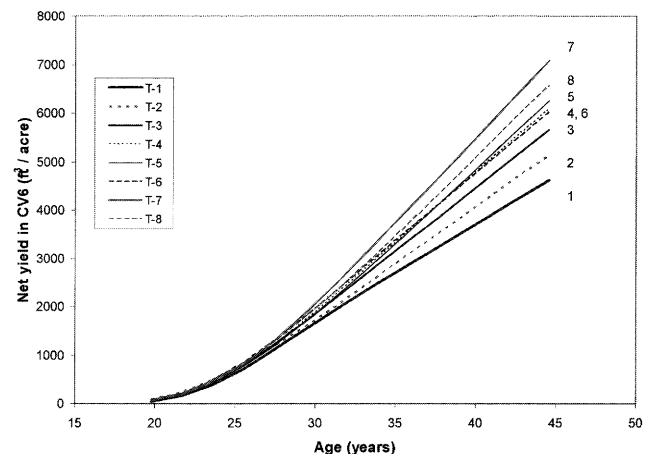


Figure 7. Treatment means of net yields in CV6 in relation to age.

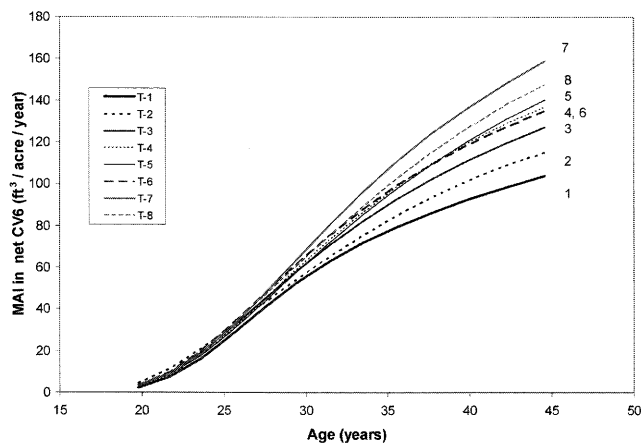


Figure 8. Treatment means of MAIs in net CV6 in relation to age.

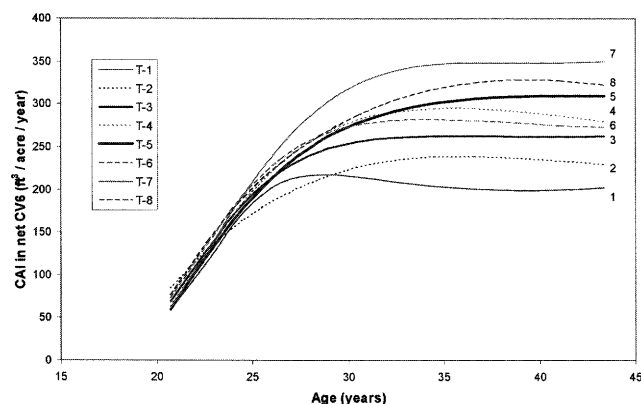


Figure 9. Treatment means of CAIs in net CV6 in relation to age.

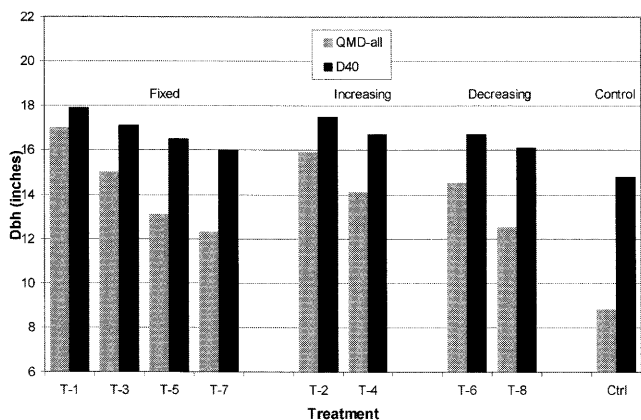


Figure 10. Comparison among treatments of quadratic mean diameters of all trees and of average diameters of the largest 40 trees per acre, at an attained height of 100 ft.

increment declines with increasing height (and age), differences in initial height among installations might also introduce some differences in thinning removals. And, the values of H40 used in the analyses were not overall installation values, but were calculated for the individual treatments within an installation. Consequently, there is some variation

Table 4. Means, standard errors of the mean, and coefficients of variation of QMD of all trees, and of D40 at H40 = 100 ft, by treatments.

Treatment	QMD, all			D40		
	Mean (in.)	SEmn (in.)	CV (%)	Mean (in.)	SEmn (in.)	CV (%)
Fixed						
1	17.0	0.6	10.0	17.9	0.5	8.1
3	15.0	0.4	7.7	17.1	0.4	6.2
5	13.1	0.3	5.5	16.5	0.3	4.8
7	12.3	0.4	7.6	16.0	0.4	7.1
Increasing						
2	15.9	0.6	0.4	17.5	0.5	7.8
4	14.1	0.4	8.2	16.7	0.5	7.4
Decreasing						
6	14.5	0.5	9.4	16.7	0.5	8.7
8	12.5	0.4	8.0	16.1	0.3	5.6
Control	8.8	0.2	6.6	14.8	0.3	5.6

in H40 values within an installation, which is a combination of sampling error and minor site differences. However, the above differences are not large and are believed to have little effect on overall means.

Installations on good sites develop faster than those on poorer sites. This fact and the differences in initial heights mean that installations differ considerably in the maximum ages and heights in the presently available data. Maximum H40 ranges from ~100 ft (Sayward) to 135 ft (Hoskins). All seven installations have completed the 60 ft of height increment specified in the study plan. One might expect a change in growth trajectory after cessation of thinning, especially in those treatments with low stocking levels.

Heights greater than 100 ft were included when fitting the individual regressions. But, for heights greater than ~100 ft, means are based on a progressively decreasing subset of the seven installations and could involve substantial biases. Consequently, the curves and interpretations presented are limited to heights less than 100 ft, although means for greater heights might be suggestive. One hundred ft approximates completion of the sequence of thinnings. For the mean site index, 100 ft corresponds approximately to age 45 (which is now a not uncommon rotation for industrial lands on the better sites).

Graphs of the individual regressions of CVTS on H40 for a given treatment form sheaves of curves of generally similar shape but differing in elevation. For the more heavily stocked regimes (treatments 4 to 8), the ordering by elevation resembles that of the controls (Figure 1). There is little evident relation to site index.

Coefficients of variation were calculated for the seven installation estimates of cumulative CVTS for each treatment for each 5-ft successive value of H40 (Figure 11). Similar values were also calculated for the variable (cumulative CVTS)/P, where P is cumulative CVTS of the control at H40 = 100 ft (Figure 12). The results show that for treatments 4 to 8, division by P markedly reduces the coefficient of variation, indicating that P is an effective measure of site productivity. A similar calculation using CVTS/S, where S is site index, showed negligible reduction in the coefficient of variation. This is consistent with Staebler's (1960) hypothesis

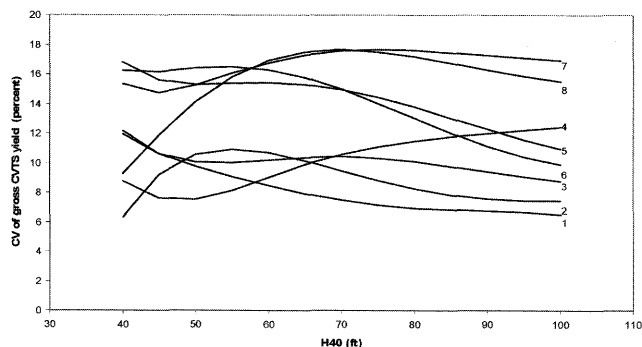


Figure 11. Coefficients of variation of CVTS in relation to H40, by treatments.

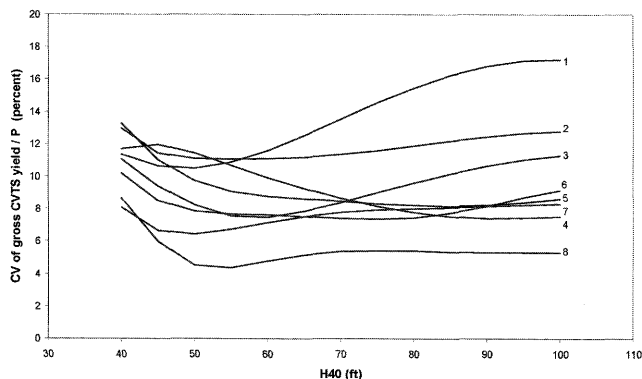


Figure 12. Coefficients of variation of the variable (CVTS/P) in relation to H40, by treatments.

that observed production of the control would be a better expression of site productivity than conventional site index. The lack of improvement when P is introduced in treatments 1 to 3 may mean simply that at these low stocking levels trees are relatively free-growing and are little influenced by position relative to whatever maximum stocking level may exist for the installation.

The procedure used here, in which cumulative volume production of thinned plots is expressed as a function of plot treatment and top height, has provided an apparently satisfactory means of reducing data from multiple installations to overall mean relationships. The seven installations involved are comparatively young and still in the period of rapid height growth, and represent a fairly restricted range of site indexes. It does not follow that the procedure would necessarily be satisfactory over a wider range of ages and site, and some European work (Assmann 1959, 1970, Hamilton and Christie 1971) suggests that a widely applicable system should involve both a conventional site index classification based on height and age, and a supplementary classification expressing productivity differences within site index classes. Seven LOGS installations with a limited range of sites and ages cannot address the question.

Management Implications

LOGS was not designed as a comparison of operationally feasible thinning regimes, but as an effort to define the relationships between stocking levels and growth. Nonethe-

less, the results do have implications for practical stand management.

Volume Production

The most striking result, consistent with previous individual installation reports, is that at age 45 on site II—corresponding to the greatest common height in the data of ~100 ft—CAI is still nearly twice MAI (Figure 13). These stands are obviously far short of culmination. Harvest at a height of 100 ft would mean a large reduction in cubic volume production compared to the potential.

The various figures presented show clearly that volume production increases with stocking level. This is much more evident in volume than in similar curves for basal area, a difference attributed to the rapid and prolonged height growth characteristic of coast Douglas-fir. Highest production among thinning treatments was attained in treatment 7, which was designed to produce a stocking just below that at which competition-related mortality can be expected.

The controls exceeded all thinned treatments in gross total volume (CVTS) production up to a height of 100 ft, with an average of 17% higher production than treatment 7, the most productive thinning treatment. In contrast, treatment 7 has on average approximately six percent higher production in net CV6 than the controls. The difference between gross CVTS and net CV6 values arises primarily from the onset of competition-related mortality on the controls, and secondarily from changes in CV6/CVTS ratios with increasing tree diameters. With the increasing mortality in the controls (associated with increase in stand density with age), this advantage in net production appears to be increasing in the most recent measurements (beyond 100 ft) in several of the more advanced installations, and in some cases includes treatments 5 and 8. Gains in net CV6 from thinning, small up to this point, can be expected to increase with increasing age.

Comparisons of production of thinned treatments with controls are somewhat suspect because of probable edge effects in these small (one-fifth acre) unbuffered plots. (Sayward, unlike the others, does have buffers). Thinned plots are generally surrounded on at least three sides by other thinned plots whose conditions are not radically different,

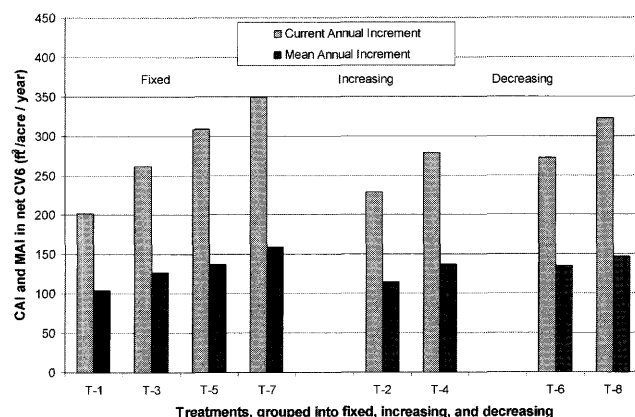


Figure 13. Comparison of CAI and MAI in net CV6 at top height of 100 ft and corresponding mean age of 45 years, treatment means.

although not identical, and large edge effects seem unlikely. In contrast, the control plots are surrounded by thinned plots of much lower stocking; a fact that must affect growth of border trees. It seems likely that production of these small control plots may be somewhat higher than would be possible on large plots with similar initial conditions, and that the relative advantage in volume production of controls over thinned treatments may therefore be slightly overestimated.

Diameter Growth

There are substantial differences in diameters attained at 100 ft height, both in quadratic mean diameter (QMD) of all trees and in average diameter of the largest 40 trees per acre (D40). Values shown in Figure 10 are means of QMD and D40 for each treatment across all seven installations, grouped by treatment categories.

Large differences in mean QMDs are obvious. On thinned plots these arise in part from removal of small trees in the calibration cut, in part from the removal in later thinnings of trees of somewhat less than the average diameter of the stand, and in part from accelerated growth. Several of the controls contain large numbers of small trees that would have been removed if there had been a calibration cut.

In contrast to the average of all trees, average diameter of the 40 largest trees per acre (D40) is little affected by selective removal of trees in thinning. If anything, it might have been slightly reduced by the initial choice of crop trees on the basis of spacing as well as size and vigor. Thinning has produced a gain in D40 of 1.9 in. for the highest versus lowest stocking regimes (T-7 versus T-1). Compared to controls, gains range from 3.1 in. for treatment 1 to 1.2 in. for treatment 7. Clearly, thinning has increased diameter growth of dominant trees as well as those of lower crown position.

Stocking

The very frequent light thinnings used in LOGS would not be feasible operationally, but were adopted to maintain close control over stocking levels and elicit biological effects of competition and site occupancy. Generally similar results could probably be obtained with considerably longer thinning cycles and larger removals, designed to provide approximately similar average stocking levels.

Maximum cubic volume production will be obtained with fairly high stocking levels, approaching the zone of imminent competition-related mortality (i.e., below a Reineke stand density index of ~350 or Curtis relative density of ~60). On very short rotations this could mean wide initial spacing (designed to reach the above levels at rotation) and no commercial thinning. On somewhat longer rotations intermediate thinning will enhance stand stability, provide some control of species composition and stem quality, increase diameter growth rates, provide some current income and modest increases in net merchantable volume production, and promote changes in

stand structure and understory vegetation that may be desirable from wildlife and amenity standpoints. These last considerations will be very important with the long rotations intended to meet biological and social objectives that are of increasing importance on some public lands.

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