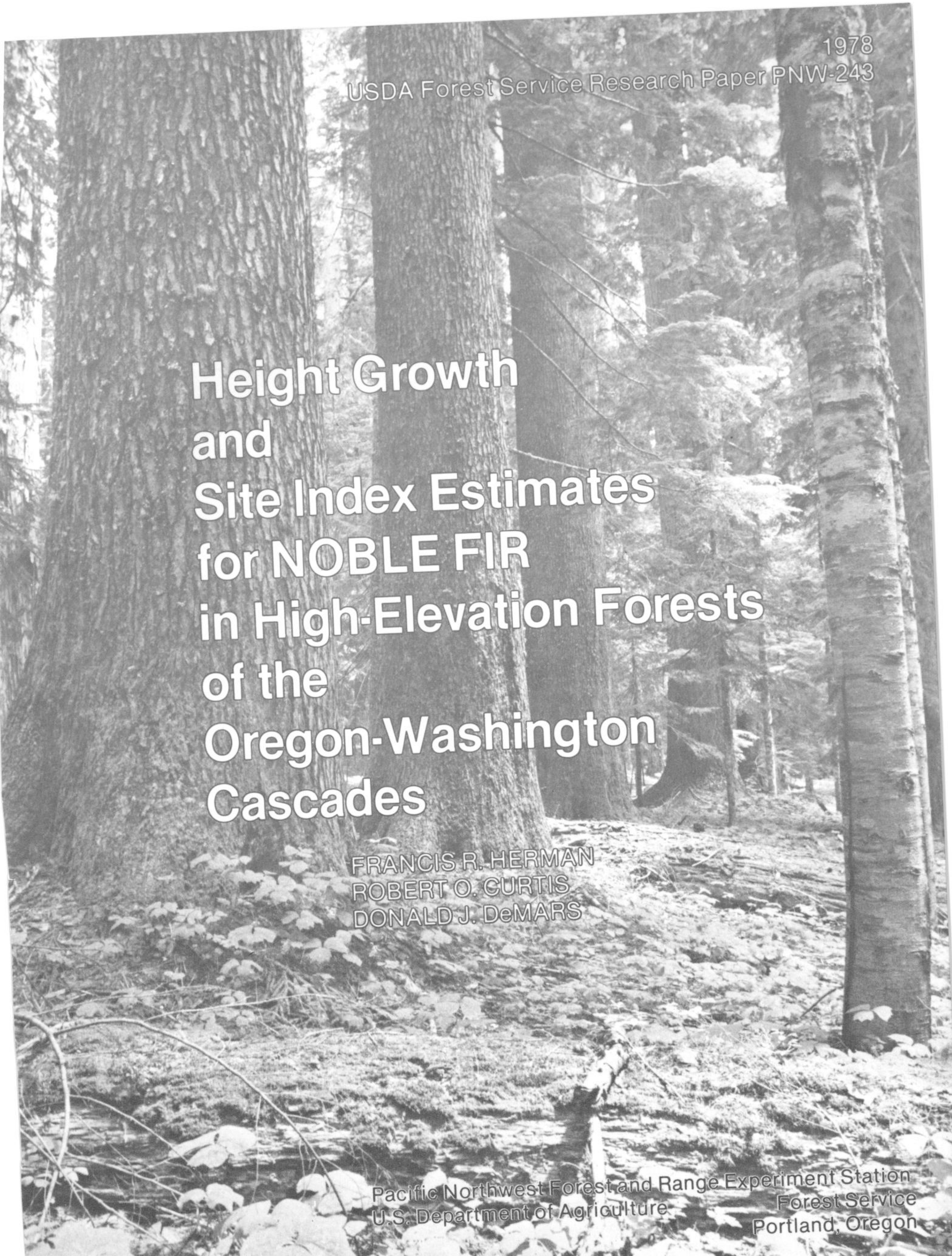

1978
USDA Forest Service Research Paper PNW-243

Height Growth and Site Index Estimates for NOBLE FIR in High-Elevation Forests of the Oregon-Washington Cascades

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HEIGHT GROWTH AND SITE INDEX ESTIMATES FOR NOBLE FIR IN HIGH-ELEVATION FORESTS OF THE OREGON-WASHINGTON CASCADES

Reference Abstract

Herman, Francis R., Robert O. Curtis, and Donald J. Demars. 1978. Height growth and site index estimates for noble fir in high-elevation forests of the Oregon-Washington Cascades. USDA For. Serv. Res. Pap. PNW-243, 15 p., illus. Pac. Northwest For. and Range Exp. Stn., Portland, Oregon.

Height growth and site index estimation equations and corresponding curves were derived from stem analyses of *Abies procera* Rehd. in the Cascade Range of Oregon and Washington. These incorporate additional data and new site index estimation procedures and replace previously published curves. Two sets of height growth and site index estimation curves and tables are given--one set with U.S. units and another set with metric units.

KEYWORDS: Site index -)stand height/age, increment (height), altitude (-site, noble fir, *Abies procera*, Oregon (Cascade Range), Washington (Cascade Range).

RESEARCH SUMMARY

Research Paper PNW-243

1978

Height growth and site index estimation equations and corresponding curves for noble fir (*Abies procera* Rehd.) were developed from stem analysis data from 60 plots located between McKenzie Pass in central Oregon and Stévens Pass in north-central Washington. This information replaces earlier information presented in 1970.

Height growth estimation curves obtained by regressing height on site index and age differ from site index estimation curves obtained by regressing site index on height and age. The former provides estimates of expected heights of noble fir at different ages for stands of specified site index. The latter provides estimates of noble fir site index for stands of known present age and height.

The new curves and tabular data can be used for estimating relative site quality of noble fir within the geographic zone represented by the basic data. Because the curves were based on the tallest, undamaged dominant in one-fourth acre (0.1 ha), the tallest, undamaged dominant should also be selected when the site index of any similar-size upper-slope forest area is estimated.

These curves for high-elevation noble fir will provide a basis for development of growth and yield estimates for true fir and hemlock (*Abies* spp. and *Tsuga* spp.) of the Oregon-Washington Cascade Range.

Contents

Introduction

This paper presents height growth and site index estimation curves for dominant noble fir (*Abies procera* Rehd.) in high-elevation forests of the Oregon-Washington Cascade Range. These curves replace those of DeMars et al. (1970). They differ through the incorporation of additional data, the use of new methods of analysis (Curtis et al. 1974a, 1974b), and the presentation of metric equations, curves, and tables.

These equations and curves are based on stem analyses (Herman et al. 1975) of selected dominant trees at 60 locations between McKenzie Pass in central Oregon and Stevens Pass in north-central Washington (fig. 1). All locations represent unmanaged stands, mainly old growth within the "*Abies amabilis* zone" of Franklin and Dyrness (1973). Similar data were collected concurrently for associated species; curves for associated Douglas-fir have been given by Curtis et al. (1974b), and curves for other species are planned.

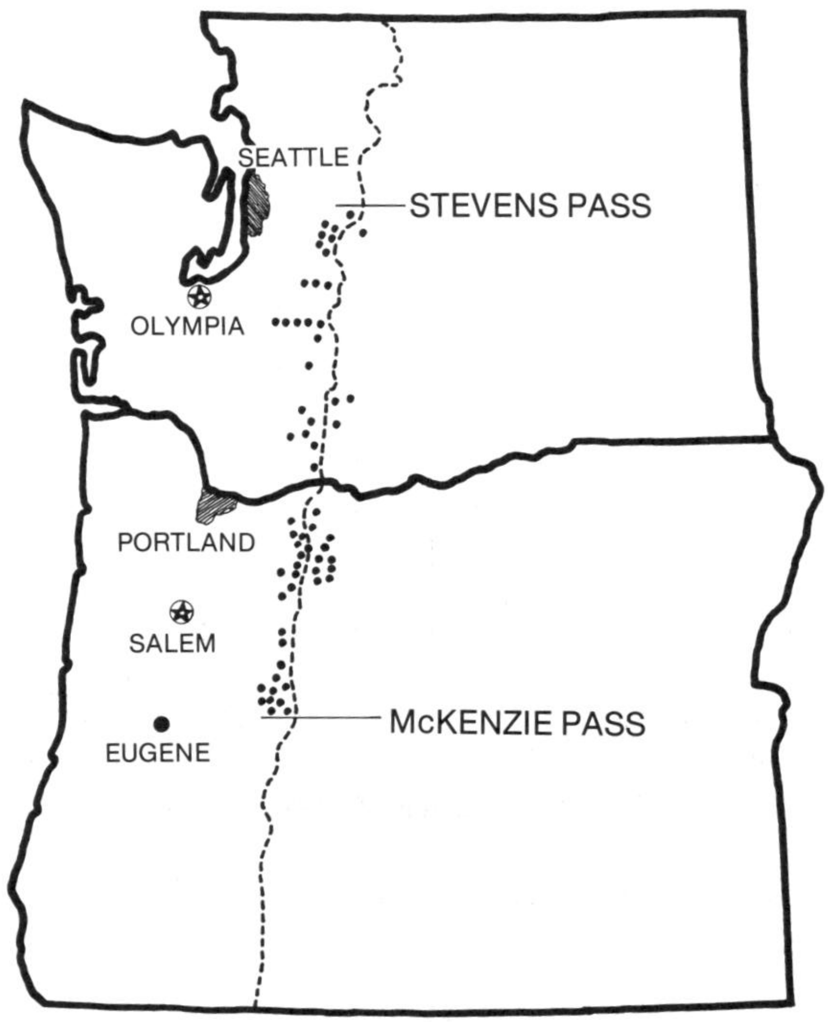

Figure 1.--Geographic distribution of the noble fir selected for stem analysis and used sample in development of height growth and site index estimation curves.

Data

Each field location was selected in an area of uniform site and stand conditions, usually about one-fourth acre (0.1 ha) within a stand or group of trees in which the dominants were estimated to be of a single age class. The single tallest undamaged dominant of each species present was felled. Sections were cut at stump, at 4.5 feet (1.4 m), and at intervals up the stem (usually 18 feet (5.5 m) in the merchantable portion of large trees, and shorter intervals in small trees and tops).

Heights were plotted over ages. Interpolated values of heights at successive 10-year intervals of age at breast height (age bh) were the values used in analyses. Examination of these graphs and comparison of tree ages led to rejection of several noble fir trees because of evidence of early damage or suppression, or differences in age class. Data from trees used in the analyses are summarized by number of sample trees present at successive ages bh in the following tabulation. The number of trees by classes of height attained at age 100 (H100) is given in figure 2.

Age at breast height	Number of trees
10-100	60
150	55
200	48
250	34
300	14
350	5
400	2

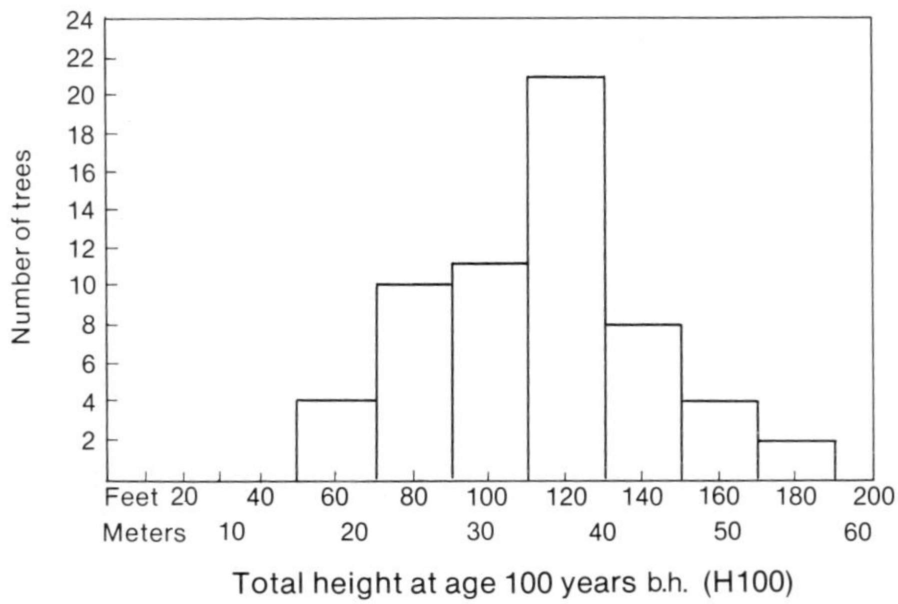

Figure 2.--Number of noble fir trees used in analysis sample by classes of H100 (attained height at age 100 years bh).

Analysis

The analysis followed, with minor differences, the general procedure used with Douglas-fir (Curtis et al. 1974b).

All ages indicated in the following discussions are in years from breast height (age bh). Site index is average height at age bh of 100 years of selected trees. Individual sample tree height at age 100 bh which is an estimate of site index is symbolized as H100; tree heights at other ages as H. The variables are age bh, H100-4.5, and H-4.5. Subtraction of 4.5 feet (1.37 m) provides a common origin for height and age scales at breast height.

HEIGHT GROWTH EQUATIONS

Preliminary Curves

The regressions (H - 4.5) = a + b (H100 - 4.5) and (H - 4.5) = a + b (H100 - 4.5) + c $(H - 4.5)^2$, using 4.5 feet[1/] for breast height, were fitted to data for individual 10-year intervals of age bh. These provided estimates for successive intervals of H100 which, when connected, gave unsmoothed trends over age--used as guides in selecting suitable equations (Heger 1968; Curtis et al. 1974a, 1974b)--and standard errors of estimate (SEE)--used as the basis for the weighting factor in subsequent computations.

Although curvilinearity was slight, the squared term was significant for ages 130+.

Trends over age were consistent and reasonably smooth up to age bh = 260 years. Beyond this age, trends became erratic and somewhat unreasonable. This condition is due to the combination of very limited sample size and prolonged height growth of a few extremely old trees. Therefore, in subsequent analyses, data for ages >260 years were omitted. Portions of the final curves and tables representing ages >260 years are extrapolations.

Height Growth Regression Fitted to Pooled Data

A series of trial fits to values read from the preliminary curves indicated that the inverse polynomial

$$H - 4.5 = (\text{age bh})^2/[a + b(\text{age bh}) + c(\text{age bh})^2],$$

previously used by DeMars et al. (1970), would satisfactorily represent the height-age relationship for given values of site index.

The condition that H = H100 at age bh = 100 was introduced by writing

$$c = 1.0 - a\ (1/100)^2 - b\ (1/100);$$

where,

$$w(H - 4.5) = w(H100 - 4.5)/[a(1/\text{age bh})^2 + b(1/\text{age bh}) + 1.0 - 0.0001(a) - 0.01(b)]$$ [2/]

and

w = 1/SEE, a weighting factor, and
a, b are unknown functions of H100.

[1/] Regressions expressed in metric equivalents:

$(H_m - 1.37 = a + b\ (H100_m - 1.37)$ and $(H_m - 1.37) = a + b\ (H100_m - 1.37) + c\ (H100_m - 1.37)^2$.

Regression coefficients appearing in equations are changed where necessary to produce valid metric expressions. Curves expressed in U.S. measurements will be slightly different in reference heights; i.e., site index 60 curves in feet have no exact counterpart in selected metric curves. Therefore, separate equations are given for feet and for meters.

[2/] Instructions for equation development is given by Curtis et al. 1974a, p. 79.

This model was fitted to the pooled data for ages bh = 20, 40, etc. Odd-numbered decades were omitted to reduce running time of the nonlinear least squares fitting program. Successive trials of a number of functions for "a" and "b" led to the following equations:

Equation I, in feet:

$$H = 4.5 + (H100 - 4.5)/[a(1/x)^2 + b(1/x) + 1.0 - 0.0001(a) - 0.01(b)];$$

where,

x = age bh,

$a = -564.38 + 22.25\ (H100 - 4.5) - 0.04995\ (H100 - 4.5)^2$, and

$b = 6.80 + 2843.21\ (H100 - 4.5)^{-1} + 34735.54\ (H100 - 4.5)^{-2}$.

Standard error of estimate of the transformed variable $w(H - 4.5)$ was 1.0055.

Height estimates by this equation are given in table 1, and corresponding height growth curves are shown in figure 3.

Equation I, in meters:

$$H_m = 1.37 + [H100_m - 1.37]/[a(1/x)^2 + b(1/x) + 1.0 - 0.0001(a) - 0.01(b)];$$

where,

x = age bh,

$a = -564.38 + 73.0044(H100_m - 1.37) - 0.5376(H100_m - 1.37)^2$, and

$b = 6.80 + 866.612(H100_m - 1.37)^{-1} + 3227.05\ (H100_m - 1.37)^{-2}$.

Height estimates in meters are given in table 2 and corresponding height growth curves are shown in figure 4.

SITE INDEX ESTIMATION CURVES

Preliminary Curves

The regressions $(H100 - 4.5) = a + b(H - 4.5)$ and $(H100 - 4.5) = a + b(H - 4.5) + c(H - 4.5)^2$ were fitted to data for individual successive 10-year intervals of age bh. Trends of coefficients over age were used as guides in selecting suitable equation forms for expression of the $\hat{H}100 = f(H, \text{age})$ relationship for all combined data. The squared term was significant only for ages of 110 years and above. Curvilinearity was slight within that range.

Site Index Estimation Equations Fitted to Pooled Data

To simplify curve fitting, we fitted the subsequent regressions of H100 on age bh and height to the pooled data in two segments: (1) ages less than 100 years bh and (2) ages over 100 years bh.

(1) Equations for ages 0-100 years: The regression of H100 - 4.5 on H - 4.5 and age bh was fitted as a weighted regression conditioned to pass through H100 = H at age bh = 100 (Curtis et al. 1974b), which--after simplication--can be written as:

Equation II, in feet:

$$\hat{H}100 = a + b(H - 4.5);$$

where,

$a = 4.5 + 0.2145(100 - \text{age bh}) + 0.0089(100 - \text{age bh})^2$ and

$b = 1.0 + 0.00386(100 - \text{age bh}) + 1.2518(100 - \text{age bh})^5/(10)^{10}$,

with standard error of estimate of the transformed variable $w(H100 - H)$ being 0.9842.

Table 1--*Expected heights for indicated ages at breast height (bh) for values of H100 (total height in feet at index age 100)*[1/]

Age at bh	Height (feet) at index age 100										
	60	70	80	90	100	110	120	130	140	150	160
Years	Feet										
10	9	10	10	10	11	11	11	11	12	12	12
20	16	18	20	21	23	24	25	26	28	29	30
30	22	26	30	33	36	39	41	44	46	49	51
40	29	34	39	44	48	53	57	61	65	69	73
50	35	41	48	54	60	65	71	76	82	87	92
60	40	48	55	63	70	77	83	90	97	103	110
70	46	54	62	71	79	87	94	102	110	117	125
80	51	60	69	78	87	95	104	113	121	130	138
90	55	65	75	84	94	103	113	122	131	141	150
100	60	70	80	90	100	110	120	130	140	150	160
110	64	75	85	95	106	116	127	137	148	158	169
120	68	79	89	100	111	122	132	143	154	165	176
130	72	83	93	104	115	126	138	149	160	172	183
140	76	86	97	108	119	131	142	154	166	178	189
150	79	90	101	112	123	135	147	159	171	183	195
160	83	93	104	115	127	139	151	163	175	187	199
170	86	96	107	118	130	142	154	166	179	191	204
180	89	99	110	121	133	145	157	170	182	195	208
190	92	102	112	124	136	148	160	173	186	198	211
200	95	104	115	126	138	150	163	176	188	201	214
210	97	107	117	128	140	153	165	178	191	204	217
220	100	109	119	131	142	155	168	181	194	207	220
230	102	111	121	133	145	157	170	183	196	209	223
240	105	113	123	134	146	159	172	185	198	211	225
250	107	115	125	136	148	161	174	187	200	213	227
260	109	117	127	138	150	162	175	188	202	215	229
270	111	119	128	139	151	164	177	190	204	217	231
280	113	120	130	141	153	165	178	192	205	219	232
290	115	122	131	142	154	167	180	193	207	220	234
300	117	123	133	144	155	168	181	194	208	222	236
310	119	125	134	145	157	169	182	196	209	223	237
320	121	126	135	146	158	170	184	197	211	224	238
330	123	128	136	147	159	172	185	198	212	226	239
340	124	129	138	148	160	173	186	199	213	227	241
350	126	130	139	149	161	174	187	200	214	228	242
360	127	131	140	150	162	175	188	201	215	229	243
370	129	133	141	151	163	175	189	202	216	230	244
380	130	134	142	152	164	176	189	203	217	231	245
390	132	135	143	153	165	177	190	204	218	232	246
400	133	136	144	154	165	178	191	205	218	232	246

[1/] From equation I (in feet). Values correspond to height growth curves shown in figure 3.

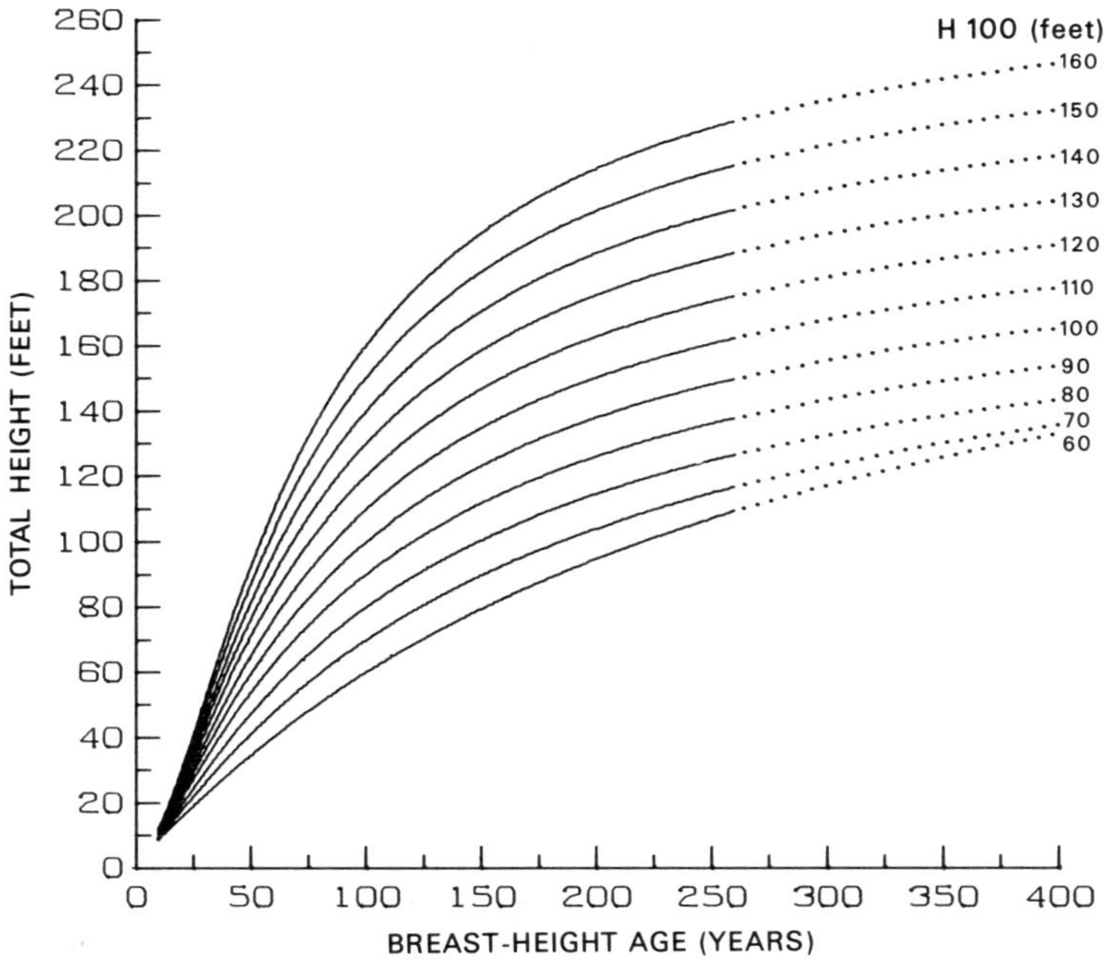

Figure 3.--Height growth curves for noble fir (in feet) corresponding to equation I (in feet). Note: These curves express the pattern of height growth of dominant trees in relation to age, within even-aged stands. They should be used for expressing height development in the construction of yield tables or yield functions representing average development of even-aged stands actually attaining specified heights at index age 100 (site indices). Use these curves where height growth and yield determinations are to be expressed in feet.

Corresponding values are shown in table 3 and figure 5, for ages bh of 10 through 100 years.

Equation II, in meters:

$$\hat{H}100_m = a + b(H_m - 1.37);$$

where,

$$a = 1.37 + 0.0654(100 - \text{age bh}) + 0.0027(100 - \text{age bh})^2 \text{ and}$$
$$b = 1.0 + 0.00386(100 - \text{age bh}) + 1.2518(100 - \text{age bh})^5/10^{10}.$$

Table 2--*Expected heights for indicated ages at breast height (bh) for values of* $H100_m$ *(total height in meters at index age 100)*[1/]

Age at bh	Height (meters) at index age 100										
	20	23	26	29	32	35	38	41	44	47	50
Years	Meters										
10	2.8	3.0	3.1	3.2	3.3	3.4	3.4	3.5	3.6	3.7	3.8
20	5.1	5.7	6.2	6.7	7.1	7.5	7.9	8.2	8.6	8.9	9.3
30	7.4	8.5	9.5	10.4	11.3	12.1	12.9	13.7	14.4	15.2	15.9
40	9.6	11.2	12.6	14.0	15.4	16.6	17.9	19.1	20.2	21.4	22.6
50	11.7	13.6	15.5	17.3	19.0	20.7	22.4	24.0	25.6	27.2	28.8
60	13.6	15.8	18.0	20.2	22.3	24.3	26.4	28.4	30.3	32.3	34.3
70	15.4	17.9	20.4	22.8	25.2	27.5	29.9	32.2	34.5	36.8	39.1
80	17.0	19.7	22.4	25.1	27.7	30.3	32.9	35.5	38.1	40.7	43.2
90	18.6	21.4	24.3	27.2	30.0	32.8	35.6	38.4	41.2	44.1	46.9
100	20.0	23.0	26.0	29.0	32.0	35.0	38.0	41.0	44.0	47.0	50.0
110	21.3	24.4	27.5	30.7	33.8	36.9	40.1	43.2	46.4	49.6	52.7
120	22.6	25.8	28.9	32.2	35.4	38.7	41.9	45.2	48.5	51.8	55.1
130	23.8	27.0	30.2	33.5	36.8	40.2	43.6	47.0	50.4	53.8	57.3
140	24.9	28.1	31.4	34.7	38.2	41.6	45.1	48.6	52.1	55.6	59.1
150	26.0	29.2	32.5	35.9	39.3	42.9	46.4	50.0	53.6	57.2	60.8
160	27.0	30.1	33.5	36.9	40.4	44.0	47.6	51.3	54.9	58.6	62.3
170	27.9	31.1	34.4	37.9	41.4	45.0	48.7	52.4	56.1	59.9	63.6
180	28.8	31.9	35.2	38.7	42.3	46.0	49.7	53.5	57.2	61.1	64.9
190	29.6	32.7	36.0	39.5	43.2	46.8	50.6	54.4	58.2	62.1	66.0
200	30.4	33.5	36.8	40.3	43.9	47.6	51.4	55.3	59.2	63.1	67.0
210	31.2	34.2	37.5	41.0	44.6	48.4	52.2	56.1	60.0	63.9	67.9
220	31.9	34.8	38.1	41.6	45.3	49.1	52.9	56.8	60.8	64.7	68.7
230	32.6	35.5	38.7	42.3	45.9	49.7	53.6	57.5	61.5	65.5	69.5
240	33.2	36.1	39.3	42.8	46.5	50.3	54.2	58.1	62.1	66.2	70.2
250	33.9	36.6	39.9	43.4	47.0	50.8	54.8	58.7	62.7	66.8	70.8
260	34.5	37.2	40.4	43.9	47.5	51.4	55.3	59.3	63.3	67.4	71.4
270	35.0	37.7	40.9	44.3	48.0	51.8	55.8	59.8	63.8	67.9	72.0
280	35.6	38.2	41.3	44.8	48.5	52.3	56.2	60.3	64.3	68.4	72.5
290	36.1	38.6	41.7	45.2	48.9	52.7	56.7	60.7	64.8	68.9	73.0
300	36.6	39.1	42.2	45.6	49.3	53.1	57.1	61.1	65.2	69.3	73.5
310	37.1	39.5	42.5	46.0	49.7	53.5	57.5	61.5	65.6	69.8	73.9
320	37.6	39.9	42.9	46.3	50.0	53.9	57.8	61.9	66.0	70.2	74.3
330	38.0	40.3	43.3	46.7	50.3	54.2	58.2	62.2	66.4	70.5	74.7
340	38.5	40.6	43.6	47.0	50.7	54.5	58.5	62.6	66.7	70.9	75.1
350	38.9	41.0	43.9	47.3	51.0	54.8	58.8	62.9	67.0	71.2	75.4
360	39.3	41.3	44.2	47.6	51.3	55.1	59.1	63.2	67.3	71.5	75.7
370	39.7	41.7	44.5	47.9	51.5	55.4	59.4	63.5	67.6	71.8	76.0
380	40.0	42.0	44.8	48.2	51.8	55.6	59.6	63.7	67.9	72.1	76.3
390	40.4	42.3	45.1	48.4	52.0	55.9	59.9	64.0	68.2	72.4	76.6
400	40.7	42.6	45.3	48.7	52.3	56.1	60.1	64.2	68.4	72.6	76.8

[1/] From equation I (in meters). Values correspond to height growth curves shown in figure 4.

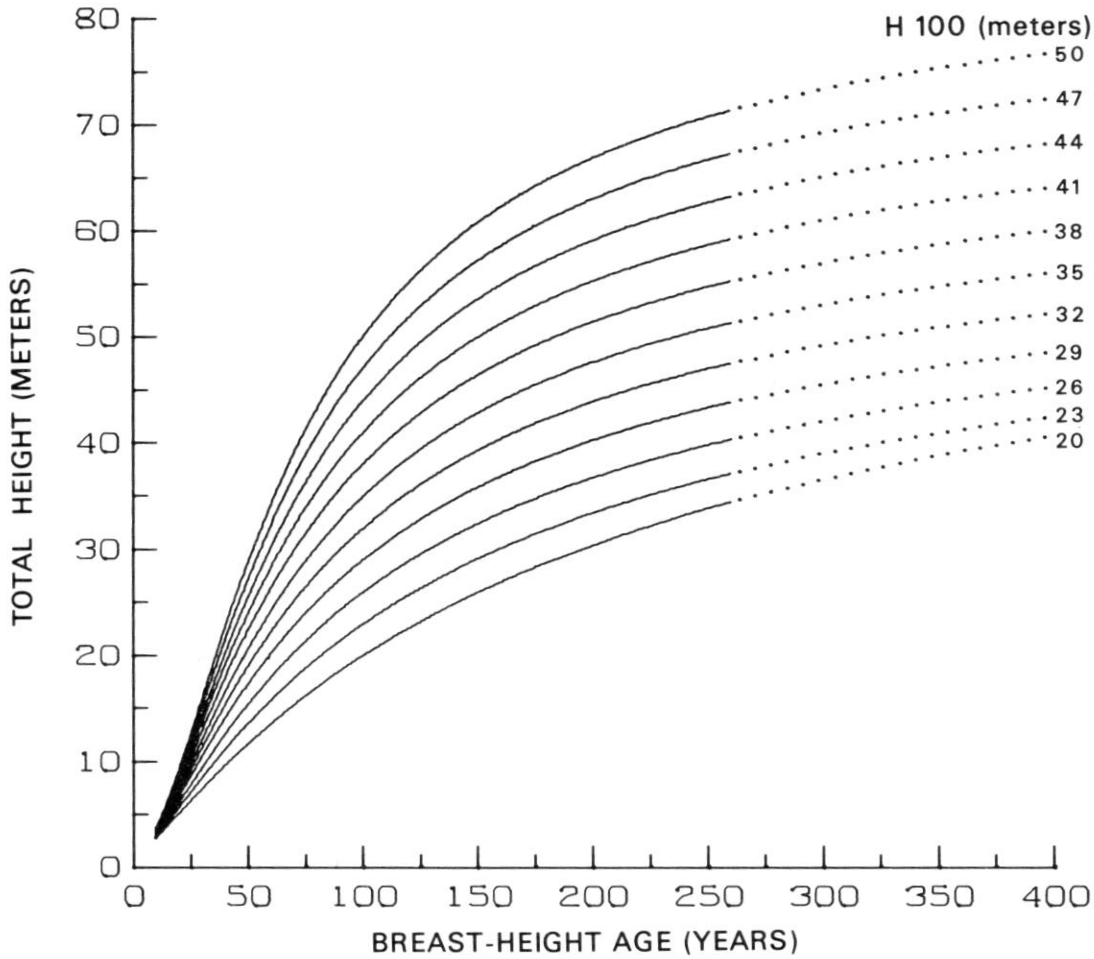

Figure 4.--Height growth curves for noble fir (in meters) corresponding to equation I (in meters). Note: These curves express the pattern of height growth of dominant trees in relation to age, within even-aged stands. They should be used for expressing height development in the construction of yield tables or yield functions representing average development of even-aged stands actually attaining specified heights at index age 100 (site indices). Use these curves where height growth and yield determinations are to be expressed in meters.

Corresponding metric values are shown in table 4 and figure 6, for ages bh of 10 through 100 years.

(2) Equations for ages 100+ years bh: The regression of H100 - 4.5 on age bh, H - 4.5, and $(H - 4.5)^2$ was fitted as a weighted and conditioned regression, using only values for ages 80, 90, and 110 to 260 years. (Ages 80 and 90 were included to insure approximate equality of slopes at age 100 for this curve and also for ages under 100 years.) To insure reasonable behavior at older ages, we expressed coefficients as polynomials in $(1/\text{age bh})^n$, $n \geq 0$, and equals 1/2, 1, 2, 3, etc., sequence in a series of stepwise trials.

Table 4--*Ages bh and total heights corresponding to indicated estimates of $\hat{H}100_m$ (height at index age 100)*[1/]

Age at bh	Height (meters) at index age 100										
	20	23	26	29	32	35	38	41	44	47	50
Years	Meters										
10	[2/] -2.9	-1.5	-.1	1.3	2.7	4.2	5.6	7.0	8.5	9.9	11.4
20	-.8	.8	2.6	4.3	6.1	7.8	9.6	11.3	13.1	14.8	16.5
30	1.9	3.9	6.0	8.0	10.0	12.0	14.1	16.1	18.1	20.1	22.2
40	5.1	7.4	9.6	11.9	14.1	16.4	18.7	20.9	23.2	25.4	27.7
50	8.3	10.8	13.2	15.7	18.1	20.5	23.0	25.4	27.8	30.3	32.7
60	11.4	14.0	16.5	19.1	21.7	24.2	26.8	29.4	31.9	34.5	37.1
70	14.1	16.8	19.5	22.1	24.8	27.5	30.2	32.9	35.5	38.2	40.9
80	16.4	19.2	22.0	24.8	27.6	30.4	33.1	35.9	38.7	41.5	44.3
90	18.4	21.3	24.2	27.1	30.0	32.9	35.7	38.6	41.5	44.4	47.3
100	20.0	23.0	26.0	29.0	32.0	35.0	38.0	41.0	44.0	47.0	50.0
110	21.3	24.4	27.5	30.6	33.7	36.8	39.9	43.1	46.2	49.4	52.5
120	22.5	25.6	28.8	32.0	35.2	38.5	41.7	45.0	48.3	51.6	54.9
130	23.5	26.8	30.0	33.3	36.6	40.0	43.3	46.7	50.1	53.6	57.1
140	24.5	27.8	31.1	34.5	37.9	41.3	44.8	48.3	51.9	55.5	59.1
150	25.4	28.7	32.1	35.6	39.1	42.6	46.2	49.9	53.6	57.3	61.1
160	26.2	29.6	33.1	36.6	40.2	43.8	47.5	51.3	55.1	59.0	63.0
170	26.9	30.4	33.9	37.5	41.2	44.9	48.7	52.6	56.6	60.6	64.7
180	27.6	31.1	34.8	38.4	42.2	46.0	49.9	53.9	58.0	62.2	66.4
190	28.2	31.8	35.5	39.3	43.1	47.0	51.0	55.1	59.3	63.6	68.1
200	28.9	32.5	36.2	40.0	43.9	47.9	52.0	56.3	60.6	65.1	69.7
210	29.4	33.1	36.9	40.8	44.7	48.8	53.0	57.4	61.8	66.4	71.2
220	30.0	33.7	37.5	41.5	45.5	49.7	54.0	58.4	63.0	67.8	72.7
230	30.5	34.2	38.1	42.1	46.2	50.5	54.9	59.4	64.1	69.1	74.2
240	30.9	34.8	38.7	42.8	46.9	51.3	55.7	60.4	65.3	70.3	75.7
250	31.4	35.3	39.2	43.4	47.6	52.0	56.6	61.3	66.3	71.6	77.1
260	31.8	35.7	39.8	43.9	48.2	52.7	57.4	62.3	67.4	72.8	78.5
270	32.2	36.2	40.3	44.5	48.9	53.4	58.2	63.1	68.4	73.9	79.9
280	32.6	36.6	40.7	45.0	49.4	54.1	58.9	64.0	69.4	75.1	81.2
290	33.0	37.0	41.2	45.5	50.0	54.7	59.6	64.8	70.3	76.2	82.6
300	33.4	37.4	41.6	46.0	50.5	55.3	60.3	65.6	71.3	77.4	84.0
310	33.7	37.8	42.0	46.5	51.1	55.9	61.0	66.4	72.2	78.5	85.3
320	34.0	38.2	42.4	46.9	51.6	56.5	61.7	67.2	73.1	79.6	86.7
330	34.3	38.5	42.8	47.3	52.1	57.0	62.3	67.9	74.0	80.7	88.0
340	34.6	38.8	43.2	47.8	52.5	57.6	62.9	68.7	74.9	81.7	89.4
350	34.9	39.2	43.6	48.2	53.0	58.1	63.6	69.4	75.8	82.8	90.8
360	35.2	39.5	43.9	48.5	53.4	58.6	64.1	70.1	76.6	83.9	92.2
370	35.5	39.8	44.2	48.9	53.9	59.1	64.7	70.8	77.5	85.0	93.6
380	35.8	40.1	44.6	49.3	54.3	59.6	65.3	71.5	78.3	86.0	95.1
390	36.0	40.3	44.9	49.6	54.7	60.1	65.9	72.2	79.1	87.1	96.6
400	36.3	40.6	45.2	50.0	55.1	60.5	66.4	72.8	80.0	88.2	98.2

[1/] Values for ages under 100 are from equation II (in meters); those for over 100 are from equation III (in meters). Corresponding site index estimation curves are shown in figure 6.

[2/] Note that biologically impossible values merely indicate that no height actually observable at that age justifies the indicated estimate of $\hat{H}100_m$ (Curtis et al. 1974a).

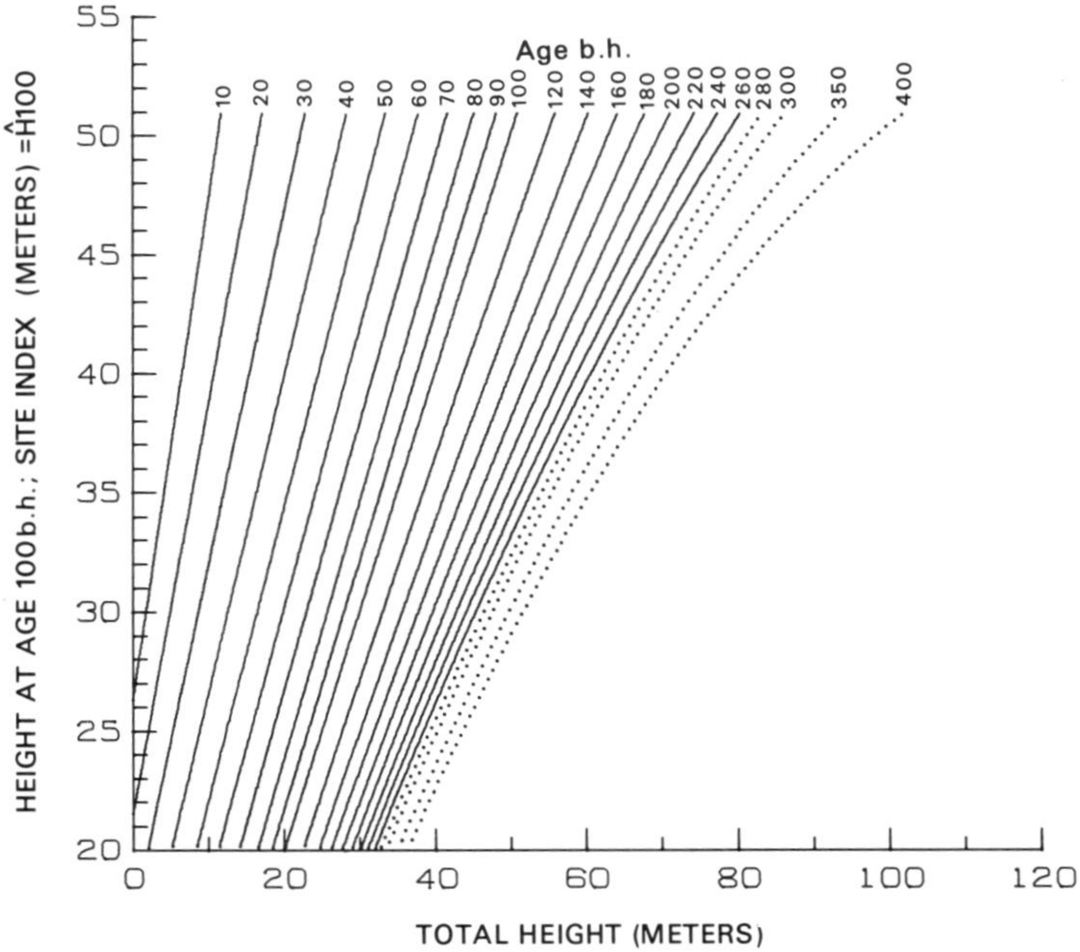

Figure 6.--Site index estimation curves for noble fir. Curves for ages bh less than 100 years correspond to equation II (in meters); those for ages over 100 correspond to equation III (in meters). Note: Use these curves for estimating site index; i.e., for estimating height at 100 years of a tree observed at some other age. These curves may also be used for estimating the probable course of future height growth up to 100 years for dominant trees younger than 100 years. Use these curves when site index is to be expressed in meters.

Corresponding numerical values are given in table 3 and curves in figure 5 for ages bh of 100+ years.

Equation III, in meters:

$$\hat{H}100_m = a + b(H_m - 1.37) + c(H_m - 1.37)^2;$$

where,

$a = -19.128 + 204.99(1/x)^{0.5}$,

$b = 0.9484 + 516.49(1/x)^2$,

$c = -0.00473 + 0.47297(1/x)$, and

$x =$ age bh.

Table 3--*Ages bh and total heights corresponding to indicated estimates of* $\hat{H}$*100 (height at index age 100)*[1/]

Age at bh	Height (feet) at index age 100										
	60	70	80	90	100	110	120	130	140	150	160
Years	Feet										
10	[2/] -12	-7	-2	2	7	11	16	21	26	31	35
20	-5	0	5	11	17	23	29	34	40	46	52
30	2	9	16	23	29	36	43	50	57	63	70
40	13	20	28	35	43	50	58	65	73	80	88
50	23	31	39	47	55	63	72	80	88	96	104
60	33	41	50	58	67	75	84	93	101	110	118
70	41	50	59	68	77	86	95	104	113	122	131
80	49	58	67	77	86	95	104	114	123	132	142
90	55	65	74	84	94	103	113	122	132	142	151
100	60	70	80	90	100	110	120	130	140	150	160
110	64	74	85	95	105	116	126	137	147	158	168
120	68	78	89	100	110	121	132	143	154	165	176
130	71	82	93	104	115	126	137	148	160	171	183
140	74	85	96	107	119	130	142	153	165	177	189
150	77	88	99	111	122	134	146	158	170	183	195
160	79	91	102	114	126	138	150	163	175	188	201
170	82	93	105	117	129	141	154	167	180	193	207
180	84	96	108	120	132	145	158	171	184	198	212
190	86	98	110	122	135	148	161	175	188	203	217
200	88	100	112	125	138	151	164	178	192	207	222
210	90	102	114	127	140	154	167	182	196	211	227
220	91	104	116	129	143	156	170	185	200	216	232
230	93	105	118	131	145	159	173	188	204	220	236
240	94	107	120	133	147	161	176	191	207	224	241
250	96	109	122	135	149	163	178	194	210	227	245
260	97	110	123	137	151	166	181	197	213	231	250
270	99	111	125	139	153	168	183	200	217	235	254
280	100	113	126	140	155	170	186	202	220	238	258
290	101	114	128	142	157	172	188	205	223	242	262
300	102	115	129	143	158	174	190	207	226	245	266
310	103	116	130	145	160	176	192	210	228	248	270
320	104	118	132	146	161	177	194	212	231	252	274
330	105	119	133	147	163	179	196	214	234	255	279
340	106	120	134	149	164	181	198	217	236	258	283
350	107	121	135	150	166	182	200	219	239	262	287
360	108	122	136	151	167	184	202	221	242	265	291
370	109	123	137	152	168	185	203	223	244	268	295
380	110	124	138	154	170	187	205	225	247	271	299
390	110	124	139	155	171	188	207	227	249	274	303
400	111	125	140	156	172	190	209	229	252	277	308

[1/] Values for ages under 100 are from equation II (in feet), those for over 100 are from equation III (in feet). Corresponding site index estimation curves are shown in figure 5.

[2/] Note that biologically impossible values merely indicate that no height actually observable at that age justifies the indicated estimate of $\hat{H}$100 (Curtis et al. 1974a).

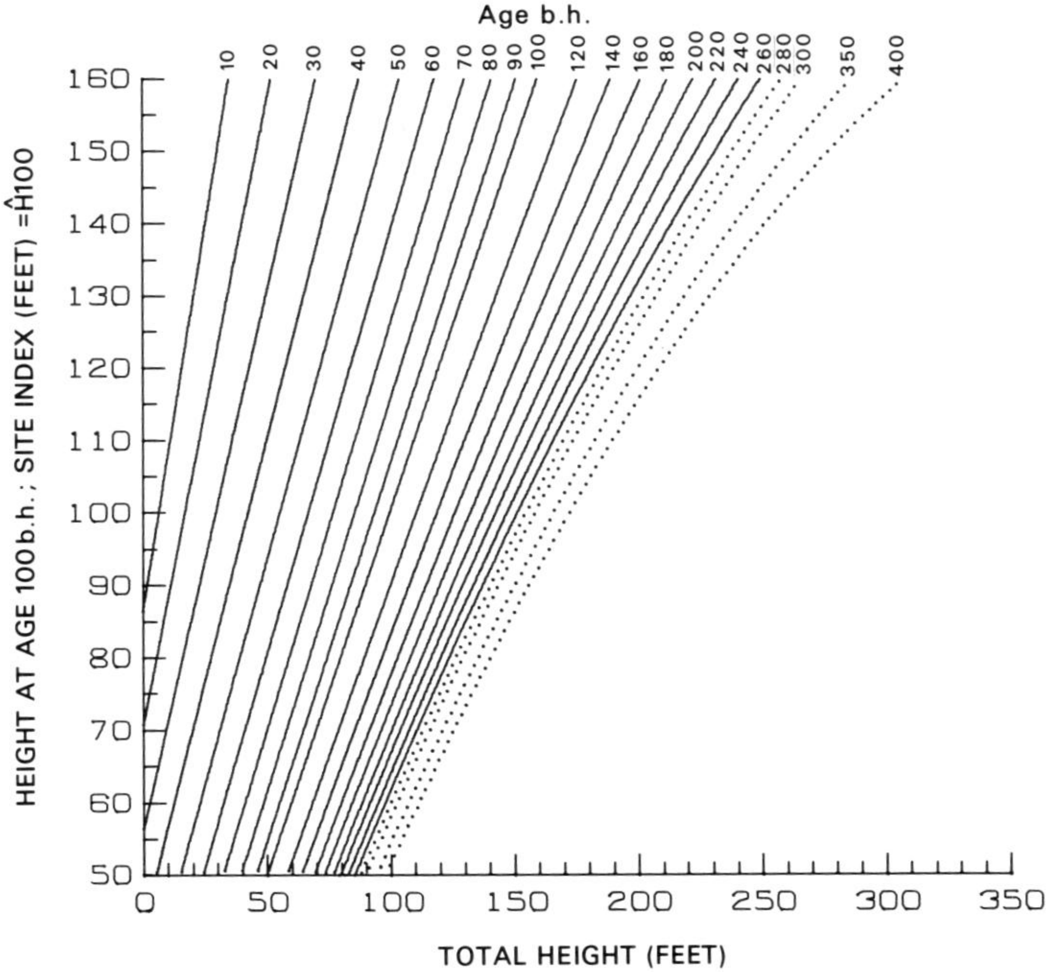

Figure 5.--Site index estimation curves for noble fir. Curves for ages bh less than 100 years correspond to equation II (in feet); those for ages over 100 correspond to equation III (in feet). Note: Use these curves for estimating site index; i.e., for estimating height at 100 years of a tree observed at some other age. These curves may also be used for estimating the probable course of future height growth up to 100 years for dominant trees younger than 100 years. Use these curves when site index is to be expressed in feet.

The resulting equation, after simplification, can be written as:

Equation III, in feet:

$$\hat{H}100 = a + b(H - 4.5) + c(H - 4.5)^2;$$

where,

$a = -62.755 + 672.55(1/x)^{0.5}$,

$b = 0.9484 + 516.49(1/x)^2$,

$c = -0.00144 + 0.1442\ (1/x)$, and

x = age bh.

Standard error of estimate of the transformed variable $w(H100 - H)$ was 0.9171.

Corresponding numerical values are given in table 4 and curves in figure 6 for ages bh of 100+ years.

Discussion

The index age of 100 years bh was chosen as consistent with precedent, with previous work with associated Douglas-fir (Curtis et al. 1974b), with growth characteristics of the species, and with the relatively long rotations which seem probable in these high-elevation forests.

The height growth equation and corresponding curves obtained by fitting regressions with height as the dependent variable differ from the site index estimation equations and curves obtained by treating attained height at the index age (H100) as the dependent variable. These curves are appropriate for different uses (Curtis et al. 1974a).

HEIGHT GROWTH CURVES

Height growth curves H = f(age, H100) represent average development of trees that actually attained a specified height at index age 100 (H100). They express the pattern of height growth of the tallest dominant trees in relation to age, within even-aged stands. They are the appropriate basis for expressing height development in the construction of yield tables or yield functions representing average development of even-aged stands actually attaining specified heights at index age (site indices).

These noble fir height growth curves (figs. 3 and 4) demonstrate the ability of undamaged trees to maintain height growth to very advanced ages. This striking characteristic has previously been noted in Douglas-fir in these high-elevation forests (Curtis et al. 1974b). Although no corresponding volume growth information is available, such a growth pattern must clearly be associated with a similar sustained increment in volume.

SITE INDEX ESTIMATION CURVES

The site index estimation curves (figs. 5 and 6), obtained by treating H100 as the dependent variable, are more efficient estimators of height at index age than the traditional inverted form of the height growth curves[3/] (when available information consists only of a measured height at some age other than index age). These site index estimation curves are the appropriate basis for estimating height at index age (100 years) of a tree observed at some other age; and also for estimating the probable course of future height growth up to this index age for a tree observed at a present age that is less than the index age.

POSSIBLE BIAS

When growth curves and site index estimation curves are prepared from stem analyses of mature trees, there is no way of evaluating stand conditions in early life, beyond limiting the sample to stands which appear even-aged and then rejecting trees showing a growth pattern suggesting past injury or early suppression. Probably not all the tallest trees were always

[3/] For a detailed and complete explanation of the relative efficiency and uses of the traditional height growth curves and these site index estimation curves, see Curtis et al. (1974a).

the tallest in early life. Bias can be introduced by such shifts in relative crown position of sample trees over time (Dahms 1963). Although it seems unlikely that this would materially alter the shape of curves within the range of substantial overlap in tree ages (in this case roughly 100 to 250 years), such unrecognized shifts in crown position could introduce considerable bias at younger ages. Usually only one noble fir tree was selected at each location, so there was no direct means of evaluating the actual importance of such bias. At the few locations where two or more noble fir trees were felled and sectioned, observed shifts in relative crown position were, however, infrequent and minor. Because of the shade intolerance of noble fir, that observation is not unexpected.

APPLICATION OF CURVES

These curves are applicable only to trees growing under essentially even-aged stand conditions.

Each sample tree was chosen as the tallest undamaged dominant on an area of about one-fourth acre (0.1 ha) in stands of mixed species composition. In these old stands, with variable composition and frequent top damage, this is a less consistent definition than in young stands of a single species. Consistency of definition and application is more important than exact adherence to this area standard, and, in the usual older mixed stands, the stand component represented by these curves is best considered as well-distributed undamaged dominants.

To estimate site index for a stand, select a sample of undamaged dominant noble fir well distributed over the area. Exclude trees showing evidence of past damage or early suppression (visible stem damage, abrupt changes in radial growth pattern on increment cores) or differences in age class from surrounding trees. Determine total height and age bh for each sample tree. Use these values and equations II and III, tables 3 and 4, or figures 5 and 6 to estimate H100 for each tree. The mean of these estimates of H100 is the estimated site index of the stand.

The height growth and site index information presented in this paper provides a basis for site classification of Cascade Range forests containing noble fir. That basis is the first step toward development of growth and yield preditions for the complex upper-slope forests of the Pacific Northwest.

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Height growth and site index estimation equations with corresponding curves and tables for noble fir in the Cascade Range between McKenzie Pass in Oregon and Stevens Pass in Washington are presented in U.S. measurements and in metric equivalents.

KEYWORDS: Site index -)stand height/age, increment (height), altitude (-site, noble fir, *Abies procera*, Oregon (Cascade Range), Washington (Cascade Range).

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