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Development of Top Heights and Corresponding Diameters in High-Elevation Noble Fir Plantations

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Abstract

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Height and diameter growth of noble fir (*Abies procera* Rehd.) trees included in the largest 40 stems per acre were compared in a study that included five precommercial thinning spacings plus no thinning, in each of eight replications, at elevations from 2,200 to 4,100 feet in the western Cascade Mountains of Washington and Oregon. Height growth rates were not affected by spacing. The unthinned treatment had slightly greater initial heights, a difference that probably arose from the method used to select leave trees in thinning. Height trends differed markedly from those given in Herman et al. (1978); which should not be used in plantations. Spacing had a considerable though highly variable effect on diameter growth of these dominant trees. New top height/age curves are presented, which can be used for interim site classification pending availability of data that includes a greater range of ages.
Keywords: Nobile fir, plantations, thinning

Summary

Height and diameter growth of noble fir (*Abies procera* Rehd.) trees included in the largest 40 stems per acre were compared in a study with eight replications of five precommercial thinning spacings plus an unthinned treatment. Elevations were from 2,200 to 4,100 feet in the western Cascade Mountains of Washington and Oregon. Seven installations were in the *Abies amabilis* Zone, and one in the *Tsuga mertensiana* Zone. Height growth rates were not affected by spacing. The unthinned treatment had slightly greater initial heights, a difference that probably arose from the method used to select leave trees in thinning. Spacing had a considerable though highly variable effect on diameter growth of these dominant trees. Height trends differed markedly from those given in Herman et al. (1978); which should not be used in plantations. Possible reasons for the difference are discussed. New top height/age curves are presented, which can be used for interim site classification pending availability of data that includes a greater range of ages.

Introduction

Background

Extensive harvesting in Pacific Northwest high-elevation true fir-hemlock forest began in the early 1950s. Early operations commonly followed practices that had been generally successful in lower elevation Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco): namely, clearcutting followed by slash burning and planting—often with Douglas-fir. Many of these early plantations failed, and regeneration by natural seeding took place over an extended period of years.

In subsequent years, better species selection combined with improvements in nursery, site preparation, and planting practices greatly improved survival of planted trees and produced many successful plantations.

Extensive precommercial thinning (PCT) began on national forests in the late 1970s. A common practice was to thin at an early age to 350 to 400 stems per acre. There were concerns about the effects of number of residual trees on future stand development and the potential productivity of such stands.

Noble fir is a highly promising species for high-elevation sites, but data for young stand development is largely lacking.

These concerns led to establishment of a spacing and yield study (C72) to compare the effects of thinning to a range of spacing on tree and stand development and to provide a basis for yield estimates for young managed stands. This study included 18 locations considered ready for PCT under then-current operational practice, located in the western Cascade Mountains and the Olympic Mountains. The overall study was described in more detail by Curtis et al. (2000) and Curtis (2008, 2013).

Noble fir (*Abies procera* Rehd.) is a highly promising species for high-elevation sites, but one for which data on young stand development is largely lacking. The present report—unlike the 2013 report—is confined to a subset of the C72 data consisting of eight noble fir plantations (including some measurements not available for the 2013 report), plus very limited data from another study (C45). A ninth C72 noble fir plantation, Alpine, was not used because several treatments did not contain sufficient noble fir.

Previous Research

Franklin (1982, 1990) has reviewed past research on noble fir. Most of the existing knowledge is derived from observation of existing stands rather than from planned experiments. Demonstrated characteristics of the species are very slow juvenile height growth, followed by a long period of relatively rapid and nearly linear growth, with moderate height growth continuing to advanced ages. It is the least shade-tolerant of the true firs, being more or less comparable to Douglas-fir in this respect. Noble fir can develop large trees of excellent stem form on relatively poor high-elevation sites and is highly resistant to snow breakage.

Harrington and Murray (1982) compared height growth patterns of noble fir with that of Douglas-fir and concluded that the long period of nearly linear height growth characteristic of noble fir could enable it to outgrow Douglas-fir on some sites, despite an initial disadvantage.

Analyses compared development of top height of noble fir among spacings. Similar comparisons were made for mean diameters of noble fir trees in the top height component.

Herman et al. (1978) developed height growth (site index) curves for noble fir, based on stem analyses of an extensive sample of mature trees in naturally established stands.

Murray et al. (1991) compared height growth of young planted noble fir with the height growth estimates of Herman et al. (1978) and concluded that the young stands they sampled were growing much more rapidly than predicted.

Objectives

The analyses here reported aimed to compare development of top height of noble fir (H40) among initial spacings, where H40 is defined as mean height of those noble fir trees included in the largest 40 trees per acre (by diameter) of all species present. Similar comparisons were also made of the mean diameters (D40) of noble fir trees in the top height component.

This definition was selected both because there is considerable precedent for use of top height, and because it provides an objective method of sample tree selection without the personal judgment element present when crown class is used as a basis. (Top height is very similar to, though not identical with, dominant height). Good estimates of trends of top height in relation to age are important for two reasons: (1) their relative position as expressed by site index provides a basis for productivity classification, and (2) top height and top height increment are important drivers in various stand simulation models.

Study area

Most data used here are from C72 installations located in the Oregon and Washington Cascade Mountains, on the Mount Hood, Gifford Pinchot, and Willamette National Forests. Elevations in C72 data used ranged from 3,000 to 4,100 feet. The C45 data (described below) are from a somewhat lower elevation (2,000 to 2,400 feet) at a single location within the Gifford Pinchot National Forest. Seven of the C72 installations are in the *Abies amabilis* Zone (Franklin and Dyrness 1973), and two in the *Tsuga mertensiana* Zone (one of which, Alpine, is of limited usefulness because of insufficient noble fir in some treatments). The C45 data is transitional between the *Abies amabilis* and *Tsuga heterophylla* Zones.

All installations used here are plantations, although some also contained substantial amounts of natural regeneration of associated species.

Study Design

C72—The C72 study design was randomized blocks, complete except for a single missing treatment in one installation (block). There are five thinning treatments plus no thinning in each block. Treatments and plot sizes are given in table 1.

Plots were square, with sides that were multiples of the desired spacing, to facilitate gridding of the area. Measurement plots were surrounded by buffers treated in the same way.

Plots to be thinned were gridded with string at intervals corresponding to the assigned spacing, and leave trees were selected as the best available tree within each grid cell.

Plots were measured at time of establishment, and at 5, 10, and either 19 or 20 years after establishment. Heights were measured on a subset of trees, ranging from 40 per acre in the unthinned, 50 percent in treatments 2 and 3, 60 percent in treatment 4, to all trees in treatments 5 and 6. Diameters were measured to the nearest 0.1 inch on all trees 1.6 inches in diameter at breast height and larger.

C72 installations are listed in table 2.

Table 1—Treatments and corresponding measurement plot size in study C72

Treatment	Spacing	Trees	Plot size
	Feet	*Per acre*	*Acres*
T-1	—	—	0.200
T-2	7.9	700	.242
T-3	10.1	430	.234
T-4	12.8	265	.241
T-5	16.4	163	.302
T-6	20.9	100	.361

C45—This study was established as a completely randomized design, including a variety of species, at a single location. The spacings and plot sizes were similar to those in C72, though not identical. Unlike C72, spacing was established in 1980 by planting, rather than by thinning. Some of the original C45 noble fir plots are unusable because of abundant natural regeneration of Douglas-fir that overwhelmed the original planting, which—on a south slope at a relatively low elevation—is not a typical true fir site. Ten plots were considered usable for present purposes. Measurement dates were 1992, 1997, 2001, 2005, and 2009. Ages at the 1992 measurement were 5 years at breast height (b.h.) and 15 years total.

Table 2—List of noble fir plantations in study C72

Installation	National forest	Year established	Age b.h.	Total age	Elevation
				Years	*Feet*
Alpine[a]	Mount Hood	1990	11	19	4,500
Cabin	Gifford Pinchot	1994	7	14	3,000
Dog Creek	Mount Hood	1991	13	20	3,600
Job	Gifford Pinchot	1992	8	17	3,700
Marys Creek	Willamette	1994	8	15	4,000
Memaloose	Mount Hood	1992	13	24	4,000
Pointer	Gifford Pinchot	1991	10	17	4,100
Twin	Gifford Pinchot	1994	10	18	3,800

Age b.h. = number of annual rings at breast height.

[a] Not used because of insufficient noble fir in some treatments.

Data Summarization

Computation of H40 and D40

At each measurement, diameters of all live trees (all species) then present were sorted in descending order within each plot. Those trees in the largest 40-per-acre component (8 to 14 in number, depending on plot size) were sorted by species, and mean values for those noble fir included were taken as H40 and D40. Thus, these were not always the same trees. Also, means were frequently based on fewer than the above number of trees, because of the presence of naturally seeded stems of other species.

When measured heights were lacking for some trees included in the largest 40 per acre, values were assigned using height/diameter equations fit to all noble fir measurements on the plot.

Stand Age

There are three possible ages:

- Years from seed (total age)
- Years from planting
- Breast-high age (number of rings at b.h.)

Planting dates are available for both C72 and C45. Planting stock was 2-1 or 3-0, according to records. Therefore, years from seed = years from planting + 3.

Breast-high age has the advantages that (1) in applications, it can be determined without knowledge of planting date, and (2) to some extent, it reduces the variable effects of early vegetative competition. There are some uncertainties in the data. In

C72, age b.h. was estimated from ring counts on cut trees, which involve sampling error and trees that presumably were generally somewhat smaller than trees in the largest 40 per acre. In C45, breast-high age was estimated by backward extrapolation of a regression of the form:

$$\ln(H40) = a + b/(\text{total age})^{0.5}$$

Differences between estimated ages at b.h. and ages from seed derived from planting dates ranged from 7 to 11 years. This suggested 9 years as an overall adjustment for use in the absence of site-specific information.

In most but not all of the following comparisons, age from seed (total age) is used as the most reliable value.

Within the age range of the data, trends of H40 over age were nearly straight lines.

Analyses of H40 in Relation to Age and Spacing

Except where specified, the following is based on the C72 data only.

Means of H40 from combined treatments, by installation—
Means of H40 were calculated for each measurement date at each installation, using the combined data for all treatments in an installation. Trends over age are shown in figure 1. Within the age range of the data, the trends are very nearly straight lines. There are substantial differences in the age ranges.

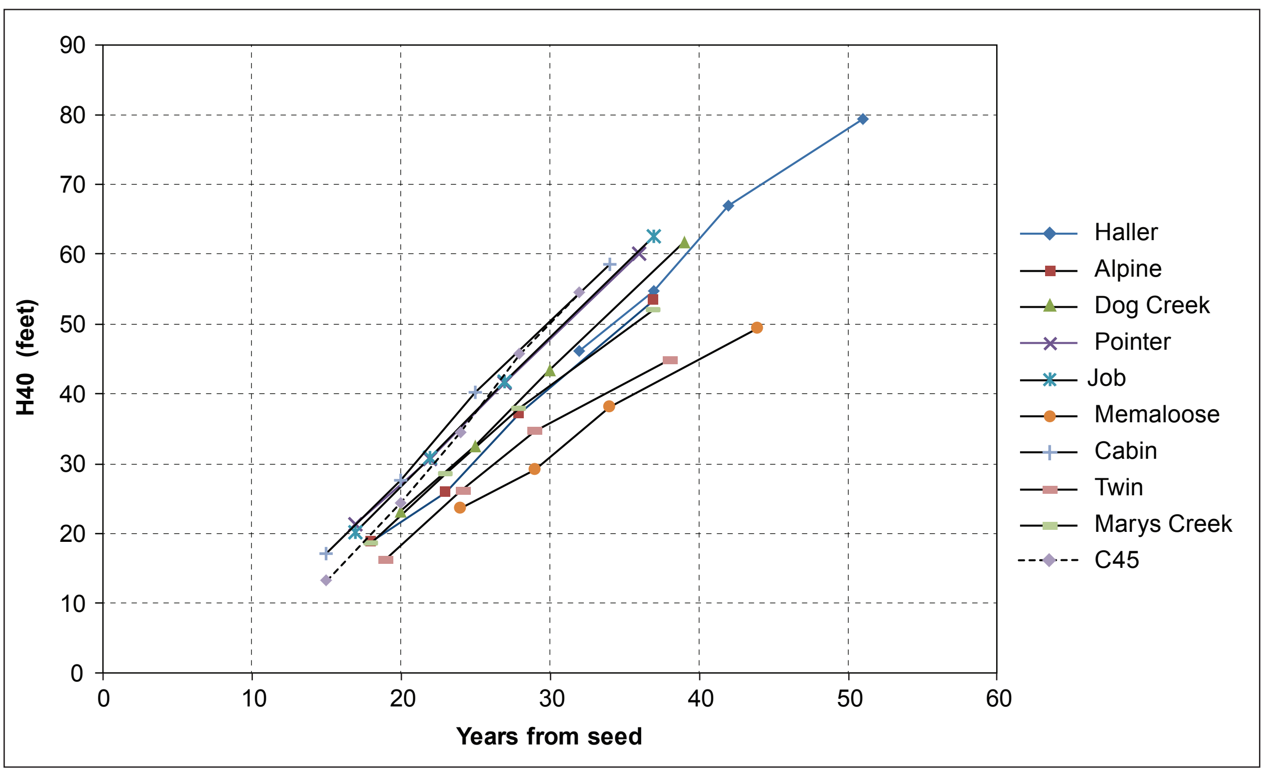

Figure 1—C72 + C45: trends of installation mean H40 over total age from seed, all treatments combined.

Except where otherwise specified, means of all treatments within an installation were used in the following comparisons.

Values of H40 by treatments within installations—
Treatment values of H40 were plotted over age from seed, by installation and treatment, in the format shown in the example in figure 2. Other installations, not shown, showed more or less similar trends.

The trends were, in general, more or less parallel and fairly regular. Points of importance that stand out:

1. In general, relative values remained much the same over the age range. Differences present immediately after thinning were still present, though reduced, at the most recent measurement. (Memaloose was considerably more variable than other installations.)

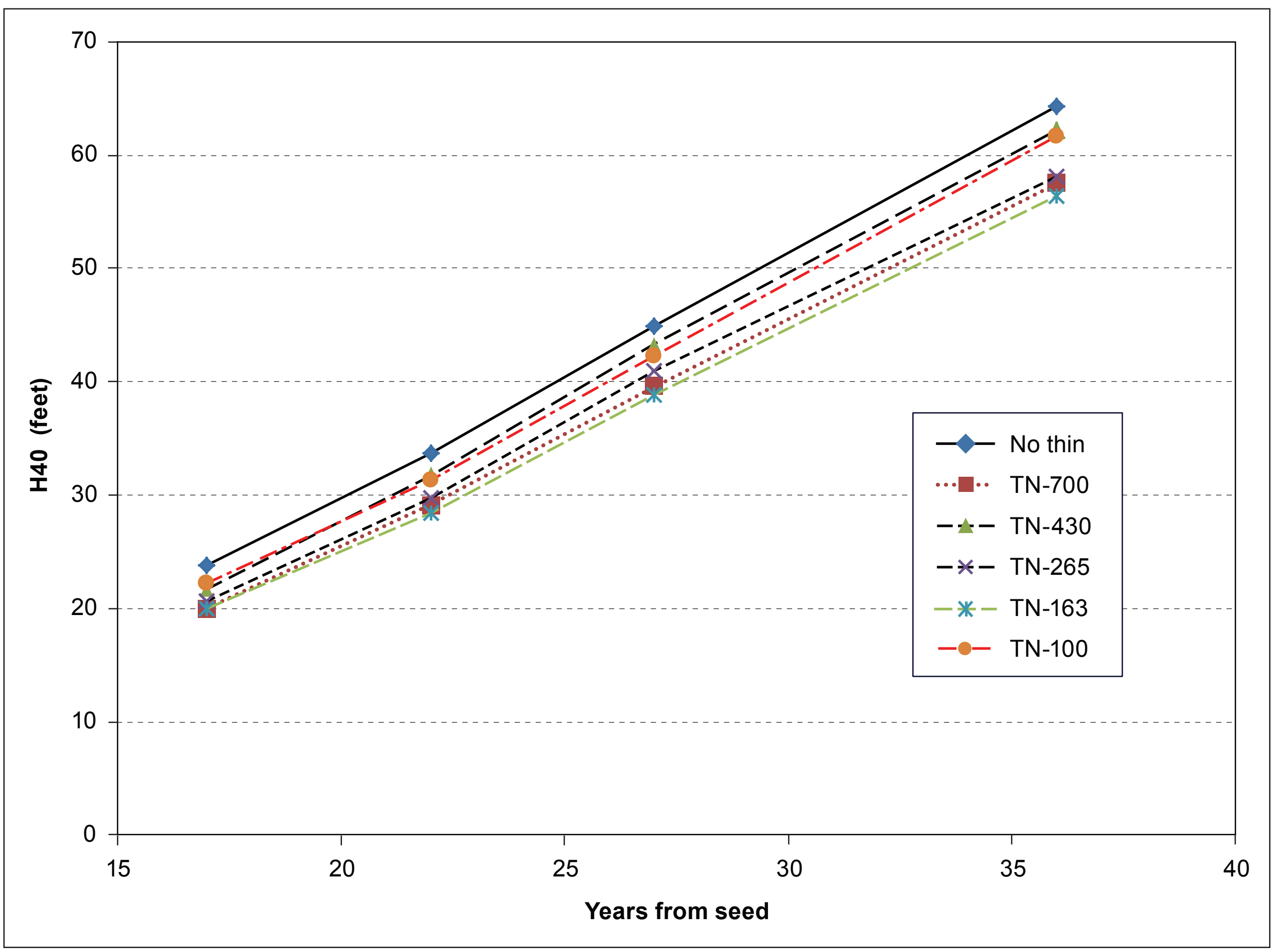

Figure 2—Trends of H40 over total age, by treatments.

2. Means by treatment at the initial and most recent measurement are shown in figure 3.
3. Treatment 1 (no thinning) was at or near the maximum in most installations, both immediately after thinning and at the most recent measurement. The one apparent exception is Cabin, in which treatment 1 was lowest. (Possibly this was a somewhat poorer site.) Differences in H40 at measurement 4 are primarily a continuation of immediate postthinning differences.
4. A comparison[1] of H40 for unthinned vs. thinned treatments at establishment was significant at the 0.05 level, but was no longer so at the 20-year measurement. Differences among thinned plots were nonsignificant at both measurements.

The apparent difference in postthinning H40 between unthinned and thinned treatments (2.37 feet) has a plausible explanation. The unthinned H40 is a mean of noble fir trees included in the largest 40 trees per acre, considering all trees on the entire plot without regard to spatial position. H40 values for thinned plots, in contrast, are calculated from leave trees that were selected as the "best" tree found in

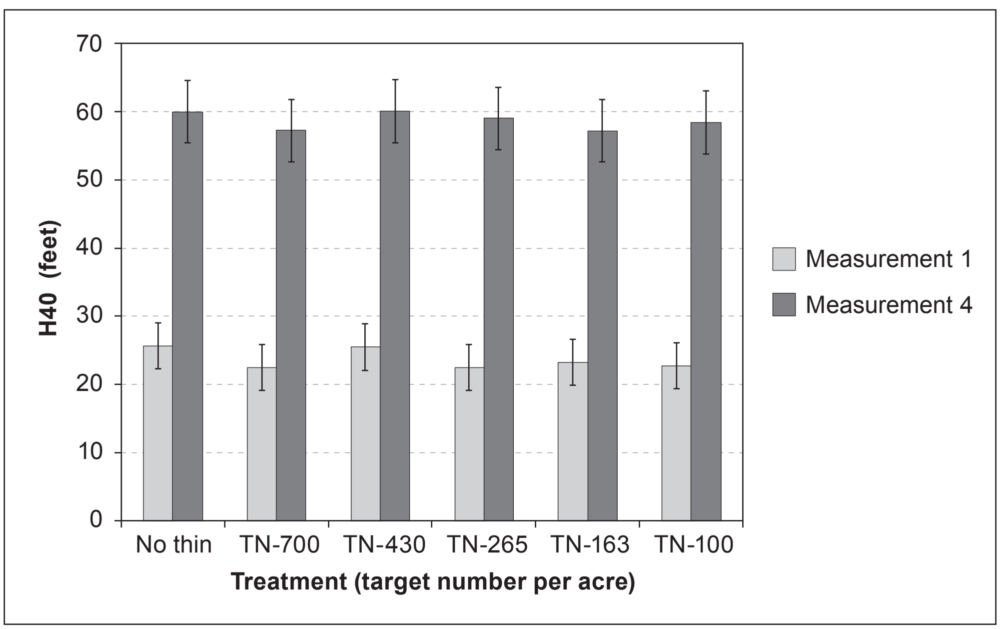

Figure 3—Treatment means of H40, with error bars for one standard error, at initial measurement and at 4th (most recent) measurement.

[1] ANOVA followed outline in Snedecor 1956, p. 294, with missing value for T-2 at Haller estimated as on p. 310.

each individual grid cell of area = spacing^2. Thus, some trees that would have been in the largest 40 per acre in the absence of spatial constraints may have been cut.

No consistent trend of H40 with treatment (spacing) is apparent in the thinned plots.

There was no consistent trend of H40 with spacing for thinned plots. Observed trends over age were more or less proportional.

Regressions of H40 on total age—

From figure 1 and other graphs, it appears that simple straight lines would likely give fits about as good as any alternatives, within the age range of the data. But these are unacceptable on logical grounds. Predicted H40 must approach 0 as Age approaches 0. And, H40 cannot increase without limit.

The observed trends shown in figure 1 are more or less proportional (“anamorphic”). There are substantial differences among installations in the range of ages represented; consequently, a simple overall fit to pooled data would likely give a biased estimate of average curve shape. Adjustment using an index H40 (analogous to site index) at some greatest common age should eliminate the problem.

Figure 1 suggests that H40 at total age 35 is a value that can reasonably be estimated from the observed values by interpolation or minimal extrapolation, and the corresponding values of H40 are hereafter referred to as S35.

Figure 2 and similar graphs for other installations show that the principal difference is unthinned vs. thinned, and that differences among thinned plots are not consistent. It is here assumed that most stands to which the results may be applied will have had some sort of density control, and that overall means across treatments will suffice.

A considerable number of functional forms have been used to express the H = f(age) relationship. Most require nonlinear fitting. With the limited age range in the data presently available, it seemed unlikely that one could distinguish between alternate forms. An equation that has had considerable use, meets the logical requirements of a growth curve, and that has the advantage of being easily fit (in logarithmic form) is:

$$H40 = ae^{b(1/Aget)^{\wedge}c}$$

whence

$$\ln(H40) = \ln(a) + b(Aget)^{-c},$$

where Aget is years from seed and “c” can be estimated by successive approximation.

Let: S35 = H40 at index Aget = 35, estimated by interpolation or very limited extrapolation.

Then:

$$\ln(S35) = \ln(a) + b(35)^{-c}$$

subtracting:

$$\ln(H40) – \ln(S35) = b[(Aget)^{-c} – (35)^{-c}],$$

whence:

$$\ln(H40) = \ln(S35) + b[(Aget)^{-c} – (35)^{-c}],$$

and

$$H40 = \exp[\ln(S35) + b[(Aget)^{-c} – (35)^{-c}],$$

which is a family of proportional ("anamorphic") curves constrained to pass through the index points (35, S35). With the limited range of ages and number of installations available, it seemed unlikely that proportional vs. polymorphic curves could be distinguished.

Successive measurements on the same plot are not independent. Therefore, the usual measures of significance are not valid. Estimated equation coefficients are unbiased, and calculated values of the coefficient of determination (RSQ) and root mean squared error (RMSE) do provide a ranking of comparative goodness of fit, even though we cannot attach probabilities.

A number of regressions of the form:

$$\ln(H40) – \ln(S35) = b[Aget)^{-c} – (35)^{-c}]$$

were run, using the combined C72 and C45 data and various trial values of the exponent c. Selection of the "best" equation was a judgment call, based on (1) near minimum values of RMSE, plus (2) biologically plausible behavior when extrapolated for several decades. This used mean values for all treatments within each installation. Results suggested that c = 0.5 was appropriate.

A fit to the C72 installation mean values gave the equation:

$$\ln(H40) – \ln(S35) = -14.5756(Aget)^{-0.5} – (35)^{-0.5}) \qquad (1)$$

with fit statistics RMSE = 0.04958 and adjusted RSQ = 0.9639. Rearranging:

$$\ln(H40) = \ln(S35) – 14.5756[(Aget)^{-0.5} – (35)^{-0.5}] \qquad (2)$$

and hence

$$H40 = \exp[\ln(S35) – 14.5756[(Aget)^{-0.5} – 0.1690)]] \qquad (3)$$

Figure 4 shows the curves corresponding to equation 3, plotted for S35 values of 35, 45, 55, and 65, which span the range of S35 values in the data. Figure 5 is the same, but overlaid on the individual installation growth trends. A similar regression using the C72 data only was not appreciably different.

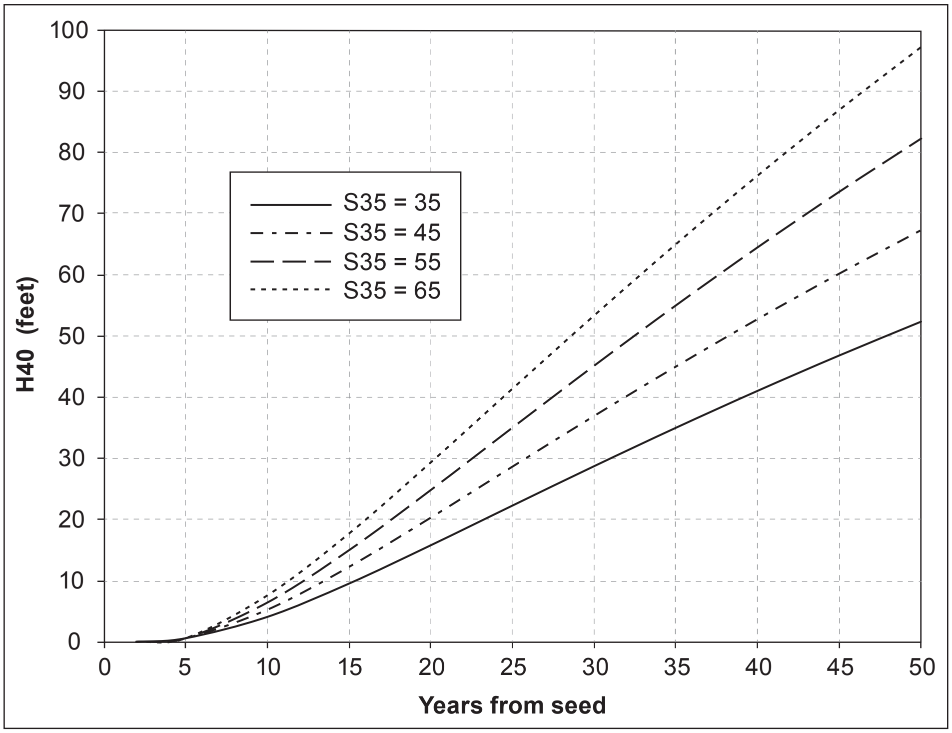

Figure 4—H40 over total age curves corresponding to equation 3.

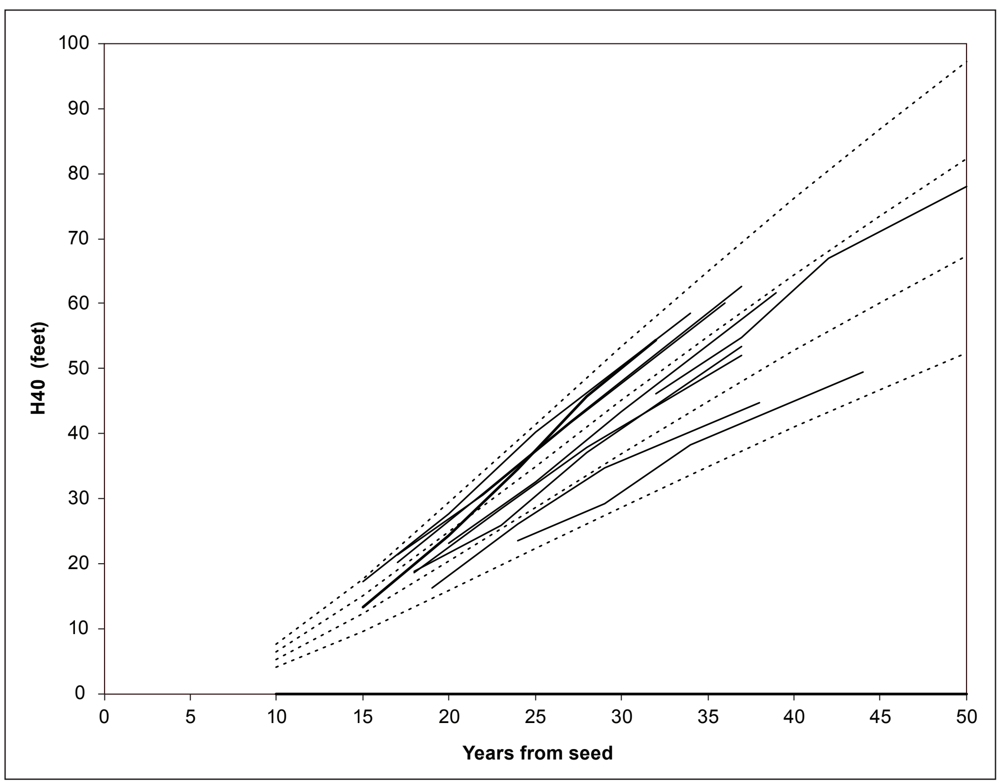

Figure 5—Curves from equation 3 (dotted) superimposed on observed installation trends of mean H40 (solid).

The pattern of residuals from equation 1 was reasonable, with no indication of bias or any trend. However, this is for the variable y = ln(H40) – ln(S35). The variable of actual interest is ln(H40) or, better, untransformed H40.

Figure 6 is a plot of the residuals from the detransformed H40 estimates, calculated from the C72 data using installation means and equation 3. Measurement 3 at Haller seems to be an unexplained outlier; otherwise the pattern appears satisfactory. Mean residual was 0.44 feet with standard deviation 1.35 feet. There was no indication of any relationship to S35.

A similar computation using equation 3 and all measurements, rather than the installation means, gave a mean deviation of 0.18 feet, with standard deviation 1.68 feet. The pattern was similar to figure 6 except for somewhat wider dispersion, as would be expected.

Regressions of H40 on breast-height age (age b.h)—
Some additional noble fir data are available from study C45 (described in more detail by Curtis 2013b). These are from an initial planting spacing trial established in 1980 on the Wind River Experimental Forest, near Carson, Washington. This trial included both pure and mixed plantings of several species, including noble fir. Spacing ranged from 2 by 2 meters to 6 by 6 meters (6.6 feet to 19.7 feet). Data used here are a subset of the original noble fir plots and exclude a number of plots, originally planted to noble fir, which have been overwhelmed by natural Douglas-fir regeneration and now have fewer than five noble fir present in the largest 40 per acre.

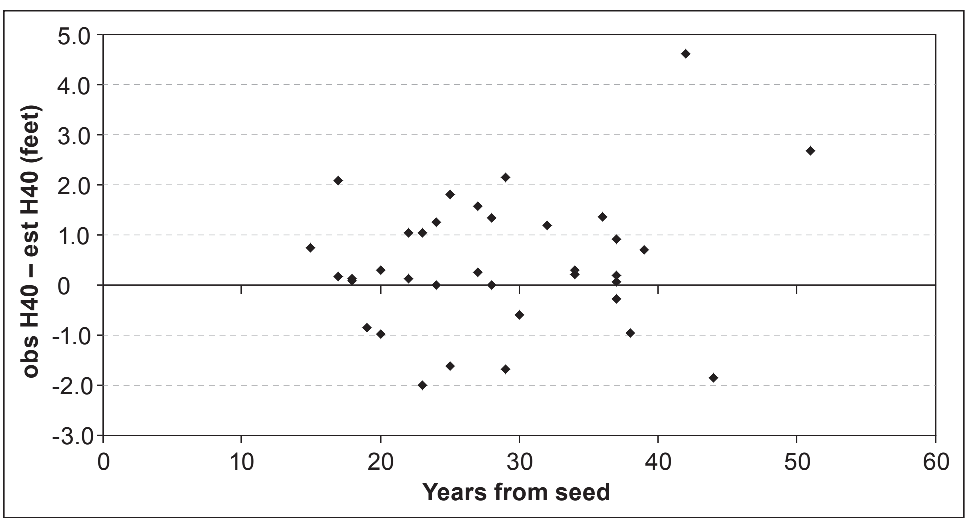

Figure 6—Plot of detransformed residuals from equation 3 over age.

The C45 data involve some differences from C72 in that:

- The plots are at relatively low elevation (2,000 to 2,400 feet) on a south slope, and thus are on a lower and warmer site than C72 and at or below the lower margin of the *Abies amabilis* Zone.
- The plots developed a heavy cover of *Ceanothus velutinus* Douglas ex Hook, which may have restricted growth somewhat, prior to mechanical release in 1990.
- No direct measurements of age at b.h. are available. Values used were estimated by backward extrapolation of a regression of H40 on total age, fit to the overall means.
- Spacings were established at time of planting, whereas those in C72 were established by precommercial thinning of initially moderately dense stands.

The C45 installation trend in H40, shown as the dotted line in figure 1, is not greatly different from the others, although it has a slightly greater slope. If we hypothesize that some part of the difference arises from the known early *Ceanothus* competition, the relationship should be improved by using age at breast height (age b.h.) rather than total age. Data plots show that this does in fact bring the C45 curve (dotted line) into a position consistent with the other installations.

H40 at total age 35 was used as the reference point in fitting equation 3 above, which provided the H40/total age curves shown in figure 4. An approximate conversion to similar curves of H40 over age b.h. can be made simply by relabeling the horizontal axis; on average, age b.h. is about 9 years less than total age. Or, equivalently, substituting the variable x = age b.h. + 9 for total age in equation 3 produces the equation:

On average, age at breast height was about 9 years less than total age.

$$H40 = \exp[\ln(S35tot) - 14.5756((\text{age b.h.}+9)^{-0.5} - 0.1690)]. \quad (4)$$

The corresponding curves are shown as the solid lines in figure 7. Although these do not meet the logical requirement that H40 = 4.5 when age b.h. = 0, the discrepancy is small and of no importance for most purposes. Like equation 3, limited extrapolations to somewhat greater ages seemed reasonable.

Alternatively, a regression can be fit directly, using age b.h. rather than total age, and an index age b.h. = 35 – 9 = 26 (used to provide comparability).

A first attempt using the equation 1 form with exponent -0.5 was clearly unsatisfactory.

A more satisfactory fit was obtained with the equation:

$$\ln(H40 - 4.5) - \ln(S - 4.5) = -14.3663[((\text{age b.h.})^{-0.5} - 0.1961) + 10.8439((\text{age b.h.})^{-1} - 0.03846)], \quad (5)$$

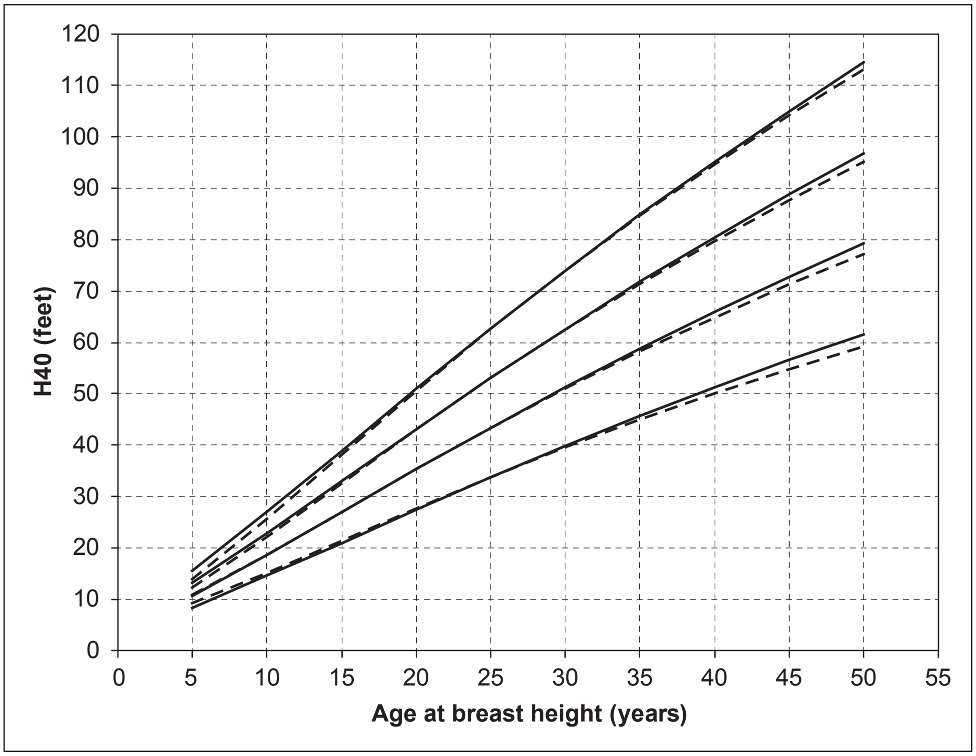

Figure 7—Curves of H40 over breast-height age (solid), corresponding to equations 4 and 6 (dashed).

with fit statistics RSME = 0.0563 and adjusted RSQ = 0.9652.

Rearranging the equation:

$$\ln(H40 - 4.5) = \ln(S - 4.5) - 14.3663((\text{age b.h.})^{-0.5} - 0.1961) + 10.8439((\text{age b.h.})^{-1} - 0.03846),$$

and

$$H40 = 4.5 + \exp[\ln(S - 4.5) - 14.3663((\text{age b.h.})^{-0.5} - 0.1961) + 10.8439((\text{age b.h.})^{-1} - 0.03846)]. \quad (6)$$

Here, $0.1961 = (26)^{-0.5}$ and $0.03846 = (26)^{-1}$, where 26 is the age b.h. corresponding to the value of S.

The corresponding curves for S26 = 35, 45, 55, and 65 are shown as dashed lines in figure 7. Within the range of the data, these are not appreciably different from those for equation 4, but diverge somewhat when extrapolated to greater ages although they are not radically different. Like equation 4, these do not meet the logical requirement that H40 approaches 4.5 as age b.h. approaches 0, but the discrepancy is evident only for ages b.h. less than 5, and is of no practical importance. The discrepancy arises from inclusion of the terms $26^{0.5}$ and 26^{-1}, used to force the condition that H40 = S at index age 26.

The data show much more rapid early height growth than do the 1978 curves of Herman et al. The 1978 curves are not suitable for site evaluation in young plantations.

Detransformed deviations, obsH40 – estH40, were calculated using equation 6. The mean deviation was 0.08 feet, with standard deviation of 1.66 feet. The pattern in relation to age b.h. was similar to that in figure 6.

Comparison with previous height growth curves—
Total ages were converted to corresponding breast-high ages, and installation means of H40 were then plotted over age at b.h. Figure 8 shows these trends superimposed on the corresponding height/age b.h. curves (dashed) for the best, medium, and poorest sites given in table 1 in Herman et al. (1978). The differences are considerable and show the same general pattern as does figure 4 in Murray et al. (1991). Namely, that the C72 and C45 data show much more rapid early height growth than do the Herman et al. curves. The 1978 curves are not suitable for site evaluation in young planted stands.

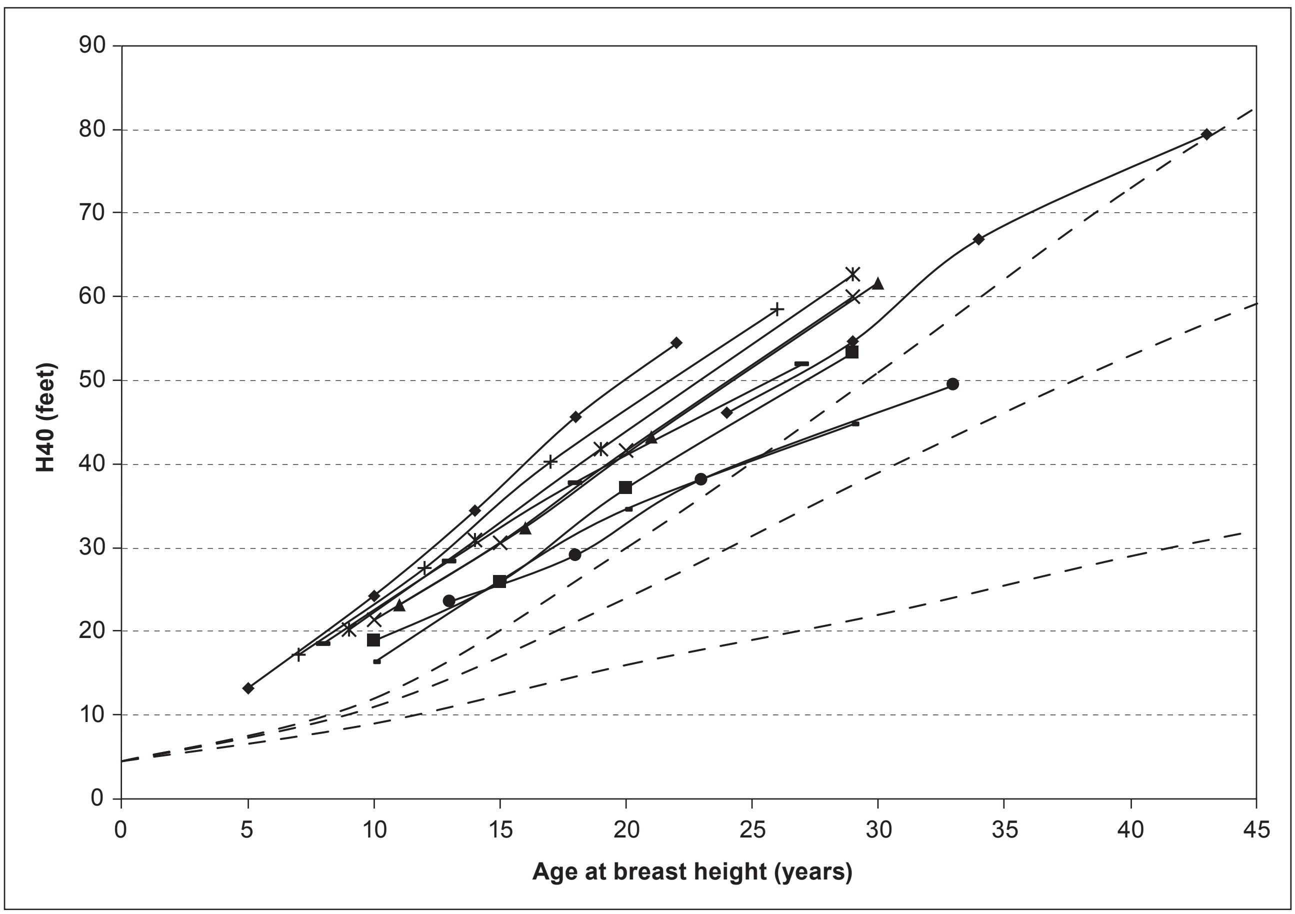

Figure 8—Observed trends of installation means of H40 over breast-high age (solid), compared with the height growth curves (dashed) for the poorest, medium, and best sites from Herman et al. (1978).

Analysis of D40 in Relation to Age and Spacing

A similar series of comparisons was made for D40, the mean diameter of those noble fir included in the largest 40 stems per acre.

Development trends of D40 were plotted in relation to total age, by installations, and by treatments within installations. In general, growth rates were greater in thinned plots than in unthinned, although there was much variation among installations. In some installations, growth trends were nearly parallel, while in others, thinned treatments had markedly greater slopes than unthinned.

Figure 9 shows treatment means of D40 by treatment immediately after thinning (measurement 1) and at the 20-year measurement (measurement 4). As with H40, the data suggest that thinning initially decreased D40. The comparison of the unthinned treatment with the combined thinned treatments at measurement 1 was significant at the 0.05 level. This corresponds to the similar indication for H40, and can plausibly be attributed to the spatial constraints on leave tree selection used in the thinned plots but not in the unthinned. Unlike H40, the comparison of unthinned vs. thinned treatments remained significant at the 20-year measurement. Differences among thinned treatments were nonsignificant at measurement 1, but became so ($p = 0.01$) by measurement 4.

Periodic annual diameter increment of the 40 largest trees per acre increased with spacing.

Figure 10 compares periodic annual increments (PAI) in D40, by treatments, for the 20-year period from measurement 1 through measurement 4. It is clear that periodic annual diameter increment of the 40 largest trees per acre increased

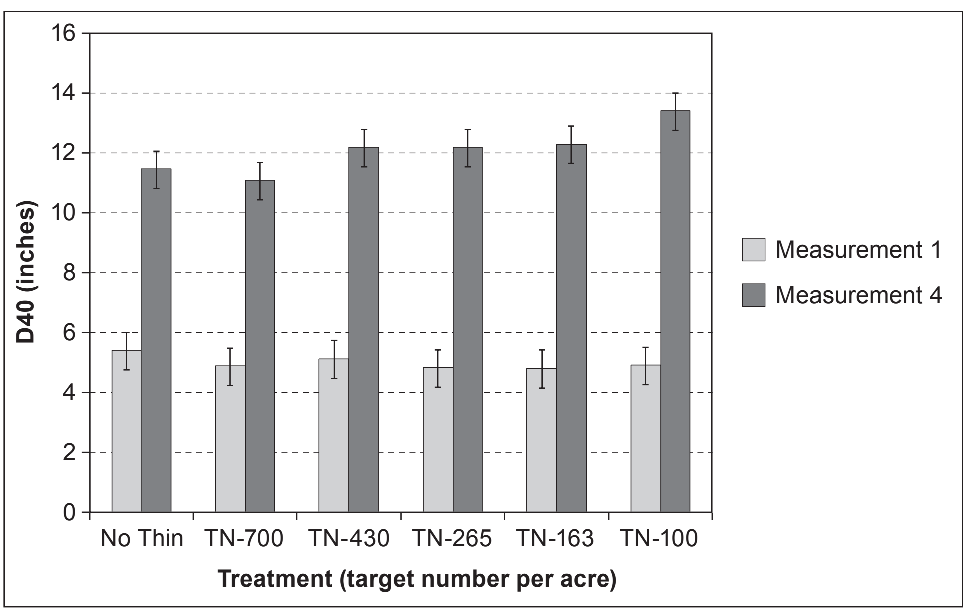

Figure 9—Treatment means of D40, with error bars for one standard error, at initial measurement and at 4th measurement.

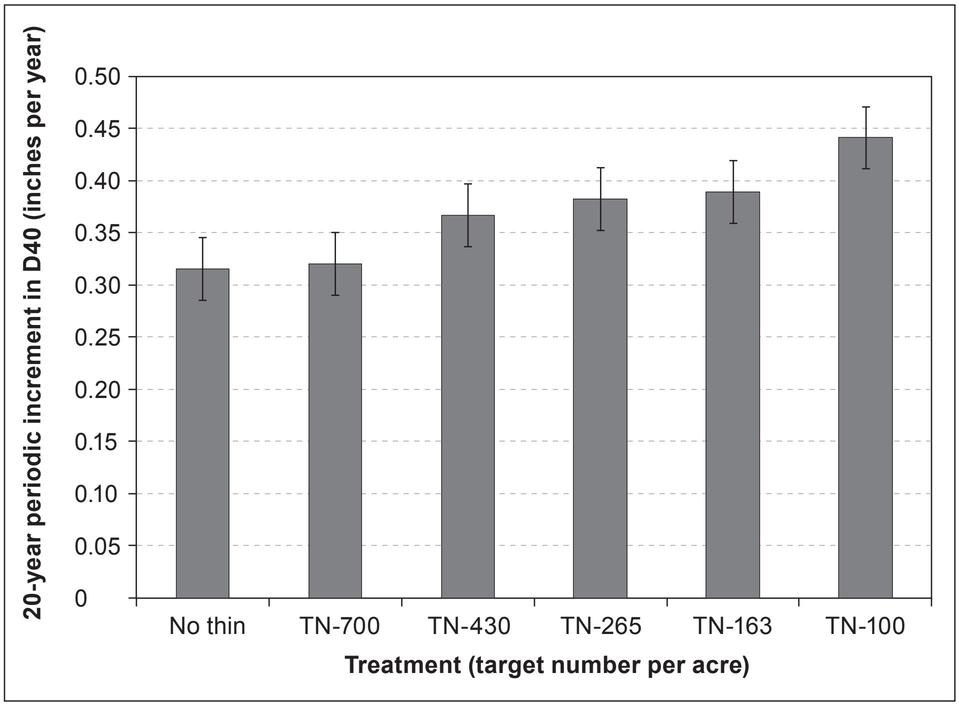

Figure 10—Treatment means of 20-year periodic annual increment in D40, with error bars for one standard error.

substantially with spacing, even though these trees were in a dominant position throughout. The relation of D40 PAI to spacing on thinned plots can be expressed by the regression equation:

$$\text{periodic annual D40 increment (inches/year)} = 0.282359 + 0.007381(\text{spacing}) \quad (7)$$

with RMSE = 0.08 and adjusted RSQ = 0.1332.

Although D40 PAI clearly increased with spacing, the amount of increase was highly variable among installations. Presumably this variation is at least in part the result of differences in initial age and differences in site quality, but with only eight complete installations, no quantitative relationship can be defined.

Discussion

The comparisons of these H40 results with Herman's curves (fig. 8) are very similar to those made by Murray et al. (1991), although the method of selection of sample trees was not identical and the present data are based on remeasured plots whereas Murray et al. used stem analyses. Both show that young noble fir plantations established on clearcuts are making much more rapid early growth than did the old naturally established trees sampled by Herman et al. (1978). Herman's curves should not be used with plantations.

The reasons for the difference are unclear, but several factors probably contribute:

- C72 plantations were established with vigorous seedlings on clearcuts, and were usually relatively free from early vegetative competition.
- The recent climate has been warmer and more favorable to tree growth than when the old trees used by Herman et al. (1978) were becoming established.
- The plantations included in C72 and C45 probably did not sample the poorest sites included in Herman's sample.
- Herman's curves were derived from stem analyses of old trees, of natural origin and unknown early competitive status. Biases could have been introduced by shifts in tree position over time.

The new curves of H40 in relation to total age can be used to estimate relative site quality in young plantations and are much preferable to the older curves for this purpose.

H40 over age curves prepared from successive measurements will not generally be identical with curves prepared from stem analyses (ex: Dahms 1963) because of tree mortality and the shifts in tree relative crown position that occur over time. Differences are probably small when direct measurements and stem analyses cover similar short time periods, but can become large when the stem analyses are made on much older trees. Curves prepared from repeated measurements of H40 are preferred, even though the trees included may change over time, because they are consistent with height measurements made in the usual one-time field applications.

The new curves of H40 in relation to total age and age b.h. (figs. 4 and 7) can be used to estimate relative site quality in young noble fir plantations, and are much preferable to the older curves for this purpose. The curves for equations 4 and 6 are almost identical within the range of the data (fig. 7), and either can be used. Extrapolations to greater ages are necessarily highly uncertain, but the curve shapes are at least plausible and more or less consistent with values for older ages given by Herman et al. (1978). Admittedly, eight locations is a weak basis, but this must suffice pending availability of more extensive data.

The index ages used here (35 total and 26 breast high) are undesirably low, but are limited by the range of the presently available data. When data become available, an index age of 50 years b.h., which is now in use for a number of other species, would be much preferable.

There is no indication of a spacing effect on H40 in the C45 data. The C72 data do suggest that unthinned H40 is generally slightly greater than that in thinned stands, but that there is little apparent relation to spacing among thinned stands. Differences at the most recent measurement, though nonsignificant, appear consistent with differences present immediately postthinning. The difference between thinned vs. unthinned in C72 may be the result of the spatial constraints applied in selection of leave trees in thinning, which probably led to removal of some trees that would have been included in the largest 40 per acre in the absence of spatial constraints.

Unlike H40, there is a definite spacing effect on D40 increment. Even these dominant trees did respond to increased growing space.

The recent loss of the Twin and Mary's Creek installations to unplanned thinning is unfortunate. Some years hence, we will need to decide whether continued measurement is justified. These would provide a continuation of H40 development, but would be useless for the original purpose of comparing the overall effects of alternate initial spacings.

It is well recognized (Franklin 1982, 1990; Harrington and Murray 1982) that noble fir characteristically has very slow juvenile height growth, followed by a long period of nearly linear growth, and substantial height growth continuing even at advanced ages. This implies the desirability of relatively long rotations for this species. Results in this study are consistent with previously reported information.

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Metric Equivalents

When you have:	Multiply by:	To find:
Inches (in)	2.54	Centimeters
Feet (ft)	0.3048	Meters
Acres (ac)	0.405	Hectares
Trees per acre	2.471	Trees per hectare

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Glossary of Symbols and Acronyms

Aget = total age = years from seed.

age b.h. = breast-high age = number of annual rings at breast height

D40 = mean diameter (inches) of those noble fir included in the largest 40 (by diameter, all species) stems per acre.

Exp(x) = e^x.

H40 = mean height (feet) of those noble fir included in the largest 40 (by diameter, all species) stems per acre.

RMSE = root mean square error = standard deviation of residuals.

RSQ = (multiple correlation coefficient)^2 = coefficient of determination.

S35 = estimated H40 at total age 35.

S26bh = S26 = estimated H40 at breast-high age 26.

TN = target number of leave trees per acre.

adjRSQ = RSQ adjusted for number of variables = 1 −(1 – (RSQ)(N −1)/(n – m – 1). (Freund and Littell 1991, 23).

XY = product of X and Y.

ln(x) = natural logarithm (base e) of x.

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