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True Fir Spacing and Yield Trials—20-Year Update

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Abstract

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This report updates data and comparisons from previous reports (Curtis and others 2000, Curtis 2008) on a series of precommercial thinning and yield trials in high-elevation true fir–hemlock stands, using data from the 12 replicates for which 20-year data are now available. The stands were varying mixtures of Pacific silver fir (*Abies amabilis* (Douglas ex Loudon) Douglas ex Forbes), western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), and noble fir (*Abies procera* Rehder). Trends noted in the 2008 report continue. Increment in top height was somewhat reduced at wide spacings. Volume increment and basal area increment increased as the residual number of trees increased. There was a small increase in diameter increment of the 80 largest trees per acre at wide spacing. Relative stand densities on the unthinned plots, as measured by stand density index (SDI) and relative density (RD), are still increasing; it appears that the maximum (not yet attained) is probably at least 20 to 25 percent greater than values observed in Douglas-fir.

Keywords: Precommercial thinning, increment, yield, *Abies amabilis*, *Tsuga heterophylla*, *Abies procera,* true firs, noble fir, Pacific silver fir.

Summary

This report updates data and comparisons from previous reports (Curtis and others 2000, Curtis 2008) on a series of precommercial thinning and yield trials in high-elevation true fir–hemlock stands, using data from the 12 replicates for which 20-year data are now available. The stands were varying mixtures of Pacific silver fir (*Abies amabilis* (Douglas ex Loudon) Douglas ex Forbes), western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), and noble fir (*Abies procera* Rehder). Treatments included five levels of the residual number of trees plus an unthinned treatment. Trends noted in the 2008 report continue. Increment in top height was somewhat reduced at very wide spacings. Volume increment increased but at a decreasing rate as the residual number of trees increased, similar to trends observed in other thinning studies. Basal area increment increased with the residual number of trees at wide spacings, but was nearly constant for 430 and 700 trees per acre. There was an increase in diameter increment of the 80 largest trees per acre at wide spacing. Relative stand densities on the unthinned plots, as measured by stand density index (SDI) and relative density (RD), are still increasing. Maximum SDI and RD (not yet attained) will probably be at least 20 to 25 percent greater than corresponding values for Douglas-fir. Differences in height growth patterns between true firs and Douglas-fir, combined with the ability of true fir–hemlock stands to develop high basal areas, imply that true fir–hemlock stands of a given site index will be considerably more productive than Douglas-fir stands of the same numerical site index. Continuation of these trials for the next several decades should provide reliable information on development patterns and silvicultural responses that is needed as part of the process of developing models to guide management decisions.

Contents

Introduction

From 1987 to 1994, 18 precommercial thinning trials were established in true fir–hemlock stands along the west side of the Cascade Range in Washington and Oregon and in Washington's Olympic Mountains. Establishment and 5-year results were reported by Curtis and others (2000), and 10-year results by Curtis (2008).

The stands studied are within the Coastal True Fir–Hemlock type (Society of American Foresters type 226: Eyre 1980), primarily within the *Abies amabilis* zone (Franklin and Dyrness 1973) but also with two in the *Tsuga mertensiana* zone. The principal tree species are Pacific silver fir (*Abies amabilis* (Douglas ex Loudon) Douglas ex Forbes), noble fir (*Abies procera* Rehder), and western hemlock (*Tsuga heterophylla* (Raf). Sarg.). Other minor associated species include western redcedar (*Thuja plicata* Donn ex D. Donn), yellow cedar (*Chamaecyparis nootkatensis* (D. Don) Spach), mountain hemlock (*Tsuga mertensiana* (Bong.) Carrière), subalpine fir (*Abies lasiocarpa* (Hook) Nutt.), western white pine (*Pinus monticola* Douglas ex D. Don) and Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco).

True fir–hemlock forests at higher elevations in the Cascade Range and Olympic Mountains play major roles as protective cover for watersheds and as scenic and recreational areas, and have in the past been important as timber-producing forests. Large areas of *Abies amabilis*–zone forest exist in the Mount Baker–Snoqualmie (MBS), Gifford Pinchot (GP), Olympic (OLY), Mount Hood (MH), and Willamette (WIL) National Forests. There are large additional areas in the national parks in the region, and limited areas on Washington Department of Natural Resources (WDNR) lands and on private ownerships. There are also large areas of similar forests that are important timber-producing areas on Vancouver Island and in the Coast Range of British Columbia.

This report is an update of the 10-year results published in 2008.

This report is a partial update of the 2008 publication, with additional data and some differences in procedure. It repeats much of the background information given in the 2000 and 2008 reports and then presents some summaries and comparisons based on the 12 installations for which 20-year data are now available. Complete 20-year measurements (at 0, 5, 10, and 20 years from establishment) from all 18 installations will not be available for several years. It seemed desirable to carry out an interim analysis to (1) present currently available information, (2) provide guidance for later workers who may analyze the complete set, and (3) utilize the author's acquaintance with the study from its inception. Any future analyst will not have this direct knowledge, and future capabilities may also be handicapped by prospective personnel and funding limitations.

Previous Research

Although there is a considerable body of information on stand development, yields, and site evaluation for low-elevation hemlock, little information is available on the true firs and high-elevation true fir–hemlock mixtures.

Herman and others (1978) and Hoyer and Herman (1989) developed height growth and site index estimates for noble fir and Pacific silver fir, based on stem analyses of trees from unmanaged old-growth stands. However, Murray and others (1991) found that early height growth of young Pacific silver fir and noble fir established on clearcuts was considerably more rapid than was predicted by the above curves. Thus, applicability of these curves to young stands appears problematic because of differences in stand establishment conditions and early competition, climatic changes, and possible biases associated with changes in competitive position over time of sample trees used in stem analyses.

Harrington and Murray (1982) compared height growth patterns in young Pacific silver fir, noble fir, and Douglas-fir. They point out that true firs characteristically have a period of slow juvenile growth, an extended period of almost linear rapid growth, and a final phase of appreciable growth extending to very advanced ages. Consequently, true firs often appear at an initial disadvantage in comparison with associated species, but may later equal or surpass their associates because of the longer period of sustained height growth.

Oliver and Kenady (1982) provided a summary of existing information for these species as of that date. Various U.S. Forest Service plant association guides have since presented several indicators of productivity by plant association (Brockway and others 1983; Hemstrom and others 1982; Henderson and Peter 1984; Henderson and others 1989, 1992; Logan and others 1987).

Past Management

A shift to planting true firs occurred after the frequent failures of earlier Douglas-fir plantations.

Extensive harvesting in the true fir–hemlock forest type began in the early 1950s. Early operations commonly followed practices that generally had been successful in lower elevation Douglas-fir: namely, clearcut, burn the slash, and plant—often with Douglas-fir. A high proportion of these early plantations failed, and regeneration to true fir–hemlock took place by natural seeding over an extended period of years. The resulting stands are often patchy and contain considerable variability in tree sizes and ages.

Over subsequent years, better species selection combined with improved nursery, site preparation, and planting practices greatly improved survival and produced many successful plantations. Favored species for planting have been noble fir or noble fir–Pacific silver fir mixtures, with other species such as Engelmann spruce

(*Picea engelmanni* Parry ex Engelm.) or western white pine used on some frost-prone sites. Reduced use of fire favored survival of natural advance regeneration of Pacific silver fir and hemlock. Numerous young true fir–hemlock stands now exist at higher elevations along the west side of the Cascade Range and in the Olympic Mountains.

Extensive precommercial thinning began in the late 1970s.

Extensive precommercial thinning (PCT) began in the late 1970s. There has been some question about the feasibility or desirability of future commercial thinning, because some stands are on steep terrain and because these thin-barked species are highly susceptible to rot arising from logging injuries.

Common practice in the late 1970s through the 1990s was to thin at an early age to 350 to 400 stems per acre. Some foresters further reduced the number of leave trees, with the expectation that no further entry might be feasible until final harvest. This raised concerns about the effects of the number of residual trees on future stand development and the average tree size at which precommercial thinning should be done.

Today, much of the land under the Northwest Forest Plan (Thomas and others 2006) is in late-successional old-growth forest reserves or wilderness currently managed for old-growth protection, restoration of old growth, or protection of old-growth-dependent species. The rest is mostly in matrix or adaptive management areas. A considerable portion of these areas is in the *Abies amabilis* zone. In some areas, the management goal is future timber production, whereas others are managed primarily for watershed, wildlife, or recreation values. Whatever the present or possible future management objectives, information about the dynamics of young true fir forests is very limited.

The Study

From 1987 to 1994, the Pacific Northwest Research Station (PNW) installed a series of 18 replicates of a spacing and yield trial in true fir–hemlock stands, with assistance from the Pacific Northwest Region of the U.S. Forest Service and the individual national forests concerned. These trials were established in stands considered ready for PCT under then-current operational practices. Seven were on the Mount Baker–Snoqualmie, one on the Olympic, five on the Gifford Pinchot, four on the Mount Hood, and one on the Willamette National Forests.

Objectives

Study objectives were to (1) determine the quantitative response of true fir–hemlock stands to a range of PCT stocking levels, and (2) obtain long-term growth data applicable to young managed stands as a basis for estimating development patterns and potential yields.

These trials should ultimately provide:

- Information on development of PCT stands needed for reliable estimates of productivity of young true fir–hemlock stands.
- Data useful, in combination with other data, for construction of simulators and stand projection systems for young-growth managed stands.
- A basis for choosing the optimum number of leave trees to meet different management goals.
- Information on successional and structural development over time for possible use in meeting landscape diversity, species habitat, and watershed management objectives.

Study Area

Most of the stands in the study area were in the *Abies amabilis* zone.

The study area consists of the true fir–hemlock type as it occurs on the Mount Baker, Gifford Pinchot, Mount Hood, and Willamette National Forests. Emphasis was on stands located within the Pacific silver fir zone; however, several trials reach into the lower portions of the mountain hemlock zone.

For some years prior to the study, the national forests had been conducting extensive PCT in young true fir–hemlock. Choice of locations was therefore constrained by the fact that many otherwise suitable stands had already been operationally thinned.

Sites selected ranged from 3,000 to 4,500 ft in elevation. Most of the plant associations found on the study sites have widespread distribution within the respective national forests, according to plant association guides. Basic descriptive information for the installations is shown in table 1.

Study Design

The study design is that of randomized blocks, with one unthinned and five thinning treatments per block. Where feasible, two plots of each treatment were established at a location for a total of 12 plots per installation. Few relatively homogeneous areas large enough to accommodate 12-plot installations were found. Of the 18 installations, 3 have 12 plots, 14 have 6 plots, and 1 has 5 plots (because initial stocking was insufficient to allow one of the thinning treatments).

Table 1—Basic descriptive information for the true fir spacing study installations

Installation	National forest[a]	Plots	Year established	Stand origin	Breast height age[b]	Age at stump	Total age	Elevation	Dominant plant association[c]
		Number	*Year*		*- - - - - - - Years*	*- - - - - - -*		*Feet*	
Alpine #4	MH	6	1990	Mixed	11	16	19	4,500	TSME/VAME/CLUN
Bonidu	OLY	6	1990	Natural	16	21	24	3,000	ABAM/VAAL/CLUN
Cat Creek	GP	6	1990	Natural	13	20	23	4,300	ABAM/RHAL
Crevice Creek	MBS	6	1988	Mixed	22	26	29	3,000	ABAM/VAAL/CLUN
Cumberland	MBS	6	1988	Natural	12	17	20	3,200	ABAM/VAAL/CLUN
Dog Creek	MH	6	1991	Planted	13	17	20	3,600	ABAM/RNMA/XETE
Evans Creek	MBS	6	1989	Natural	32	38	41	3,700	ABAM/VAAL/CLUN
Haller Pass	MBS	5	1989	Planted	24	29	32	4,200	ABAM/VAME
Iron Mountain	MBS	12	1987	Natural	19	25	28	3,500	ABAM/VAAL/CLUN
Pointer #3	GP	12	1991	Planted	10	14	17	4,100	TSME/VAME/XETE
Rattrap Pass	MBS	6	1988	Mixed	14	20	23	3,200	ABAM/VAAL/CLUN
Tonga Ridge	MBS	6	1989	Mixed	20	26	29	3,800	ABAM/VAAL/CLUN
The following installations were not used in this report because 20-year measurements were not yet available									
Job #2	GP	6	1992	Planted	8	14	17	3,700	ABAM/ACTR/CLUN
Marys Creek	WIL	6	1994	Planted	8	12	15	4,000	ABAM/RHMA/BENE
Memaloose	MH	6	1992	Planted	13	21	24	4,000	ABAM/RHMA/XETE
North Mountain #2	MH	6	1993	Mixed	12	17	20	3,200	ABAM/VAAL/COCA
Cabin #2	GP	6	1994	Planted	7	11	14	3,000	ABAM/BENE
Twin #1	GP	12	1994	Planted	10	15	18	3,800	ABAM/VAME/CLUN

[a] National forest (NF) as follows: GP = Gifford Pinchot, MH = Mount Hood, MBS = Mount Baker–Snoqualmie, OLY = Olympic, WIL = Willamette.
[b] Years since attaining breast height.
[c] Plant associations are given in table 4.

Treatments—

The treatments consisted of five spacings, plus no treatment (NT). The corresponding target values in number of trees per unit area were as follows:

Spacing (ft)	Trees per acre	Area per tree (sq ft)
7.9	700	62.2
10.1	430	101.2
12.8	265	164.6
16.4	163	267.7
20.9	100	436.5

Seven hundred and 100 trees per acre were chosen as the limits of the range considered for thinning treatments, and intermediate values were calculated using a constant percentage change in area per tree.

Treatments were randomly allocated to plots within an installation.

Plot design—

Measurement plots were square within a larger treatment plot, of the dimensions given in table 2. In the first installation (Iron Mountain), the treatment plot was 200 ft on a side. Thereafter, it was reduced to 180 ft (occasionally 160 ft) because of the difficulty in fitting plots into the available area. The plot sizes selected were thought sufficient to (1) give reasonably smooth diameter distributions, (2) give values reasonably stable in the presence of minor mortality, and (3) allow continuation of the plot to advanced ages, with or without one later thinning.

Measurement plot size was about 0.25 ac, with a slightly smaller plot (0.20 ac) for the unthinned plot and somewhat larger plots for the widest spacings, so that a reasonable number of leave trees would be included. To facilitate control of leave-tree marking, the sides of the measurement plots were made multiples of the desired spacings, thus allowing subdivision of the plots into strips corresponding to the desired spacings.

Table 2—Standard dimensions of plots used in true fir spacing trials

	Treatment plot			Measurement plot		
Treatment	**Spacing**	**Area**	**Side**	**Area**	**Side**	**Buffer width**
Number/acre	*Feet*	*Acres*	*Feet*	*Acres*	*Feet*	*Feet*
No thin	—	0.7438	180	0.200	93.3	43.4
700	7.9	.7438	180	.242	102.7	38.6
430	10.1	.7438	180	.234	101.0	39.5
265	12.8	.7438	180	.241	102.4	38.8
163	16.4	.7438	180	.302	114.8	32.6
100	20.9	.7438	180	.361	125.4	27.3

— = not applicable.

Plot Establishment and Measurement

Plot layout—

True fir–hemlock stands are characteristically patchy, and variation is unavoidable, but plot locations were selected to be as nearly comparable in site conditions and initial stand conditions as feasible. Plots were either contiguous or quite close to each other. Obvious site changes and root rot pockets were excluded. Treatments were assigned randomly after the treatment plots were located on the ground but before the measurement plots were established.

After initial plot location and treatment assignment, the corners of treatment plots and interior measurement plots were established with staff compass and tape. All distances were measured horizontally. Measurement plot boundary closure was within 2 ft.

Initial tree measurements and marking—

Plots were subdivided with string at intervals equal to the desired spacing, and leave trees were selected as the best tree within each grid cell. To the extent possible, all treatment plots within an installation were adjusted to nearly comparable species composition. Tree vigor was given precedence over strict adherence to spacing or species criteria. Occasional exceptionally large (and presumably older) trees were excluded to make leave-tree diameter distributions and average diameters more comparable. All trees 0.6 in and larger in diameter at breast height (d.b.h.) were tallied by species and 1-in d.b.h. classes before thinning.

Because some cells within the grid lacked suitable leave trees, the specified numbers of leave trees were not met in all cases. Shifts in overall species composition caused by the thinning treatments were generally minor.

Leave-tree measurements—

Trees were measured after the growing season. Diameters at breast height were measured to the nearest 0.1 in (by diameter tape) on all leave trees on thinned plots, and on all trees 0.6 in d.b.h. and larger present on the unthinned plots. Initial number of trees 0.6 in and larger ranged from 395 per acre at Haller to 4,195 at Cumberland.

Heights and heights to live crown were measured to the nearest 0.1 ft (with height poles or—in later remeasurements—with a laser instrument). Heights were measured on all leave trees at the two widest spacings, on the first two of every three trees at the 12.8-ft spacing, and on every other tree at the two closest spacings.

In unthinned plots, heights and heights to live crown were measured for at least 40 trees, more in mixed-species stands. Trees were selected across the entire plot and across the full range of diameter classes present, with about two-thirds of selected trees above the average diameter and one-third below.

Stand age estimates—

Ring counts were made at breast height (b.h.) and stump height on a sample of trees cut in thinning, excluding trees showing a suppressed core. There was considerable variation because of differences in species growth rates, and because natural regeneration often occurred over several years. Regressions of ring count on d.b.h. were fit to all sample tree data from an individual installation. These equations were then used to estimate the average number of rings at breast and stump heights corresponding to mean diameter of leave trees on all thinned plots at an installation. Total age was taken as the estimated number of rings at stump +3, and was checked against date of planting in cases of known planting date and good survival. Seedlings established as advance regeneration (principally, Pacific silver fir) may have widely differing numbers of years in a suppressed condition and were not included in the above age estimates.

Estimated total stand ages at establishment ranged from 14 to 41 years. Elevations ranged from a low of 3,000 ft (Bonidu) to 4,500 ft (Alpine).

Description of ground vegetation—

All installations were classified by dominant plant association, in most cases by the area ecologist for the given national forest. More detailed descriptions were made for those installations located in the Mount Baker–Snoqualmie and Olympic National Forests (Curtis and others 2000), including ground vegetation species identification and inventory. Species acronyms and plant associations are shown in tables 3 and 4.

Table 3—Species names in true fir spacing trials

Common name	Scientific name	Acronym
Trees:		
Pacific silver fir	*Abies amabilis (*Douglas ex Loudon) Douglas ex Forbes	ABAM
Subalpine fir	*Abies lasiocarpa* (Hook.) Nutt	ABLA
Noble fir	*Abies procera* Rehder	ABPR
Yellow cedar	*Chamaecyparis nootkatensis* (D. Don) Spach	CHNO
Engelmann spruce	*Picea engelmanni* Parry ex Engelm.	PIEN
Western white pine	*Pinus monticola* Douglas ex D. Don	PIMO
Douglas-fir	*Pseudotsuga menziesii* (Mirb.) Franco	PSME
Western redcedar	*Thuja plicata* Donn ex D. Don	THPL
Western hemlock	*Tsuga heterophylla* (Raf.) Sarg.	TSHE
Mountain hemlock	*Tsuga mertensiana* (Bong.) Carrière	TSME
Shrubs and herbs:		
Vanilla leaf	*Achlys triphylla* (Sm.) DC.	ACTR
Dwarf Oregon grape	*Berberis nervosa* Pursh	BENE
Queencup beadlily	*Clintonia uniflora* (Menzies ex Schult. & Schult. f.) Kunth	CLUN
Bunchberry	*Cornus canadensis* L.	COCA
Cascades azalea	*Rhododendron albiflorum* Hook.	RHAL
Rhododendron	*Rhododendron macrophyllum* D. Don ex G. Don	RHMA
Alaska huckleberry	*Vaccinium alaskaense* Howell	VAAL
Big huckleberry	*Vaccinium membranaceum* D. Don ex G. Don	VAME
Beargrass	*Xerophyllum tenax* (Pursh) Nutt.	XETE

Remeasurement schedule—

All plots were remeasured at 5 and 10 years after establishment. Thereafter, they were placed on a 10-year remeasurement schedule, because of limitations in personnel and funding. Ingrowth trees 1.6 in in diameter or greater were tagged and recorded, on the entire plot at years 5 and 10 and thereafter on a subsampling basis (because of the large numbers present on some widely spaced plots).

Table 4—Plant associations in true fir spacing trials

Plant associations[a]	
Pacific silver fir/Alaska huckleberry/queencup beadlily	ABAM/VAAL/CLUN
Pacific silver fir/big huckleberry	ABAM/VAME
Pacific silver fir/big huckleberry/queencup beadlily	ABAM/VAME/CLUN
Pacific silver fir/Cascade azalea	ABAM/RHAL
Pacific silver fir/rhododendron/queencup beadlily	ABAM/RHMA/XETE
Pacific silver fir/vanilla leaf/queencup beadlily	ABAM/ACTR/CLUN
Pacific silver fir/Alaska huckleberry/bunchberry	ABAM/VAAL/COCA
Pacific silver fir/rhododendron/dwarf Oregon grape	ABAM/RHMA/BENE
Pacific silver fir/dwarf Oregon grape	ABAM/BENE
Mountain hemlock/big huckleberry/queencup beadlily	TSME/VAME/CLUN

[a] Sources: Brockway and others 1983; Henderson and others 1989, 1992; Logan and others 1987.

Because of scheduling and access problems, not all intended 20-year measurements were made at exactly 20 years, although to date the maximum deviation has been 2 years.

Data Summarization

Height Estimates

Height/diameter equations of the form

$$\ln(H - 4.5) = a + b \cdot \ln(D) + c \cdot \ln^2(D)$$

were fit to data for each plot and each measurement, separately for each species for which reasonable samples were available. When samples were small, the squared term was omitted. These equations were then used to assign estimated heights to all trees for which actual measured heights were not available.

Volume Estimates

Cubic volumes of the entire stem (CVTS) were calculated using the following equations entered with measured d.b.h. and either measured or estimated height, as available.

- Pacific silver fir and noble fir: table 10 in Browne (1962).
- Redcedar and yellow cedar: table 4 in Browne (1962).
- Western hemlock and mountain hemlock: Wiley (1978).
- Douglas-fir: Bruce and DeMars (1974).
- Other miscellaneous species: Browne (1962).

Site Index Estimates

Site index estimates are based on the heights of Pacific silver fir.

Site index estimates are based on mean height (measured or estimated) of silver fir included in the 80 largest diameter trees per acre. Silver fir was selected as the reference species because it is the most abundant. Eighty trees per acre rather than the more usual 40 per acre was chosen because, with these mixed-species stands and relatively small plots, 40 per acre often gives very small samples for a species.

Previous work (Curtis 2008) had shown that top heights (H80) at the 10-year measurement in the widest spacings were often lower than the installation mean. For the 20-year data, graphs of H80 by treatment were plotted for each installation. In some installations, there was no apparent relation; in others, values for the widest spacings were markedly less. In the latter cases, site index estimates were based on treatments 1 through 4 only. A single mean site index was used for all plots within an installation.

The estimated site index for silver fir used here is a weighted mean of estimates from measured or estimated heights of silver fir included in the largest 80 trees per acre, and estimates based on conversion of corresponding values for noble fir and for hemlock to a silver fir site index. A site index based on silver fir measurements only is not feasible because not all plots have silver fir present.

Silver fir site indices were calculated using equations from Nigh (2009). Hemlock site indices were based on Wiley (1978) and converted to corresponding silver fir site indices using Nigh (1998).

Murray and others (1991) showed that the existing site index equations for noble fir (Herman and others 1978) are not satisfactory for young stands established on recent clearcuts. Limited comparisons suggested that height trends in the current data are more or less proportional to the silver fir trends, and Nigh (2009) was therefore used to assign noble fir site indices. Murray and others (1991) found that for silver fir and noble fir of comparable age established on clearcuts, the noble fir was about 10 percent taller than the associated silver fir at age 20. This value appeared consistent with the very limited comparisons possible with the current data, and was therefore used to convert noble fir estimates to corresponding silver fir estimates.

Species Composition

Species composition was calculated as the percentage of total basal area represented by each species at the most recent (20 year) measurement on each plot. This was done on an individual plot basis because in some installations there are considerable differences among plots. It is evident both from other knowledge and from graphical comparisons that noble fir and western hemlock generally outgrow silver fir.

Therefore, in the analyses discussed below, species composition is represented by a single variable, "%nfwh," equal to the sum of the basal area percentages of noble fir and hemlock.

Analyses

The regression analyses discussed below were preceded by fairly extensive graphical comparisons, most of which are omitted here.

Stocking can be expressed as either target spacing (spac), target number of trees (TN), or actual number of tagged leave trees (TPA) present after thinning. In general, there is little difference between TN and TPA. Average area per tree = spacing^2 = 43,560/TN, and therefore spacing = 208.7/sqrt(TN). Thus, TN and spacing are alternate transformations of the same basic variable. Below, I have generally used TN in preference to TPA; primarily because TN lends itself to simple graphical comparisons.

In the following work, regressions were fit using the stepwise option of PROC REG in SAS (Freund and Littell 1991). As is often the case with stepwise regressions, there were frequently several combinations of variables that gave similar values of the coefficient of determination (RSQ). Selection of equations here presented was a judgment call based on a combination of (1) RSQ values, (2) nominal significance of individual variables, (3) avoidance of equations with large numbers of predictor variables, and (4) consistency with trends shown in graphical comparisons. Because the equation forms were derived from the data rather than from any pre-specified hypotheses, nominal significance values (generally $p < 0.01$ for variables included) were interpreted only as guides to relative importance of variables. Goodness of fit was expressed as adjusted RSQ, which measures the reduction in the mean square due to regression and compensates for the effect of increase in the number of variables (Freund and Littell 1991, 23).

Parallel analyses were done of 20-year increment and yield.

Two parallel analyses were done for each of the variables: CVTS, basal area (BA), and mean diameter of the largest 80 trees per acre (D80). The first analysis was a series of regressions of 20-year net change on stand variables. (In those cases where the measurement interval differed from 20 years, values were adjusted by proportion to a 20-year basis.) Twenty-year H80 increment was also regressed on stand variables. The number of 20-year observations available in each case was 59.

The second analysis was a series of yield regressions relating the logarithm of attained values of CVTS, BA, and D80 at years 0, 5, 10, and 20 to stand variables. Here, the number of observations was 59 × 4 measurements = 236.

20-year Increment Analyses

20-year change in H80 (ΔH80)—

Figure 1 shows mean values of 20-year increments in H80 by treatments, for thinned plots only with all species combined. Average increments were considerably less at the widest spacings (treatments 5 and 6), although this trend was not apparent in all individual installations.

Top height increments were considerably less at the widest spacings.

A simple regression of 20-year ΔH80 on spacing showed that 20-year ΔH80 was significantly ($p = 0.02$) though very loosely correlated with spacing. Addition of the variables %nfwh and site index markedly improved the fit. The coefficient of spacing was negative and remained virtually unchanged as additional variables were added (table 5). There is on average a reduction in H80 growth associated with the wide spacings. This effect was considerably smaller than the effects of species composition and of site index. Also, as might be expected, height growth declines somewhat with increase in age at thinning—which is associated to some degree with site quality.

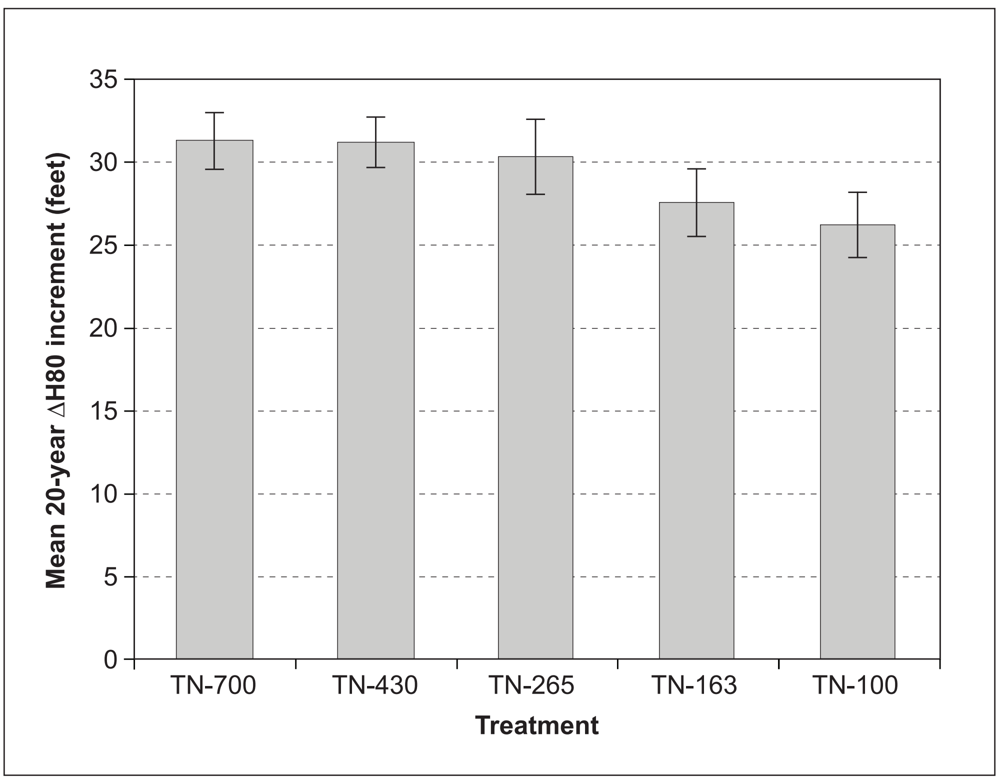

Figure 1—Means of 20-yr ΔH80 by treatment, thinned plots only, all species combined, with error bars for ± 1 standard error. TN = number of trees per acre left after thinning.

Table 5—Coefficients in regression: 20-year ΔH80 = a + $\Sigma b_1 \cdot X_1$ + ……. Thinned plots only; n = 59

Equation number	Constant	%nfwh	Spacing	Site index	Initial age at breast height	Adj RSQ
1	35.2939		-0.43517			0.074
2	27.7941	0.14310	-0.42537			0.632
3	19.4926	0.12423	-0.43059	0.12287		0.671
4	22.5574	0.10179	-0.42438	0.16053	-0.28357	0.727

RSQ = coefficient of determination.

Note: See "Glossary of Symbols and Acronyms" for definition of terms.

20-year net change in CVTS (ΔCV)—

Means, maximums, and minimums of 20-year net change in CVTS by treatments are shown in figure 2. It is evident that volume growth declines with decreasing number of trees.

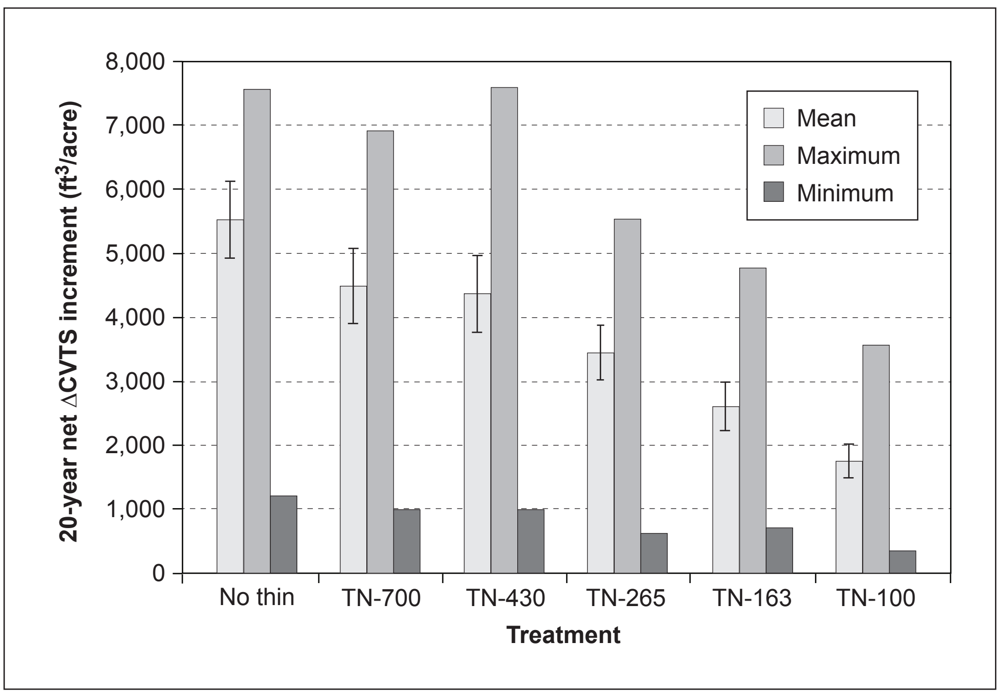

Figure 2—Means, maximums, and minimums of 20-year net ΔCVTS, with error bars for ± 1 standard error. TN = number of trees per acre left after thinning.

Volume increments declined with a reduced number of leave trees.

In most, although not all, of these and later regressions, species composition as expressed by %nfwh appeared to be an important variable. This is consistent with general knowledge of species characteristics. In the regressions presented, %nfwh was forced into the regressions.

Other variables that are obviously important are site index (S) and target number (TN) or transformations or combinations of these variables. In applications, A1 would generally be readily available, D1 and B1 (which are based on trees ≥1.6 in d.b.h.) less so.

For regressions fit to thinned plots only, RSQs of those including B1 were greater than those with D1, which were greater than those with A1. A1 did not enter when D1 was included. Table 6 gives the equations of apparent best fit for each case.

Table 6—Coefficients in regressions: 20-year net ΔCV = a + $\Sigma b_1 \cdot X_1$ + … Thinned plots only; n = 59

Equation	Constant	%nfwh	S	S/TN	S/sqrt(TN)	S·ln(TN)	ln(elev)	A1	S·A1	S·D1	B1	AdjRSQ
5	17088		100.98	-4385.1			-2424.56					0.761
6	30243	10.16			-627.4319		-3171.07	-404.12	6.55394			0.872
7	26167	10.723	48.381		-583.29		-3226.31			4.87		0.909
8	23454	7.73268		-1047.61		8.6863	-3024.49				28.5206	0.919

Note: See “Glossary of Symbols and Acronyms” for definition of terms.

Figure 3 shows the curves for sites 60, 75, and 90 based on equation 6 in table 6 and the data mean values of %nfwh = 53, A1 = 17, and D1 = 5.9.

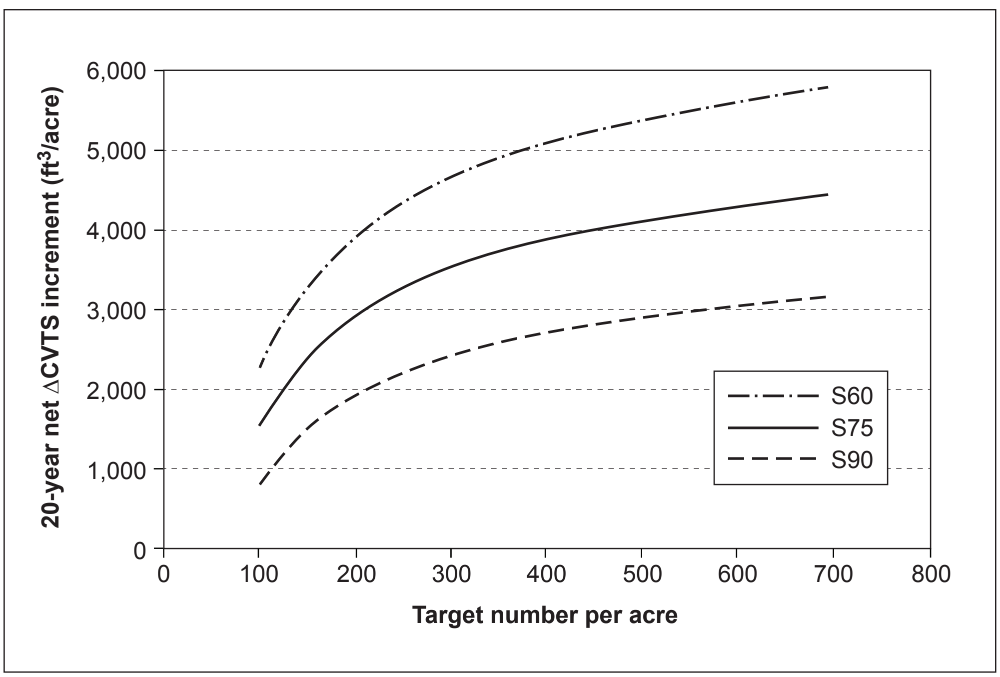

Figure 3—Estimated 20-year net CVTS increment, based on equation 6 in table 6 using data means of %nfwh = 53, A1 = 17, D1 = 5.9, and elevation = 3,666. CVTS = cubic volume of entire stem.

20-year net change in basal area (ΔBA)—
Means, maximums, and minimums of 20-year net change in BA by treatments (thinned plots only) are shown in figure 4. Clearly, BA increment decreases with decrease in the number of residual trees.

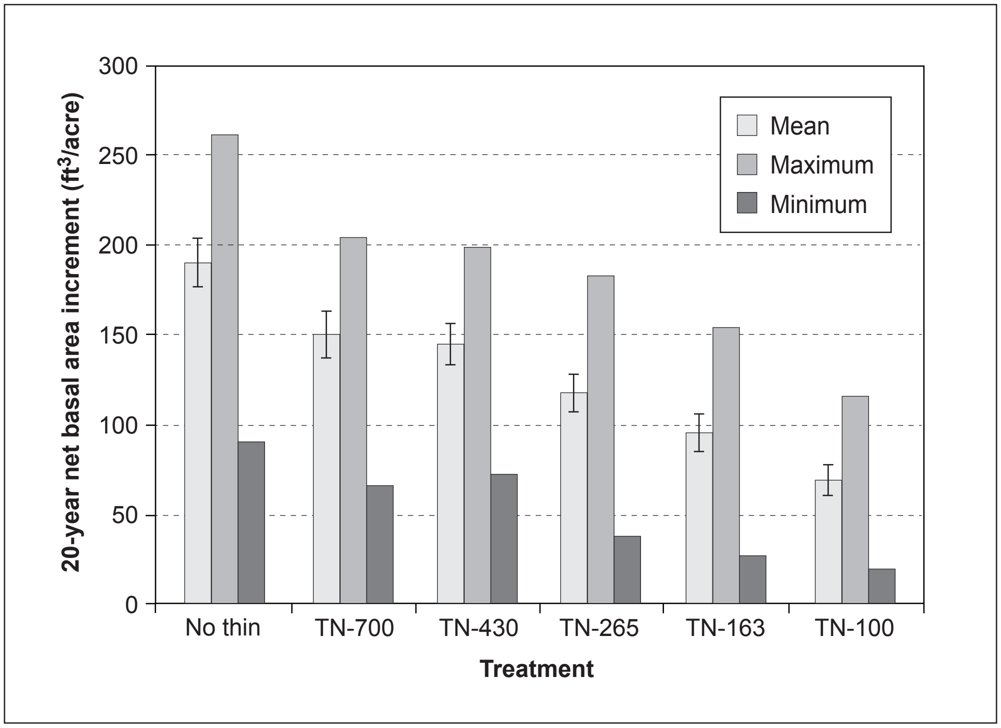

Figure 4—Means, maximums, and minimums of 20-year net ΔBA, with error bars for ± 1 standard error.

Basal area increments declined with a reduced number of leave trees.

Regressions were fit to data for thinned plots only. The two best equations obtained are given in table 7. Neither D1 nor A1 was effective individually, although the combination of A1 and D1 was. Interpretation of the combination of A1 and D1 is unclear, as this is probably related to site quality.

Table 7— Coefficients in regressions: 20-year net ΔBA – a + $\Sigma b_1 \cdot X_1$ + … Thinned plots only; n = 59

Equation	Constant	%nfwh	S · TN	$S \cdot TN^2$	S · ln(TN)	S/TN	ln(elev)	A1	D1	Adj RSQ
9	1211.72	0.16564			0.26945	-68.2816	-145.75			0.900
10	1224.86	0.08007	0.00468	-0.00000383			-145.16	-2.2986	7.2173	0.926

Note: See “Glossary of Symbols and Acronyms” for definition of terms.

The relationships of 20-year net ΔBA to TN for sites 60, 75, and 90 are shown in figure 5. These curves are based on equation 10 in table 7, using the data mean values of %nfwh = 53, A1 = 17, D1 = 5.9, and elevation = 3,666.

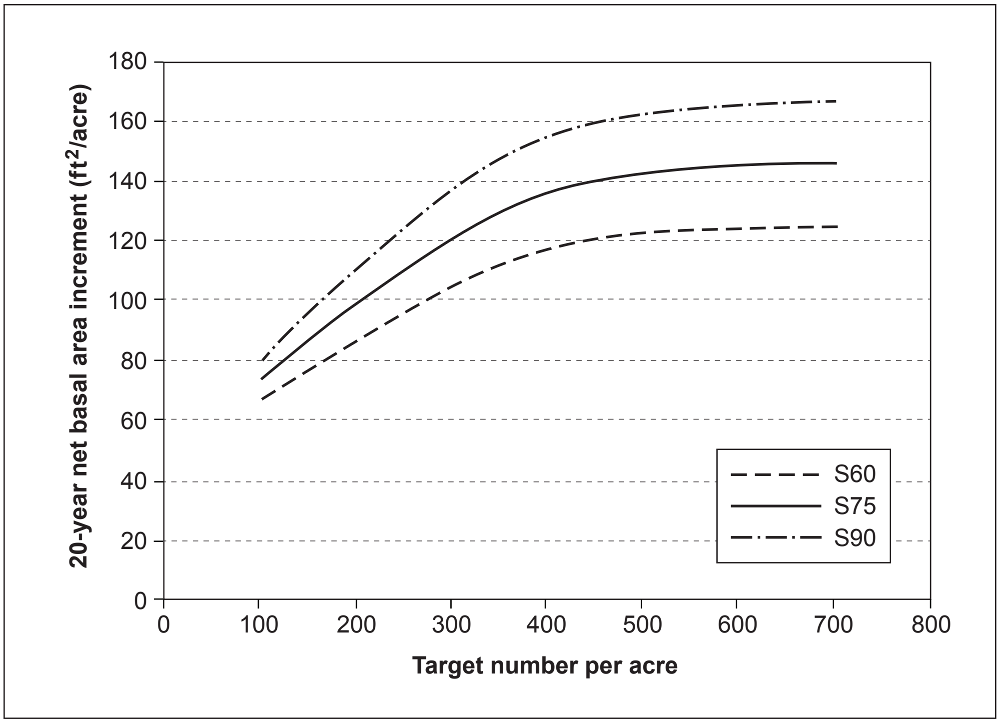

Figure 5—Estimated 20-year net basal area increment, based on equation 10 in table 7, using data means of %nfwh = 53, A1 = 17, D1 = 5.9, and elevation = 3,666.

20-year change in mean diameter of the largest 80 trees per acre (ΔD80)— Means, maximums, and minimums of 20-year net change in D80 (thinned plots only) are shown in figure 6. ΔD80 decreased as the number of residual trees increased, although the differences are less striking than in the case of volume and of BA.

A series of regressions of 20-year ΔD80 on various independent variables, fit to thinned plots only, are shown in table 8. Fits were considerably poorer than those for CVTS and BA. Estimates were poor when either initial age or initial D80 were omitted. Inclusion of either initial age or initial D80 markedly improved the fit, although RSQs were still much below those for the CVTS and BA regressions. Initial age and initial D80 did not enter together. The RSQ values were virtually the same for several variations of equations with five predictor variables. Initial age (b.h. age at time of thinning) is likely to be a more readily available value than initial D80, which also suggests that equation 13 is to be preferred.

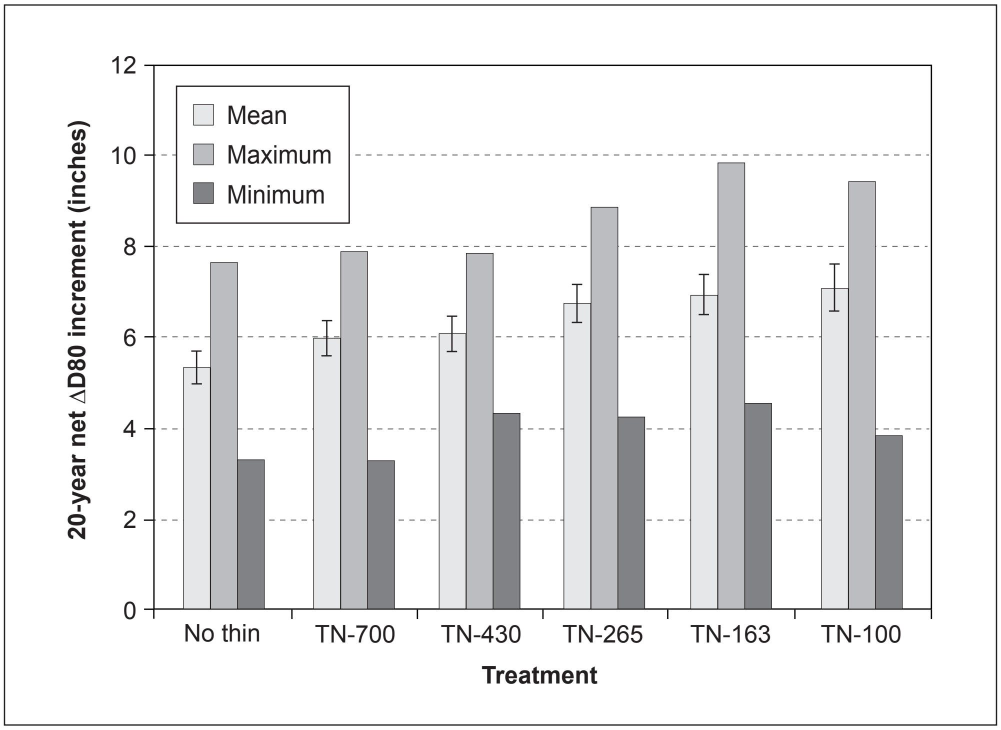

Figure 6—Means, maximums, and minimums of 20-year net ΔD80, with error bars for ± 1 standard error.

Table 8—Coefficients in regressions: 20-year ΔD80 = a +$\Sigma b_1 \cdot X_1$ +… Thinned plots only; n = 59

Equation	Constant	%nfwh	1/sqrtTN	S/sqrtTN	S · ln(TN)	S^2	ln(elev)	A1	D1	Adj RSQ
11	35.11	0.01646			-0.00882	0.0005157	-3.49883			0.542
12	32.72	0.00994	-53.7625	0.92283			-3.1190		-0.36034	0.728
13	33.96	0.00562	-35.0461	0.71273			-3.2596	-0.12751		0.786

Note: See “Glossary of Symbols and Acronyms” for definition of terms.

Figure 7 shows estimates of 20-year ΔD80 given by equation 13 in table 8 for sites 60, 75, and 90, using the data means of %nfwh = 53, A1 = 17, and elevation = 3,666.

The equations show response to TN increasing with site index, with little gain on the poorest sites.

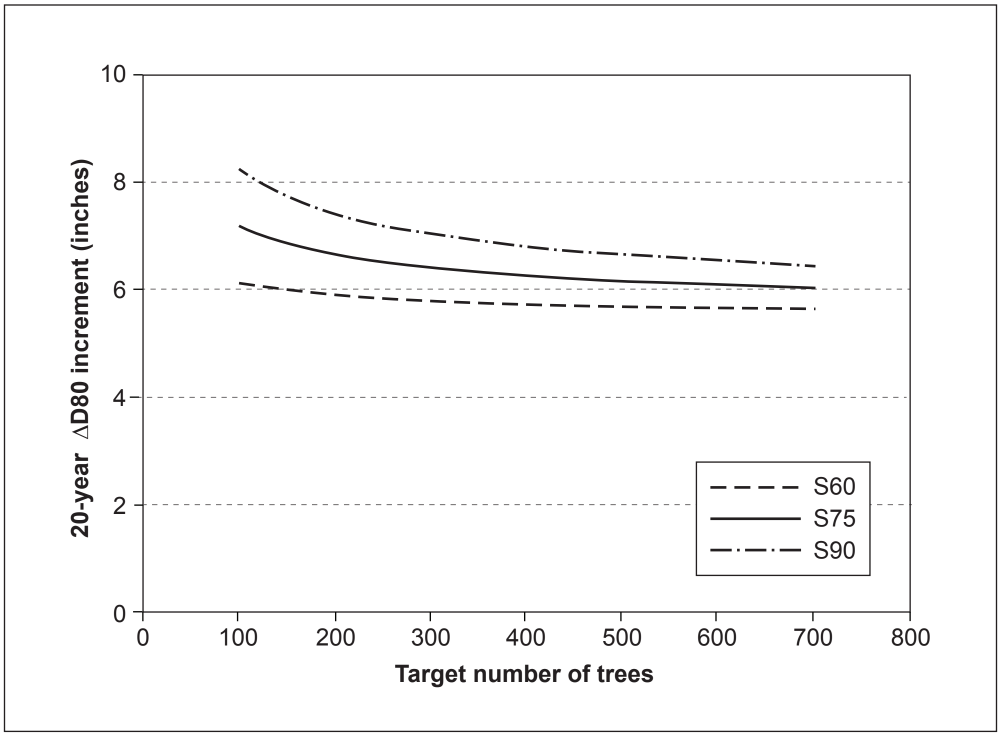

Figure 7—Estimated 20-year D80 increment for site indexes 60, 75, and 90, from equation 13 in table 8, entered with data means of %nfwh = 53, A1 = 17, and elevation = 3,666.

Yield Analyses

Cubic volume (CVTS)—

Regressions of the logarithm of net cubic volume yield on TN plus various stand variables gave the results shown in table 9. Inclusion of initial age (A1) made a small improvement in fit. Initial D80 (D1) had a negligible effect when considered alone. Including both A1 and D1 made a further slight improvement in RSQ, but at the cost of an excessively complicated equation; this is therefore not included in the table. Initial BA (B1) was an effective predictor but is inherently related to TN, and is therefore not included here.

Table 9—Coefficients in regressions: ln(CVTS) = a + $\Sigma b_1 \cdot X_1$ +… Thinned plots only, all measurements; n = 236

Equation	Constant	%nfwh	1/TN	ln(S)·ln(Agebh)	ln(S)·Agebh	S·ln(Agebh)	ln(elev)	ln(A1)	ln(D1)	Adj RSQ
14	-3.10416	0.00486	-116.92964	0.80576	-0.00706					0.948
15	-2.49088	0.00403	-116.57042	0.82540	-0.00622			-0.33732		0.952
16	5.55841	0.00361	-104.35798	0.78639		-0.00612	-0.72396	-1.49203	1.37866	0.971

Note: See "Glossary of Symbols and Acronyms" for definition of terms.

Curves of CVTS over breast-high age for sites 60, 75, and 90, based on equation 14 in table 9, using the data mean values of %nfwh, site index, and elevation, are shown in figure 8 for TN-100, figure 9 for TN-265, and figure 10 for TN-700, respectively. The curves are concave upward within the range of ages in the data; volumes are rising steeply on the better sites. There are marked differences among treatments (TN), within sites. The curves (solid) are overlaid on the curves (dotted) obtained by connecting the four data points available for each plot(s) in the specified treatment in each installation.

Volume increments were strongly related to site index, age, and number of trees.

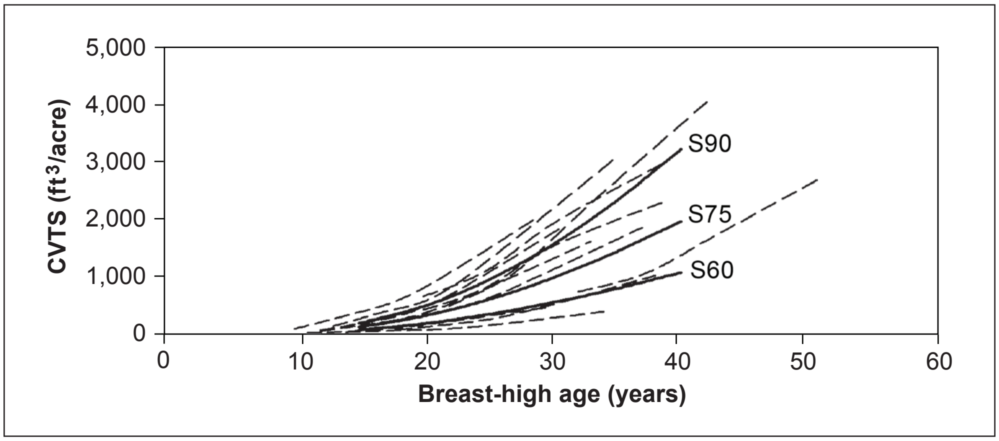

Figure 8—Estimated stand volume (CVTS) for site indexes 60, 75, and 90 (solid lines) by age at breast height, from equation 14 in table 9 for TN-100 (100 trees per acre) and overall data means of %nfwh and elevation. Dashed lines represent observed development of TN-100 (100 trees per acre) plots.

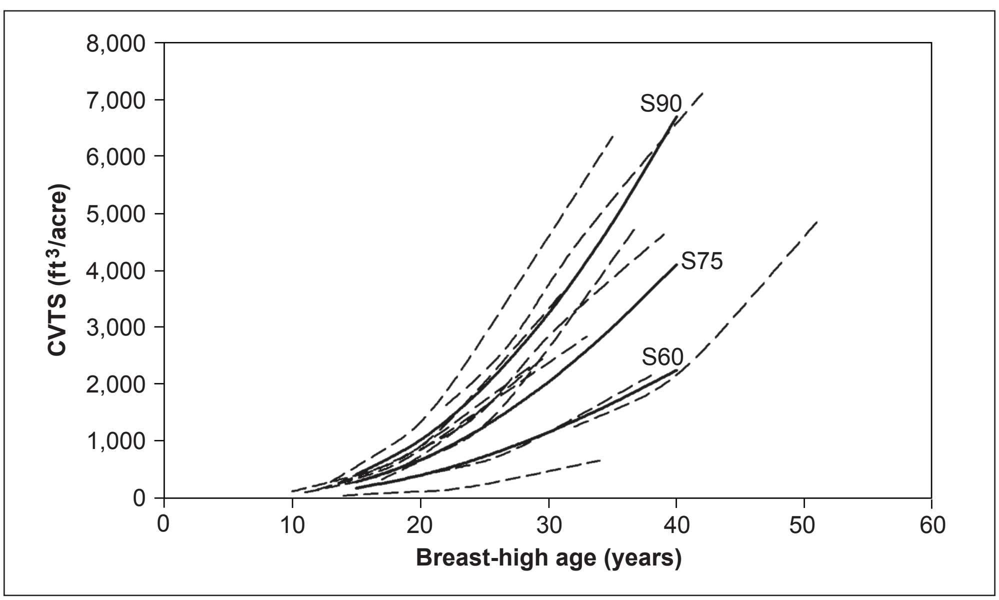

Figure 9—Estimated stand volume (CVTS) for site indexes 60, 75, and 90 (solid lines) by age at breast height, from equation 14 in table 9 for TN-265 (265 trees per acre) and overall data means of %nfwh and elevation. Dashed lines represent observed development of TN-265 (265 trees per acre) plots.

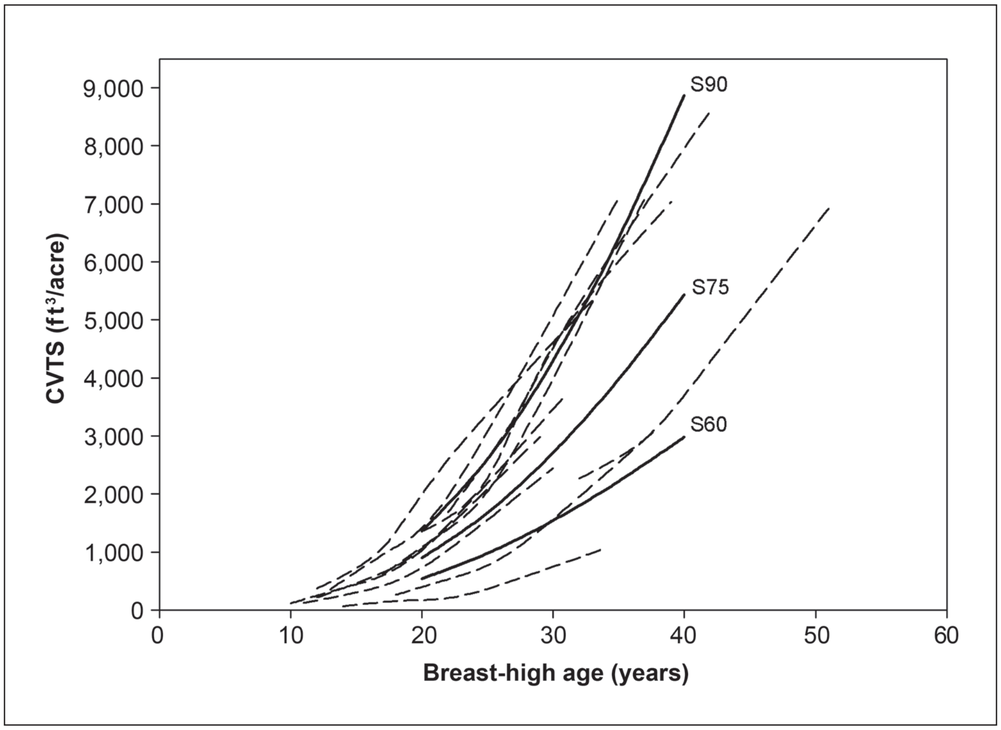

Figure 10—Estimated stand volume (CVTS) for site indexes 60, 75, and 90 (solid lines) by age at breast height, from equation 14 in table 9 for TN-700 (700 trees per acre) and overall data means of %nfwh and elevation. Dashed lines represent observed development of TN-700 plots.

Basal area (BA)—

Similar logarithmic regressions of net BA yield on TN plus various stand variables gave the results shown in table 10. Inclusion of age at thinning (A1) made an appreciable improvement in fit. Inclusion of initial D80 (D1) had little effect. Inclusion of both A1 and D1 made a marked improvement in RSQ, but does not have a clear interpretation; although the combination of A1 and B1 specifies an initial condition, it is also likely related to site quality, and would be usable only if both values are available for a stand.

Table 10—Coefficients in regressions: $\ln(BA) = a + \Sigma b_1 \cdot X_1 + \ldots$ Thinned plots only, all measurements; n = 236

Equation	Constant	%nfwh	1/TN	ln(S)·ln(Agebh)	ln(S)·Agebh	In(elev)	ln(A1)	ln(D1)	Adj RSQ
17	-3.01920	0.00332	-119.22599	0.60054	-0.00692				0.928
18	0.81964	0.00221	-118.39108	0.58769	-0.00434	-0.32371	-0.44852		0.943
19	2.58270	0.00132	-113.50706	0.47837		-0.36636	-0.96022	0.60549	0.953

Note: See “Glossary of Symbols and Acronyms” for definition of terms.

Curves of BA over b.h. age for sites 60, 75 and 90, based on equation 17 in table 10, using the overall means of %nfwh = 53, elevation = 3666, and A1 = 17, are shown as figures 11 (TN-100), 12 (TN-265), and 13 (TN-700).

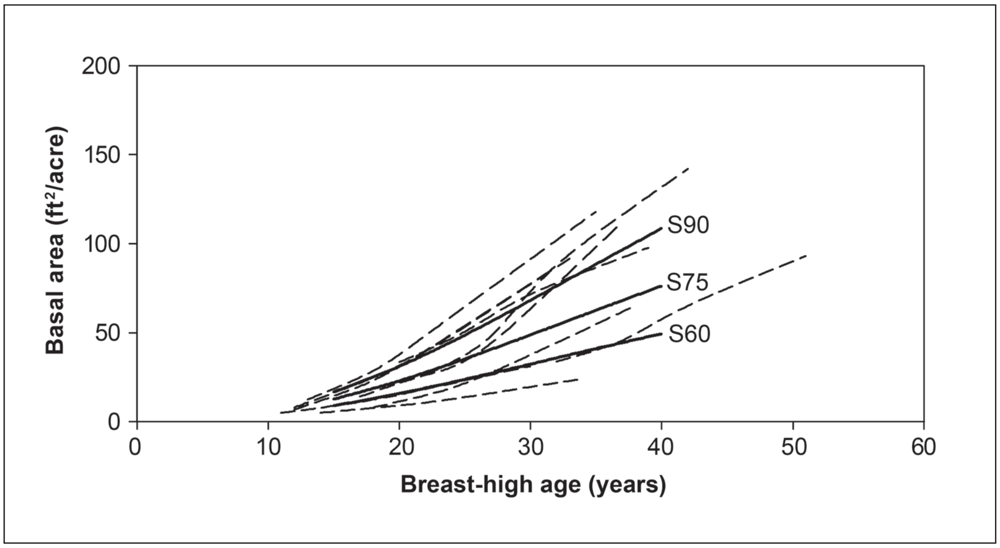

Figure 11—Estimated basal area (BA) for site indexes 60, 75, and 90 by age at breast height, from equation 17 in table 10 for TN-100 (100 trees per acre) and overall data means of %nfwh, elevation, and A1. Dashed lines represent observed development of TN-100 plots.

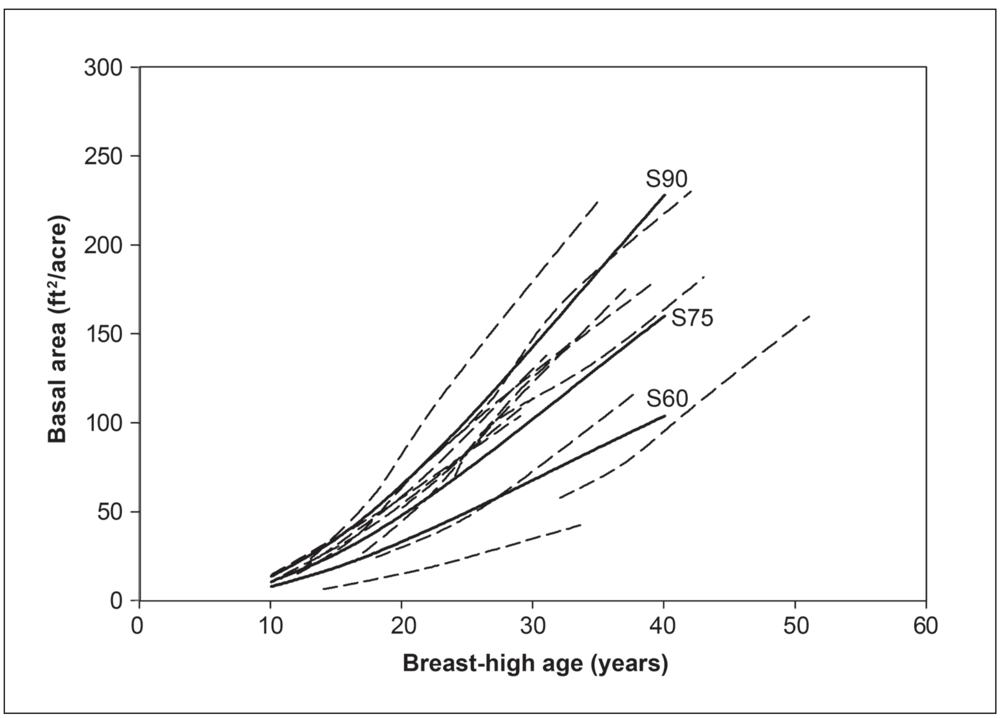

Figure 12—Estimated basal area (BA) for site indexes 60, 75, and 90 by age at breast height, from equation 17 in table 10 for TN-265 (265 trees per acre) and overall data means of %nfwh, elevation, and A1. Dashed lines represent observed development of TN-265 plots.

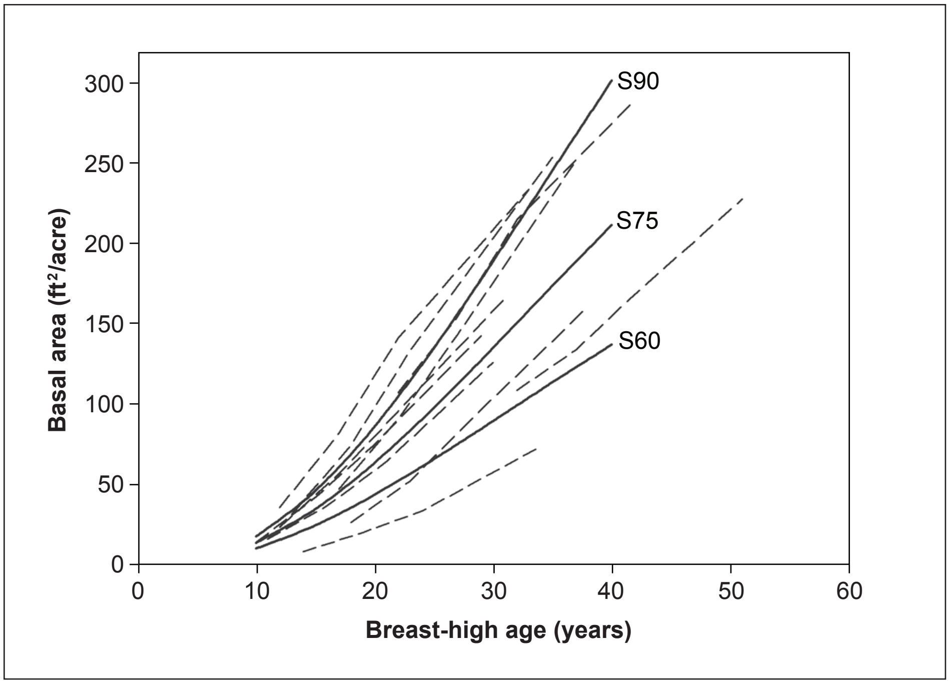

Figure 13—Estimated basal area (BA) for site indexes 60, 75, and 90 by age at breast height, from equation 17 in table 10 for TN-700 (700 trees per acre) and overall data means of %nfwh, elevation, and A1. Dashed lines represent observed development of TN-700 plots.

Diameter of the largest 80 trees per acre (D80)—

A series of stepwise regressions were run, including TN and various stand variables. It became apparent that it was necessary to include D1 and A1. The probable explanation is that initial D80 (D1) comprises a large part of attained D80 (much more than in the case of CVTS and BA). The selected equation (of several with similar RSQs) was equation 20:

$$\ln(D80) = -1.51013 + 0.00091316 \cdot \%nfwh + 0.00589 \cdot S \cdot (agebh - A1)/TN - 0.02127 \cdot agebh + 0.03036 \cdot (agebh - A1) + 0.24375 \cdot \ln(S) \cdot \ln(agebh) - 0.00019812 \cdot S \cdot agebh + 0.51489 \cdot \ln(D1)$$

with adjusted RSQ = 0.953.

The corresponding curves for TN-100, TN-256, TN-265, TN-430, and TN-700 using overall means of %nfwh, S, A1, and D1, are shown in figure 14.

Figure 14—Trends of D80 over time by treatments, from equation 20 using overall means of predictor variables %sfwh, S, A1 and D1.

Relative Stand Density Limits

Two measures of relative stand density that are widely used in the region are Curtis relative density (RD) (Curtis 1982) and stand density index (SDI) (Reinecke 1933). These measures are nearly equivalent except for a scale factor. They are often used as guides to desirable stocking and position of stands relative to the maximum possible relative density. Although the usual forms of these measures are based on quadratic mean diameter, it has been shown that alternative summation forms (RDsum and SDIsum) are less influenced by the numerous small stems of shade-tolerant species that are often present (Curtis 2010, Long and Daniel 1990) in stands with a skewed diameter distribution.

Unthinned plots have not reached a clearly defined maximum relative density.

Trends of RDsum and SDIsum over time on the unthinned plots are shown in figures 15 and 16. As the highest stocking present, these unthinned plots are nearest to some maximum possible relative density. None of the thinned plots are as yet close to a maximum.

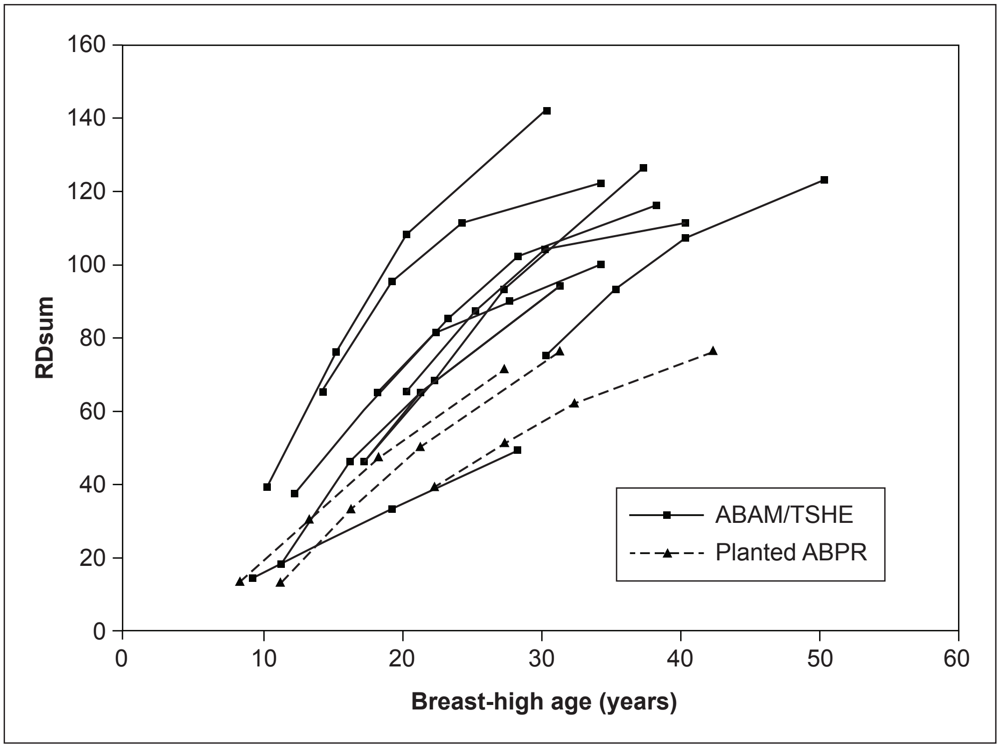

Figure 15—Observed trends of RDsum over age for unthinned plots, for (1) mixed Pacific silver fir and hemlock, and (2) noble fir plantations. ABAM = Pacific silver fir; TSHE = western hemlock; ABPR = noble fir.

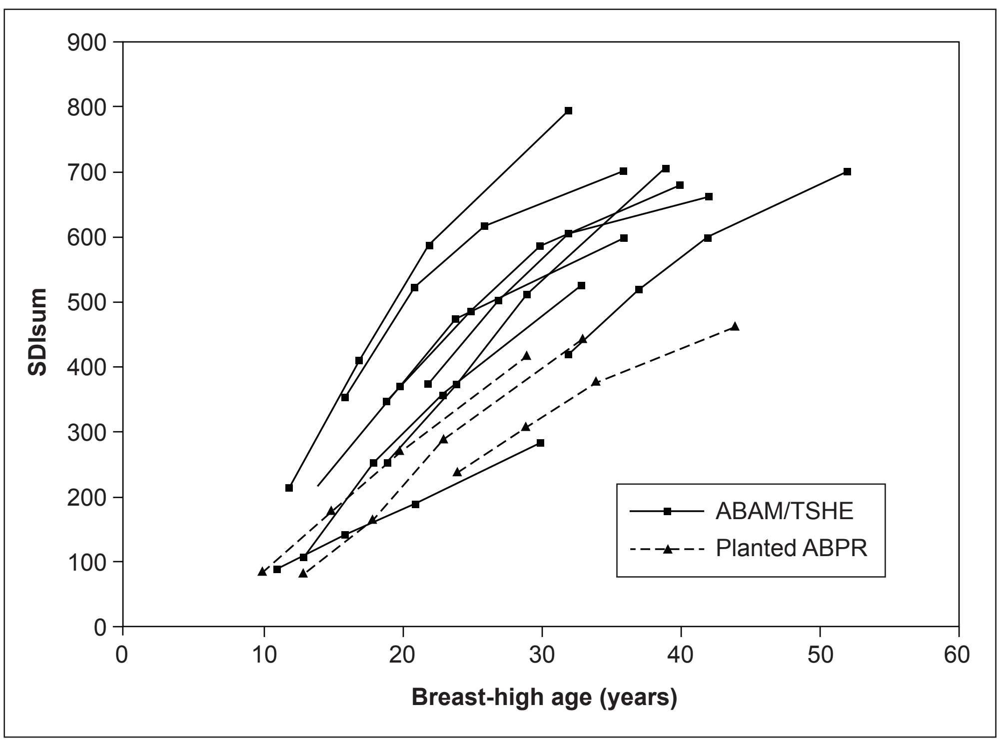

Figure 16—Observed trends of SDIsum over age for unthinned plots for (1) mixed Pacific silver fir and hemlock, and (2) noble fir plantations. ABAM = Pacific silver fir; TSHE = western hemlock; ABPR = noble fir.

Discussion

Overall, the trends shown in the 20-year data are similar in kind to those found in the 10-year analysis (Curtis 2008).

- Top height (H80) increment was reduced in the 100- and 163-trees-per-acre treatments.
- Volume increment on thinned plots increased as number of residual trees increased, but at a decreasing rate.
- Basal area increment in thinned plots increased as number of residual trees increased, up to the 430 trees per acre. However, there was little difference between the 430- and 700-trees-per-acre treatments.
- There was a modest increase in diameter growth of the 80 largest trees per acre as number of residual trees decreased.

Thus, the decrease in top height increment at the widest spacings was at least partially offset by increased diameter increment. There was a re-allocation of growth from height increment to diameter increment.

The yield regressions (equations 14 to 20) were fit to all data combined, without regard to the fact that there were four measurements on each plot. The expected effect of such serial correlation is that estimates of regression coefficients will be unbiased, but that measures of fit and significance such as RSQ and F will be biased upward. Because a primary point of interest is the shape of the growth curves, it was necessary to include the intermediate measurements. The number of repeated measurements per plot (4) is small compared to the total number of measurements (265), and it was assumed that the coefficients in prediction equations would be unaffected and that RSQ values could be used for ranking different equations. Variables of borderline nominal significance were generally omitted.

In figures 8 through 13, the calculated volume and BA yield curves are overlaid on the observed growth trends of the same treatment in individual installations. This format (1) provides a visual impression of the concordance of the fitted yield curves with the actual data, and (2) shows the actual range of the basic data. The empirical equations presented here summarize actual observed development, but should not be extrapolated outside this range. One would expect yield curves to follow one of the commonly used sigmoid growth functions, but as yet the age range of the data is insufficient to allow fitting of these.

Residuals from even the best fitting regressions (both for 20-year increment and for yield) show differences associated with individual installations. These differences are attributable in part to imprecise site index estimates, and probably to incomplete expression of effects of species differences. The frequent occurrence of elevation as an effective predictor may also be substituting for these deficiencies.

Inclusion of initial age (A1) or initial D80 (D1) frequently improved fits. It is reasonable of expect that stage of development at time of thinning would have an effect on response. Ther combination of A1 and D1 is probably also related to site productivity, and may in part offset the deficiencies in the site index estimates. But with only 12 locations represented in the sample, one can have little confidence in the generality of the numerical coefficients for A1 and D1.

Growth is accelerating on the better sites.

The volume yield curves show a wide difference in yield between the minimum (S60) and maximum (S90) site indexes present. The curves are concave upward and growth is accelerating on the better sites. This is in accord with the characteristic growth patterns of noble fir and Pacific silver fir; these typically have a prolonged period of slow juvenile growth followed by a long sustained period of much more rapid and nearly linear growth. This pattern, combined with the ability of true firs to develop high BAs, implies that a given 50-year site index for true firs indicates considerably greater potential productivity than the same site index for Douglas-fir although the biological rotation would likely be longer. (Also, because the site index used here was based on trees included in the largest 80 per acre, site index values based on the more usual 40 per acre would be slightly greater.)

This analysis has not summarized ingrowth as a separate component. The wider spacings frequently have abundant ingrowth, which because of its small size has as yet had little influence on volume and BA. But this is changing. It seems likely that the widest spacings will develop into two-storied stands, a characteristic that may be of importance from the wildlife and visual effects standpoints. There are also major differences—visually apparent but not addressed here—in shrub understory composition and vigor that may be important to both wildlife and recreational uses (such as huckleberry production).

Mortality on thinned plots has not been summarized, but has been very minor to date.

The original motivation for this study was a perceived need for guidelines for precommercial thinning. From this standpoint, it is clear that there is no gain in production by retaining more than about 400 trees per acre. This would be an appropriate choice for short rotations or if early commercial thinning were considered feasible. However, the true firs are susceptible to rot entering through logging injuries. Also, these lands involve high recreational and scenic values. These considerations, the growth patterns of the species, and the fact that the majority of these lands are in public ownership, all suggest that any future management for timber production will likely involve relatively long rotations and infrequent entries, in contrast to typical management of low-elevation Douglas-fir.

Considerably lower residual stocking—perhaps 200 well-distributed stems per acre—is probably appropriate.

At this time, it seems that evaluation of the long-term development patterns and yield potential of these stands are likely to become the most important aspect of the study. This will require that the study be continued for a considerable period of years.

There are still six installations that have not reached the 20-year measurement, and these were therefore not included in these comparisons. The analysis should be reworked when the additional data become available.

Noble fir development is of particular interest.

A particular point of interest is the development patterns of noble fir plantations, which make up substantial areas in the region. When all 18 installations become available, the data will include 8 such plantations. The noble fir plantations included were generally comparable to other successful plantations of the species, whereas those plots in naturally regenerated stands were highly selected for better initial stocking and greater relative uniformity than the average of existing naturally regenerated stands, which tend to be patchy and somewhat irregular.

Both early observations in noble fir plantations and observation of older, naturally established stands indicate that noble fir is a highly desirable species. A separate analysis of the eight noble fir installations would be desirable. Analysis of these single-species even-aged stands would be considerably neater, and would allow addressing a number of questions. In particular, is the assumption made above, that height growth curves of young noble fir are proportional to the existing Pacific silver fir curves (Nigh 2009), valid? If not, we should be able to develop new curves for young noble fir that—with only limited extrapolation—would provide improved site estimates for stands under age 50 at b.h.

The relative density trends for the unthinned plots (figs. 15 and 16) do not clearly define a maximum relative density. The denser plots have lost considerable numbers of trees, although many mortality trees were below the 1.6 -in diameter limit used in the summaries. The trends do suggest that for Pacific silver fir and Pacific silver fir/hemlock mixtures, the upper limit is at least 20 to 25 percent greater than values typical of Douglas-fir. This result is consistent with Long (1985), with estimates by Poage and others (2007) for western hemlock–Sitka spruce in southeast Alaska, and with the expectation that the limit will be higher for shade-tolerant species. The low position of the three noble fir stands included in figures 15 and 16 probably reflects some combination of the lesser shade tolerance of the species and the fact that—being plantations—the initial number of trees was much lower than in unthinned silver fir and hemlock, and tree distribution was more uniform.

Aside from immediate limitations in personnel and funding, the recent deemphasis of timber production as an objective on the national forests has meant a loss of the strong support that originally made this study possible. Yet, all history indicates that policies and needs will change over time. Although some people tend to dismiss the importance of these high-elevation forests for timber production, these forests include a wide range of topography and potential productivity, and there are very considerable areas that are highly productive and well-suited to timber production. Their potential productivity and response to treatment are also pertinent to estimates of carbon storage. Although this study was originally established with a timber production objective in mind, many nontimber values can be enhanced through silviculture, and traditional practices can be modified to be compatible with multiple objectives. There is no substitute for reliable information on development patterns and silvicultural responses as a basis for future decisions on management options. Basic data provided by this study will be valuable in developing models for this purpose.

We cannot anticipate all future information needs, but all past experience indicates that long-term studies such as this have great value for a variety of purposes, including some not envisioned at the time of study establishment. It is therefore important that measurement of this study be continued for the next several decades.

Acknowledgments

Helpful reviews were provided by Peter Gould, David Marshall, Aaron Weiskittel, and Ashley Steel. Dave Thornton maintained and edited the data. Leslie Brodie assisted in preparation of figures.

Metric Equivalents

When you have:	Multiply by:	To find:
Inches (in)	2.54	Centimeters
Feet (ft)	0.3048	Meters
Square feet (ft^2)	0.929	Square meters
Acres (ac)	0.405	Hectares
Trees per acre	2.471	Trees per hectare
Square feet per acre (ft^2/ac)	0.229	Square meters per hectare
Cubic feet per acre (ft^3/ac)	0.07	Cubic meters per hectare

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Glossary of Symbols and Acronyms

%nfwh = Sum of percentage basal area in noble fir and hemlock at measurement 4.

S = Site index = Estimated mean height of largest 80 silver fir per acre at breast high age 50.

S60 , etc. = Site index 60, feet.

TN = Target number of leave trees per acre.

spac = Spacing of leave trees after thinning, feet.

elev = Elevation, feet.

age b.h. = agebh = Breast-high age, years.

A1 = Breast-high age at time of thinning.

D1 = D80 at time of thinning, inches.

CVTS = Volume of entire stem, cubic feet per acre.

BA = Basal area, square feet per acre.

D80 = Mean diameter of the largest 80 trees per acre, inches.

ΔCV = Periodic net change in CVTS, cubic feet per acre

ΔBA = Periodic net change in basal area, square feet per acre.

ΔD80 = Periodic net change in D80, inches.

ln(X) = Natural logarithm (base e) of X.

X • Y = Product of X and Y.

sqrtX = Square root of X.

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

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

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