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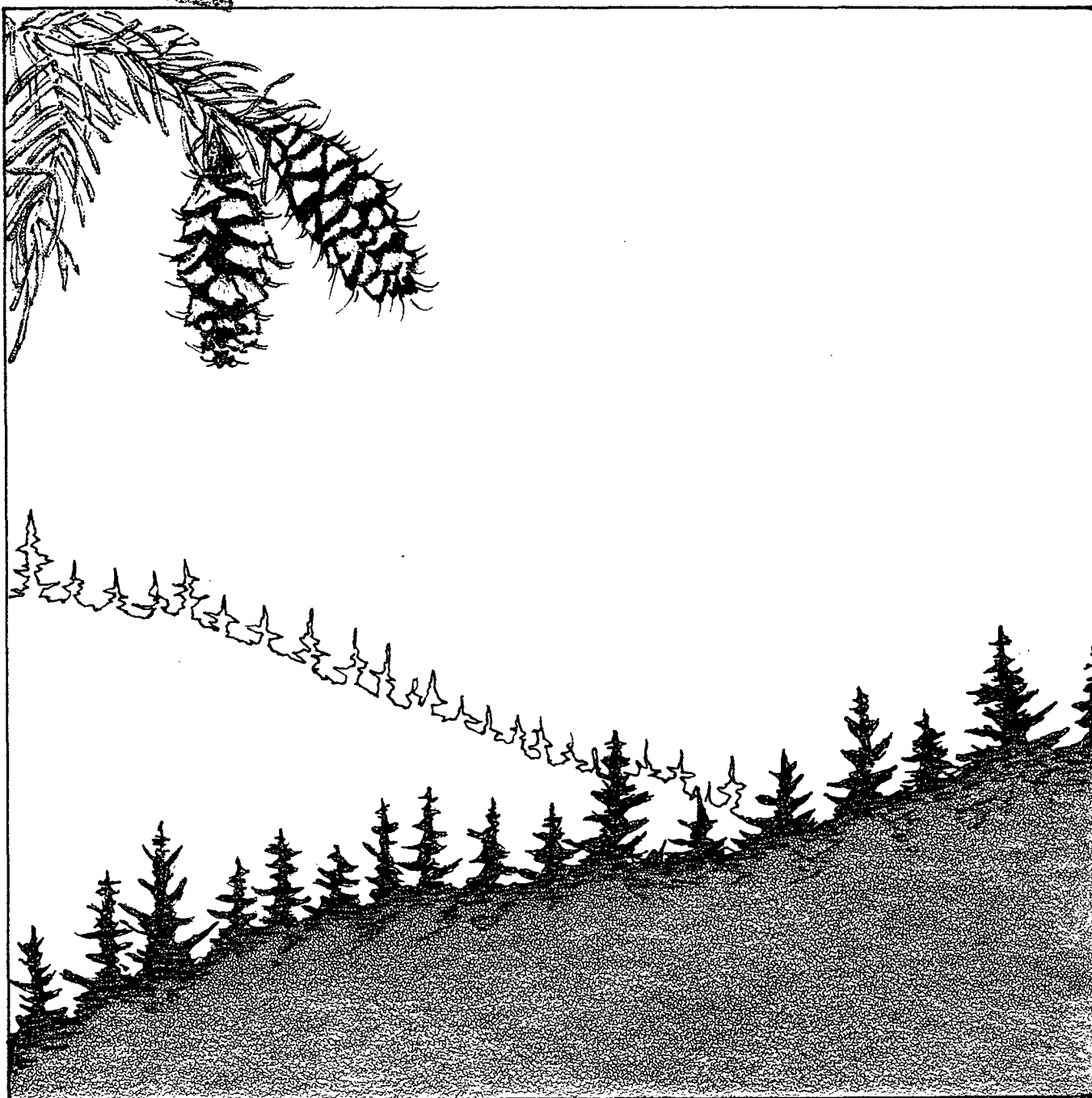
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# Estimates of Site Index and Height Growth for Douglas-Fir in High- Elevation Forests of the Oregon- Washington Cascade Range: Curves and Tables for Field Application

Donald J. DeMars and Francis R. Herman

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## Abstract

**DeMars, Donald J.; Herman, Francis R. 1987.** Estimates of site index and height growth for Douglas-fir in high-elevation forests of the Oregon-Washington Cascade Range: curves and tables for field application. Res. Pap. PNW-RP-378. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 16 p.

Estimation equations for height growth and site index were derived from stem-analysis data of Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco var. *menziesii*) in the high-elevation forests of the Cascade Range in Oregon and Washington. Two sets of height-growth and site-index estimation curves and tables produced from previously published equations are presented—one set with U.S. customary units of measure and another set with metric units. These curves and tables were designed for use in the field by forest managers.

Keywords: Site index, increment (height), stem analysis, stand age, altitude (-site, Douglas-fir (coast), Oregon (Cascade Range), Washington (Cascade Range).

## Summary

Equation and curves for height growth and site index were developed from stem-analysis data for selected, dominant Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco var. *menziesii*) trees collected at 52 locations between McKenzie Pass in central Oregon and Stevens Pass in north-central Washington. This paper presents previously published equations in tabular and graphic form suitable for field use.

Curves were based on the tallest, undamaged dominant in 0.25-acre (0.1-ha) plots from unmanaged stands. Trees with similar attributes should be selected when the site index of an upper slope forest stand is estimated.

Estimation curves for site index obtained by regressing site index on height and age differed from estimation curves for height growth obtained by regressing height on site index and age. Site-index curves should be used to predict the height of stands at the index age, given present age and height; curves for height growth should be used to predict expected heights of Douglas-fir at different ages for stands of a given site index.

Both the site-index curves and the height-growth curves will serve as a basis for developing growth and yield estimates for Douglas-fir in high-elevation forests of the Cascade Range in Oregon and Washington.

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## Introduction

This paper presents estimation curves for height growth and site index in tabular and graphic form for Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco var. *menziesii*) in the high-elevation forests of the Cascade Range in Oregon and Washington. The curves are based on equations previously presented by Curtis and others (1974a). Methods of analysis were those used for both Douglas-fir and noble fir (*Abies procera* Rehd.) (Curtis and others 1974a, 1974b; Herman and others 1978.) Equations, curves, and tables are presented in both U.S. customary and metric units.

The equations and curves were developed from stem-analysis data for selected dominant Douglas-fir trees collected at 52 locations between McKenzie Pass in central Oregon and Stevens Pass in north-central Washington (fig. 1). All locations were in unmanaged stands, mainly old growth in the *Abies amabilis* zone of Franklin and Dyrness (1973). Data from section trees were also collected for associated species: curves for associated noble fir were developed by Herman and others (1978), and Douglas-fir curves were presented by Curtis and others (1974b). Site-index and height curves for other species are planned.

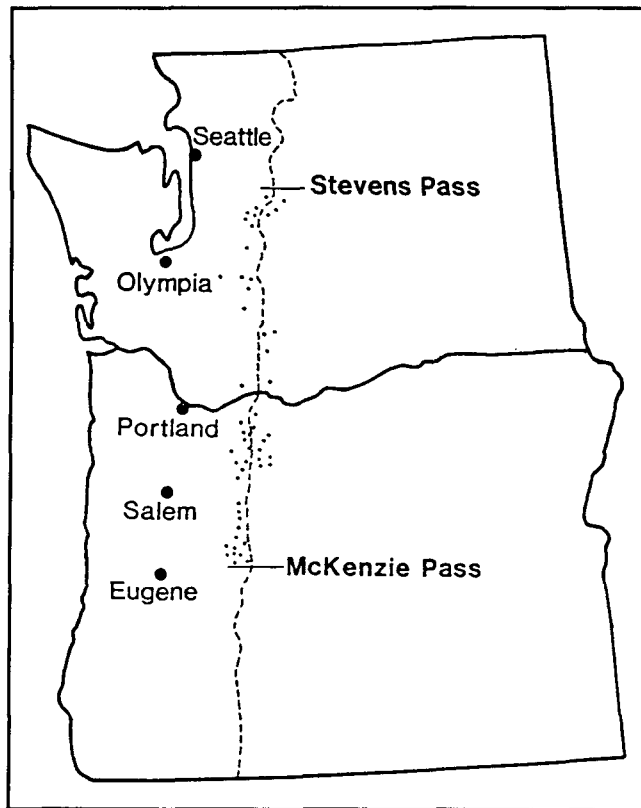


Figure 1—Geographic distribution of the Douglas-fir selected for stem analysis and used in the development of estimation curves for height growth and site index. All plot locations are in unmanaged stands, mainly old growth within the *Abies amabilis* zone of Franklin and Dyrness (1973).

## Data

An area of uniform site and stand conditions was selected, usually about 0.25-acre (0.1-ha) within a stand or group of trees in which the dominants were judged to be of one age class. The tallest dominant or codominant tree of each species present was selected and felled for stem analysis. Trees with indicators of rot and obvious defects, such as thin crowns, were avoided as were trees with stag, forked, or broken tops and bent and crooked stems. Sections were cut at the stump (stump height varied), at 4.5 feet (1.37 m), and at intervals up the stem (usually 18 feet [5.5 m]) in the merchantable portion of large trees and at shorter intervals in small trees and tops.

For each tree, a graph of height over age was plotted by computer, and the height-growth pattern of the tree was examined for signs of early suppression or history of past top damage. Because Douglas-fir is a shade-intolerant species, few trees showed abnormal early growth reduction, and only a few trees were rejected for a history of top damage. In the following tabulation, data from trees used in the analysis are summarized by number of sample trees present at successive breast height ages (age bh) (Curtis and others 1974b):

<u>Age bh</u>	<u>Number of trees</u>
10-80	52
100	49
150	47
200	40
250	31
300	10
350	7
400	4

The number of trees by classes of height attained at age 100 (H100) is given in figure 2.

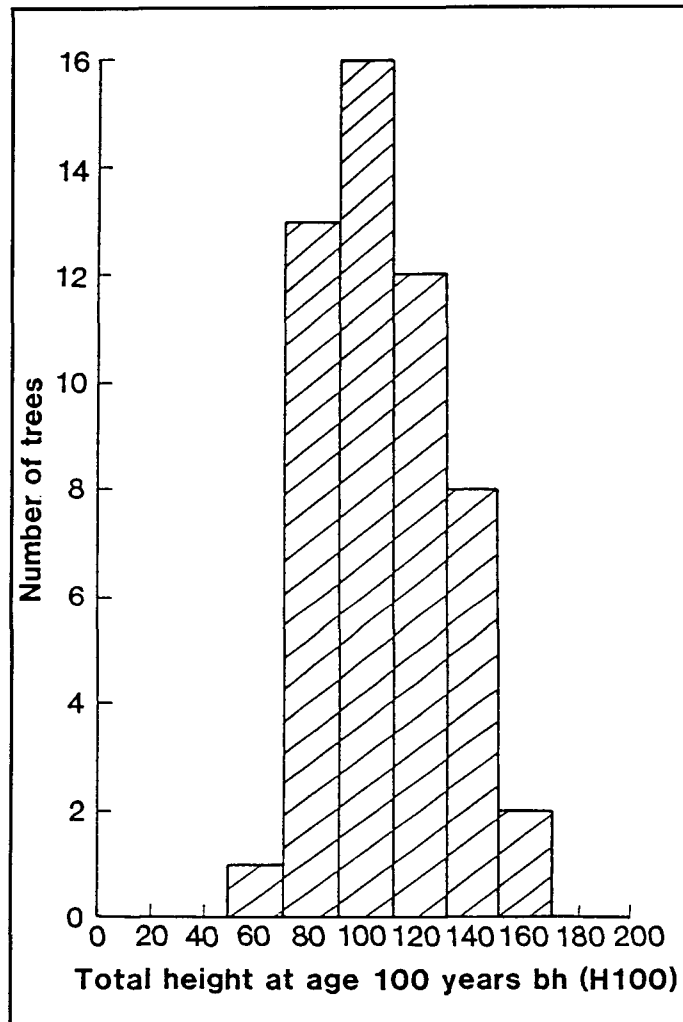


Figure 2—Number of Douglas-fir trees used in analysis sample by classes of H100 (attained height at age 100 years bh) (data from Curtis and others 1974b).

## Analysis

Interpolated values of height at successive 10-year intervals of age bh were the values used in the analysis. With minor modifications, the analysis follows the methods used with noble fir (Curtis and others 1974a, Herman and others 1978).

Two symbols used in the discussion and equations need to be defined:

- H100 is individual sample-tree height (in feet) at age 100 bh; it is an estimate of site index.
- H is total height of the tree at any specified age bh (age bh is the number of annual rings at 4.5 feet on the stem).

To fit equations, we subtracted 4.5 feet (1.37 m) from H100 and H to provide a common origin for scales of height and age at bh.

## Equations for Height Growth

The regression  $(H - 4.5) = a + b(H100 - 4.5)$ , where 4.5 feet<sup>1</sup> is breast height, was fitted to data for individual 10-year intervals of age bh. These regressions provided estimates of H for successive intervals of H100 that, when connected, gave unsmoothed trends over age which were used as guides in selecting suitable equation forms (Curtis and others 1974a, 1974b; Heger 1968). The standard errors of estimates (SEE) from the regressions were used as the basis for the weighting factor in subsequent computations. Details of the analysis are given in Curtis and others (1974b).

Equations for height estimation are:

Equation 1, in feet:

$$H = 4.5 + \frac{(H100 - 4.5)}{[a + b/(H100 - 4.5) + c(A^n) + d/(H100 - 4.5)(A^n)]};$$

where:

A = age bh,

a = 0.6192,

b = -5.3394,

c = 240.29,

d = 3368.9,

n = -1.4,

H = height of tree in feet, and

H100 = total height (feet) of an individual tree at age 100 bh, which is an estimate of site index.

Standard error of estimate of the transformed variable w (H-4.5) was 0.954.

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

<sup>1</sup> The regressions expressed in metric equivalents:

$$(H_m - 1.37) = a + b(H100_m - 1.37);$$

where 1.37 meters is breast height.

Regression coefficients appearing in equations are changed where necessary to produce valid metric expressions. Curves expressed in metric units will be slightly different in reference height; that is, site-index curves for 32 in meters have no exact counterpart in selected curves for U.S. customary units. Separate equations are therefore given for feet and for meters.



**Table 1—Expected heights in feet for indicated ages at breast height (bh) for values of H100 (total height at index age 100 years bh)<sup>1</sup>**

Age bh	Height at index age 100										
	60	70	80	90	100	110	120	130	140	150	160
Years	Feet										
10	9	10	11	12	13	14	15	16	17	18	19
20	16	18	20	22	25	27	29	32	34	36	39
30	22	26	30	34	37	41	45	48	52	56	60
40	29	34	39	44	49	54	59	64	69	74	79
50	36	42	48	54	60	66	72	79	85	91	97
60	42	49	56	63	70	77	84	92	99	106	113
70	47	55	63	71	79	87	95	103	111	119	127
80	52	60	69	78	87	96	104	113	122	131	140
90	56	66	75	84	94	103	113	122	132	141	150
100	60	70	80	90	100	110	120	130	140	150	160
110	64	74	84	95	106	116	126	137	148	158	168
120	67	78	88	100	110	121	132	143	154	165	176
130	70	81	92	104	115	126	137	149	160	171	183
140	72	84	95	107	119	130	142	154	165	177	189
150	74	86	98	110	122	134	146	158	170	182	194
160	77	89	101	113	126	138	150	162	174	187	199
170	78	91	103	116	128	141	153	166	178	191	203
180	80	93	106	118	131	144	156	169	182	194	207
190	82	95	108	120	133	146	159	172	185	198	211
200	83	96	109	122	136	149	162	175	188	201	214
210	85	98	111	124	138	151	164	177	190	204	217
220	86	99	113	126	139	153	166	180	193	206	220
230	87	101	114	128	141	155	168	182	195	209	222
240	88	102	115	129	143	156	170	184	197	211	224
250	89	103	117	130	144	158	172	185	199	213	227
260	90	104	118	132	145	159	173	187	201	215	229
270	91	105	119	133	147	161	174	188	202	216	230
280	92	106	120	134	148	162	176	190	204	218	232
290	92	107	121	135	149	163	177	191	205	220	234
300	93	107	122	136	150	164	178	192	207	221	235
310	94	108	122	136	151	165	179	194	208	222	237
320	94	109	123	137	152	166	180	195	209	224	238
330	95	109	124	138	152	167	181	196	210	225	239
340	96	110	124	139	153	168	182	197	211	226	240
350	96	110	125	140	154	168	183	198	212	227	241
360	97	111	126	140	155	169	184	198	213	228	242
370	97	112	126	141	155	170	185	199	214	229	243
380	98	112	127	141	156	171	185	200	215	229	244
390	98	112	127	142	156	171	186	201	216	230	245
400	98	113	128	142	157	172	187	201	216	231	246

<sup>1</sup> From equation 1 (in feet). Values correspond to height-growth curves shown in figure 3. Estimates for ages greater than 270 years bh are extrapolations of the data base.

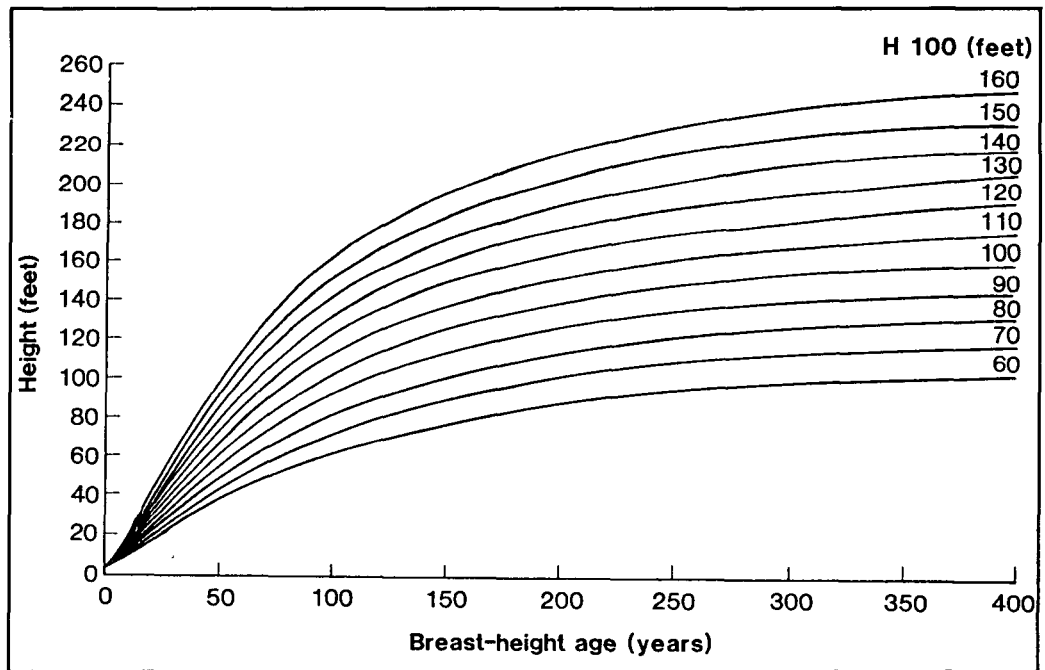


Figure 3—Height-growth curves for Douglas-fir (in feet) corresponding to equation 1 (in feet). These curves express the pattern of height growth of dominant trees in relation to age, within even-aged stands. The curves should be used to express height development in the construction of yield functions representing average development of even-aged stands actually attaining specified heights at index age 100 (site indices).

Equation 1, in meters:

$$H_m = 1.3716 + [a + b / (H100_m - 1.3716) + c(A^n) + d / (H100_m - 1.3716)(A^n)];$$

where:

A = age bh,

a = 0.6192,

b = -1.6274,

c = 240.29,

d = 1026.83,

n = -1.4,

$H_m$  = height of tree in meters, and

$H100_m$  = total height (meters) of an individual tree at age 100 bh, which is an estimate of site index.

Height estimates calculated by this equation are given in table 2, and corresponding metric height-growth curves are shown in figure 4.

**Table 2—Expected heights in meters for indicated ages at breast height (bh) for values of H100<sub>m</sub> (total height at index age 100 years bh)<sup>1</sup>**

Age bh	Height at index age 100										
	20	23	26	29	32	35	38	41	44	47	50
Year	Meters										
10	2.9	3.2	3.5	3.8	4.0	4.3	4.6	4.9	5.2	5.5	5.8
20	5.1	5.8	6.5	7.2	7.9	8.6	9.3	10.0	10.7	11.4	12.1
30	7.5	8.6	9.7	10.8	11.9	13.0	14.1	15.3	16.4	17.5	18.6
40	9.8	11.3	12.7	14.2	15.7	17.2	18.7	20.2	21.7	23.2	24.8
50	11.9	13.7	15.6	17.4	19.3	21.1	23.0	24.8	26.6	28.5	30.3
60	13.9	16.0	18.2	20.3	22.4	24.6	26.7	28.9	31.0	33.2	35.3
70	15.7	18.1	20.5	22.9	25.3	27.7	30.1	32.5	34.9	37.3	39.7
80	17.3	19.9	22.5	25.2	27.8	30.4	33.1	35.7	38.3	41.0	43.6
90	18.7	21.5	24.4	27.2	30.0	32.9	35.7	38.5	41.3	44.2	47.0
100	20.0	23.0	26.0	29.0	32.0	35.0	38.0	41.0	44.0	47.0	50.0
110	21.2	24.3	27.5	30.6	33.8	36.9	40.1	43.2	46.4	49.5	52.7
120	22.2	25.5	28.8	32.0	35.3	38.6	41.9	45.2	48.4	51.7	55.0
130	23.1	26.5	29.9	33.3	36.7	40.1	43.5	46.9	50.3	53.7	57.1
140	24.0	27.5	31.0	34.5	38.0	41.5	45.0	48.5	52.0	55.5	59.0
150	24.7	28.3	31.9	35.5	39.1	42.7	46.3	49.9	53.5	57.0	60.6
160	25.4	29.1	32.8	36.4	40.1	43.8	47.4	51.1	54.8	58.5	62.1
170	26.1	29.8	33.5	37.3	41.0	44.8	48.5	52.3	56.0	59.7	63.5
180	26.6	30.4	34.2	38.0	41.9	45.7	49.5	53.3	57.1	60.9	64.7
190	27.2	31.0	34.9	38.7	42.6	46.5	50.3	54.2	58.1	62.0	65.8
200	27.6	31.5	35.5	39.4	43.3	47.2	51.1	55.1	59.0	62.9	66.8
210	28.1	32.0	36.0	40.0	43.9	47.9	51.9	55.8	59.8	63.8	67.8
220	28.5	32.5	36.5	40.5	44.5	48.5	52.5	56.6	60.6	64.6	68.6
230	28.9	32.9	36.9	41.0	45.0	49.1	53.2	57.2	61.3	65.3	69.4
240	29.2	33.3	37.4	41.4	45.5	49.6	53.7	57.8	61.9	66.0	70.1
250	29.5	33.6	37.7	41.9	46.0	50.1	54.3	58.4	62.5	66.6	70.8
260	29.8	34.0	38.1	42.3	46.4	50.6	54.7	58.9	63.1	67.2	71.4
270	30.1	34.3	38.4	42.6	46.8	51.0	55.2	59.4	63.6	67.8	72.0
280	30.4	34.6	38.8	43.0	47.2	51.4	55.6	59.8	64.0	68.3	72.5
290	30.6	34.8	39.0	43.3	47.5	51.8	56.0	60.2	64.5	68.7	73.0
300	30.8	35.1	39.3	43.6	47.8	52.1	56.4	60.6	64.9	69.2	73.4
310	31.0	35.3	39.6	43.8	48.1	52.4	56.7	61.0	65.3	69.6	73.9
320	31.2	35.5	39.8	44.1	48.4	52.7	57.0	61.3	65.6	70.0	74.3
330	31.4	35.7	40.0	44.3	48.7	53.0	57.3	61.6	66.0	70.3	74.7
340	31.6	35.9	40.2	44.6	48.9	53.3	57.6	61.9	66.3	70.7	75.0
350	31.8	36.1	40.4	44.8	49.1	53.5	57.9	62.2	66.6	71.0	75.3
360	31.9	36.3	40.6	45.0	49.4	53.7	58.1	62.5	66.9	71.3	75.7
370	32.1	36.4	40.8	45.2	49.6	54.0	58.3	62.7	67.1	71.5	75.9
380	32.2	36.6	41.0	45.4	49.8	54.2	58.6	63.0	67.4	71.8	76.2
390	32.3	36.7	41.1	45.5	49.9	54.4	58.8	63.2	67.6	72.1	76.5
400	32.5	36.9	41.3	45.7	50.1	54.5	59.0	63.4	67.9	72.3	76.7

<sup>1</sup> From equation 1 (in meters). Values correspond to height-growth curves shown in figure 4. Estimates for ages greater than 270 years bh are extrapolations of the data base.

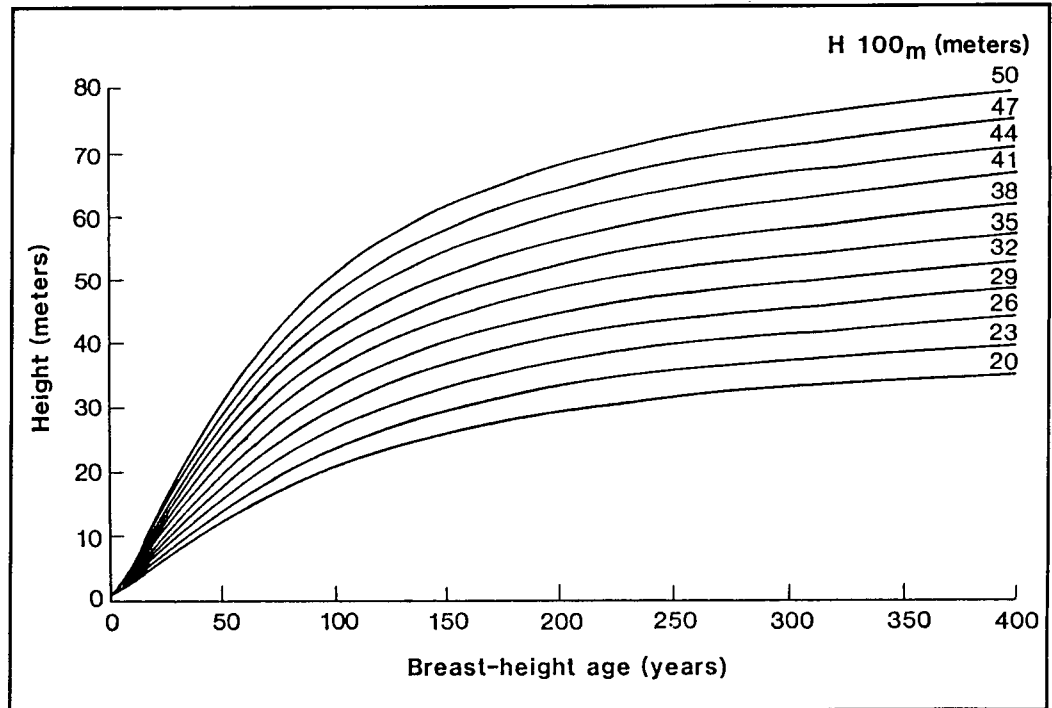


Figure 4—Height-growth curves for Douglas-fir (in meters) corresponding to equation 1 (in meters). These curves express the pattern of height growth of dominant trees in relation to age, within even-aged stands. The curves should be used to express height development in the construction of yield functions representing average development of even-aged stands actually attaining specified heights at index age 100 (site indices).

#### Equations for Site Index

Preliminary regression equations  $(H100 - 4.5) = a + b(H - 4.5)$  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  $bh$ . Estimated regression coefficients were plotted over age and the resulting graphs examined to determine if regression coefficients are related to age  $bh$ . Identified trends were used as guides in the selection of equation models for expressing the  $H100 = f(H, \text{age})$  relationship for all combined data.

We encountered difficulties when we tried to develop a single site-index estimation equation for the complete data set because of the wide range in ages and the small number of data points in the upper portion of the age range. To overcome these difficulties and to simplify curve fitting, we divided the pooled data into two groups: (1) ages less than or equal to 100 years bh, and (2) ages over 100 years bh. Separate, weighted regression equations were fitted to each data group. Both equations were conditioned so that  $H_{100} = H$  at age bh = 100 (Curtis and others 1974b).

Equation 2, in feet (ages  $\leq 100$  years bh):

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

where:

$$a = 0.01006(100 - A)^2 , \text{ and}$$

$$b = 1.0 + 0.00549779 (100 - A) + 1.46842 \times 10^{-14} (100 - A)^7 .$$

Standard error of estimate of the transformed variable,  $w(H_{100} - H)$ , was 0.241.<sup>2</sup>

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

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<sup>2</sup>  $w(H_{100} - H)$  was the dependent variable used to derive the equation (Curtis and others 1974b).

**Table 3—Ages bh and total heights in feet corresponding to indicated estimates of H100 (height at index age 100 years bh)<sup>1</sup>**

Age bh	Height at index age 100										
	60	70	80	90	100	110	120	130	140	150	160
<i>Years</i>	<i>Feet</i>										
10	<sup>2</sup> -7	-2	2	6	11	16	20	25	29	34	38
20	0	5	11	17	22	28	34	40	45	51	57
30	9	15	22	29	35	42	49	55	62	69	75
40	19	26	33	41	48	55	62	70	77	84	92
50	28	36	44	52	59	67	75	83	90	98	106
60	37	45	53	61	70	78	86	94	102	110	119
70	44	53	62	70	79	87	96	104	113	122	130
80	51	60	69	78	87	96	105	114	123	132	141
90	56	66	75	85	94	104	113	122	132	142	151
100	60	70	80	90	100	110	120	130	140	150	160
110	63	74	85	95	106	116	127	138	148	159	169
120	66	77	88	99	110	121	132	143	154	166	176
130	68	80	91	103	114	126	137	148	160	172	183
140	70	82	94	106	118	130	142	153	165	177	189
150	72	84	97	109	121	133	146	158	170	182	194
160	74	86	99	111	124	136	149	162	174	187	199
170	75	88	101	114	126	139	152	165	178	191	204
180	76	89	102	116	129	142	155	168	182	195	208
190	77	90	104	117	131	144	158	172	185	199	212
200	77	91	105	119	133	147	161	175	188	202	216
210	78	92	107	121	135	149	164	178	192	206	220
220	79	94	108	123	137	152	166	181	195	210	224
230	80	95	110	124	139	154	169	184	198	213	228
240	81	96	111	126	142	157	172	187	202	217	232
250	82	98	113	128	144	159	174	190	205	220	236
260	83	99	114	130	146	162	177	193	208	224	240
270	84	100	116	132	148	164	180	196	212	228	244
280	85	102	118	134	150	166	183	199	215	231	248
290	86	103	119	136	152	169	186	202	218	235	252
300	88	104	121	138	155	172	188	205	222	239	255
310	89	106	123	140	157	174	191	208	225	242	259
320	90	107	124	142	159	176	194	211	228	246	263
330	91	109	126	144	161	179	197	214	232	250	267
340	92	110	128	146	164	182	199	217	235	253	271
350	93	112	130	148	166	184	202	220	238	257	275
360	94	113	131	150	168	187	205	223	242	260	279
370	96	114	133	152	170	189	208	226	245	264	283
380	97	116	135	154	173	192	211	230	248	268	286
390	98	117	136	156	175	194	213	233	252	271	290
400	99	119	138	158	177	197	216	236	255	275	294

<sup>1</sup> Values for ages under 100 are from equation 2 (in feet); those for ages over 100 are from equation 3 (in feet). Corresponding site-index estimation curves are shown in figure 5. Estimates for ages greater than 270 years bh are extrapolations of the data base.

<sup>2</sup> Biologically impossible values indicate merely that no height actually observable at that age justifies the indicated estimate of H100 (Curtis and others 1974a).

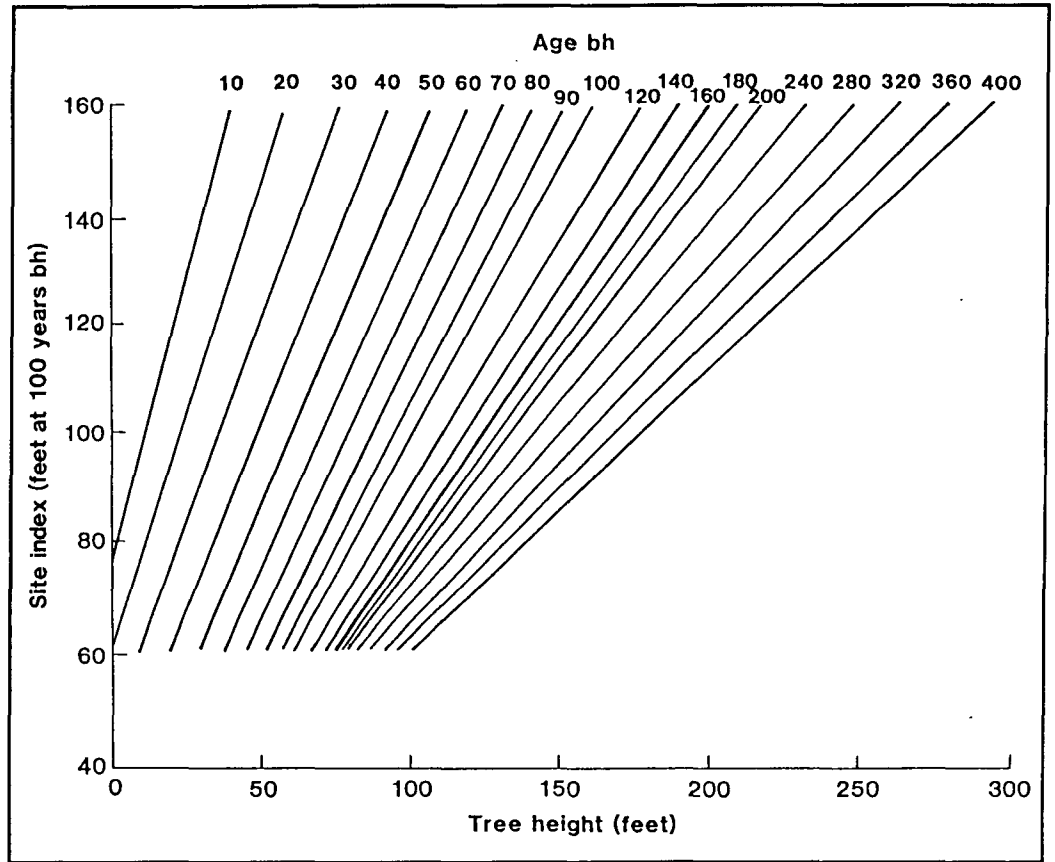


Figure 5—Estimation curves for site index for Douglas-fir. Curves for ages less than 100 years bh correspond to equation 2 (in feet); those for ages over 100 years bh correspond to equation 3 (in feet). Use these curves for estimating site index; that is, for estimating height at 100 years bh of a tree observed at some other age.

Equation 2, in meters (ages  $\leq 100$  years bh):

$$H_{100m} = 1.3716 + a + b (H_m - 1.3716) ;$$

where:

$$a = (0.00305 (100 - A)^2), \text{ and}$$

$$b = [1.0 + 0.00549779(100 - A) + 1.46842 \cdot 10^{-14} (100 - A)^7].$$

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

**Table 4—Ages bh and total heights in meters corresponding to indicated estimates of H100<sub>m</sub> (height at index age 100 years bh)<sup>1</sup>**

Age bh	Height at index age 100										
	20	23	26	29	32	35	38	41	44	47	50
Years	Meters										
10	<sup>2</sup> -1.3	0.0	1.3	2.7	4.1	5.4	6.8	8.2	9.5	10.9	12.3
20	0.9	2.6	4.3	6.0	7.7	9.4	11.2	12.9	14.6	16.3	18.0
30	3.8	5.8	7.8	9.8	11.8	13.8	15.8	17.8	19.8	21.7	23.7
40	7.0	9.1	11.3	13.5	15.7	17.9	20.1	22.3	24.5	26.6	28.8
50	9.9	12.3	14.6	16.9	19.3	21.6	23.9	26.3	28.6	30.9	33.2
60	12.6	15.1	17.5	20.0	22.4	24.9	27.3	29.8	32.3	34.7	37.2
70	15.0	17.6	20.2	22.7	25.3	27.9	30.4	33.0	35.6	38.2	40.7
80	17.1	19.8	22.5	25.2	27.9	30.6	33.3	36.0	38.7	41.4	44.1
90	18.7	21.6	24.4	27.3	30.1	33.0	35.8	38.6	41.5	44.3	47.2
100	20.0	23.0	26.0	29.0	32.0	35.0	38.0	41.0	44.0	47.0	50.0
110	21.1	24.3	27.5	30.7	33.9	37.0	40.2	43.4	46.6	49.8	53.0
120	22.0	25.3	28.6	31.9	35.3	38.6	41.9	45.2	48.5	51.9	55.2
130	22.8	26.2	29.6	33.1	36.5	40.0	43.4	46.9	50.3	53.7	57.2
140	23.5	27.0	30.6	34.1	37.7	41.3	44.8	48.4	51.9	55.5	59.0
150	24.1	27.8	31.4	35.1	38.8	42.4	46.1	49.8	53.4	57.1	60.8
160	24.6	28.4	32.1	35.9	39.7	43.5	47.2	51.0	54.8	58.6	62.3
170	25.0	28.9	32.8	36.6	40.5	44.4	48.3	52.1	56.0	59.9	63.8
180	25.4	29.3	33.3	37.3	41.3	45.2	49.2	53.2	57.2	61.1	65.1
190	25.7	29.7	33.8	37.9	42.0	46.0	50.1	54.2	58.2	62.3	66.4
200	26.0	30.2	34.3	38.5	42.6	46.8	51.0	55.1	59.3	63.5	67.6
210	26.3	30.6	34.8	39.1	43.3	47.6	51.8	56.1	60.4	64.6	68.9
220	26.6	31.0	35.3	39.7	44.0	48.4	52.7	57.1	61.4	65.8	70.1
230	27.0	31.4	35.8	40.3	44.7	49.2	53.6	58.0	62.5	66.9	71.3
240	27.3	31.8	36.4	40.9	45.4	49.9	54.5	59.0	63.5	68.0	72.6
250	27.7	32.3	36.9	41.5	46.1	50.7	55.3	60.0	64.6	69.2	73.8
260	28.0	32.7	37.4	42.1	46.8	51.5	56.2	60.9	65.6	70.3	75.0
270	28.4	33.2	38.0	42.8	47.5	52.3	57.1	61.9	66.7	71.5	76.3
280	28.8	33.7	38.5	43.4	48.3	53.1	58.0	62.9	67.7	72.6	77.5
290	29.2	34.1	39.1	44.0	49.0	53.9	58.9	63.8	68.8	73.8	78.7
300	29.6	34.6	39.6	44.7	49.7	54.7	59.8	64.8	69.9	74.9	79.9
310	29.9	35.1	40.2	45.3	50.4	55.5	60.7	65.8	70.9	76.0	81.1
320	30.3	35.5	40.7	45.9	51.1	56.4	61.6	66.8	72.0	77.2	82.4
330	30.7	36.0	41.3	46.6	51.9	57.2	62.4	67.7	73.0	78.3	83.6
340	31.1	36.5	41.9	47.2	52.6	58.0	63.3	68.7	74.1	79.4	84.8
350	31.5	37.0	42.4	47.9	53.3	58.8	64.2	69.7	75.1	80.6	86.0
360	32.0	37.5	43.0	48.5	54.1	59.6	65.1	70.6	76.2	81.7	87.2
370	32.4	38.0	43.6	49.2	54.8	60.4	66.0	71.6	77.2	82.8	88.4
380	32.8	38.5	44.1	49.8	55.5	61.2	66.9	72.6	78.3	84.0	89.7
390	33.2	38.9	44.7	50.5	56.3	62.0	67.8	73.6	79.3	85.1	90.9
400	33.6	39.4	45.3	51.1	57.0	62.8	68.7	74.5	80.4	86.2	92.1

<sup>1</sup> Values for ages under 100 are from equation 2 (in meters); those for ages over 100 are from equation 3 (in meters). Corresponding site-index estimation curves are shown in figure 6. Estimates for ages greater than 270 years bh are extrapolations of the data base.

<sup>2</sup> Biologically impossible values indicate merely that no height actually observable at that age justifies the indicated estimate of H100<sub>m</sub> (Curtis and others 1974a).



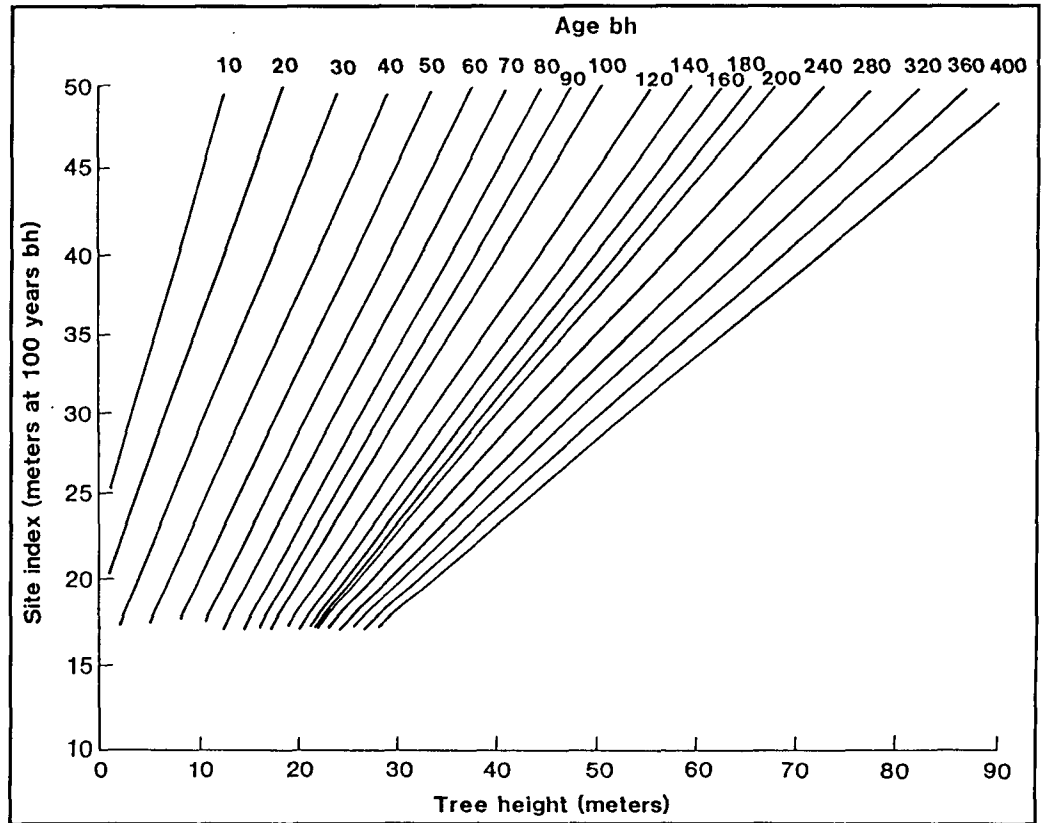


Figure 6—Estimation curves for site index for Douglas-fir. Curves for ages less than 100 years bh correspond to equation 2 (in meters); those for ages over 100 bh correspond to equation 3 (in meters). Use these curves for estimating site index; that is, for estimating height at 100 years bh of a tree observed at some other age.

Equation 3, in feet (ages > 100 years bh):

$$H_{100} = 4.5 + [7.6672 (e^{-0.95(100/(A-100))^2})] + [1.0 - 0.730948 (\log_{10} A - 2.0)^{0.8}] [H - 4.5].$$

Standard error of estimate of the transformed variable,  $w(H_{100} - H)$ , was 1.008.

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

Equation 3, in meters (ages > 100 years bh):

$$H_{100_m} = 1.3716 + [2.33709 (e^{-0.95(100/(A-100))^2})] + [1.0 - 0.730948 (\log_{10} A - 2.0)^{0.8}] [H_m - 1.3716].$$

Corresponding metric values are shown in table 4 and curves in figure 6, for ages 100+ years bh.

## Discussion

Primary reasons for selecting 100 years bh as the index age were (1) the growth characteristics of Douglas-fir at high elevations and (2) the relatively long rotations that seem probable given the growth characteristics of the species.

As pointed out by Curtis and others (1974a), the dependent variable used to develop site-index equations should be different from the one used to develop height-growth equations. Corresponding curves from these equations are appropriate for different uses.

## Estimation Curves for Height Growth

Height curves presented in this paper express the pattern of height growth of the tallest dominant Douglas-fir trees in relation to age, within even-aged stands. "H" was the dependent variable used to fit equations. Appropriate uses for these curves include estimating height development of stands actually attaining specified heights at index age (site index) and estimating stand-height development in the construction of yield tables.

Figures 3 and 4 demonstrate the ability of the tallest undamaged Douglas-fir trees (about 5 trees per acre) to maintain a good rate of height growth at advanced ages. Curtis and others (1974b) compared the height-growth curves for high elevation to two sets of height-growth curves (King 1966; McArdle and others 1930, 1961) developed for low-elevation Douglas-fir and found their shapes to be quite different. Although no data are available, such differences in height growth must be associated with similar differences in volume growth.

## Estimation Curves for Site Index

H100 was the dependent variable used to fit site-index equations. For ages other than index age, the site-index estimation curves shown in figures 5 and 6 provide better estimates of height at index age than does the traditional inverted form of height-growth curves. Thus, the primary use of these curves should be to estimate stand height at index age 100.

## Possible Bias

The height-growth and the site-index curves appear to be unbiased. Plots were established in carefully chosen stands that were evaluated as even-aged. Within these stands, only the tallest, undamaged, dominant tree of each species was selected for stem analysis. Trees that were sectioned and later found to have unusual growth patterns (caused by broken tops, suppression, insects and disease, or other damaging agents) were either replaced or discarded.

A possible bias could exist, even after we used these careful selection criteria, if undetected effects of broken tops, suppression, insects and disease, or other damaging agents were present or if the tallest trees selected at the time of cutting were not always the tallest throughout the life of the stand. As pointed out by Dahms (1963), bias can be introduced by such shifts in relative crown positions of sample trees over time. These shifts probably would not materially alter the shape of the curves within the age range of 100-250 years but could introduce bias at the younger ages.

Because of the shade intolerance of upper slope Douglas-fir, bias caused by shifts in relative crown position is not expected.

## Application of Curves

The following criteria for applying the noble fir curves presented by Herman and others (1978) are also valid for the Douglas-fir curves:

- Trees must be growing in even-aged stands.
- Each Douglas-fir selected for site-index estimation must be the tallest, undamaged, dominant tree on an area of about 0.25 acre.
- Trees that are of a different age class from surrounding trees should be avoided.
- Curves are applicable to upper elevation forests in the Cascade Range between McKenzie Pass in Oregon and Stevens Pass in Washington.

When estimating the site index for a stand:

- Select a sample of undamaged, dominant Douglas-fir trees well distributed over the area (about 4 or 5 per acre).
- Determine total height and age bh for each tree.
- Use values from step 2 and equations 2 and 3, tables 3 and 4, or figures 5 and 6.
- Calculate the mean of the site-index values to estimate the site index of the stand.

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Estimation equations for height growth and site index were derived from stem-analysis data of Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco var. *menziesii*) in the high-elevation forests of the Cascade Range in Oregon and Washington. Two sets of height-growth and site-index estimation curves and tables produced from previously published equations are presented—one set with U.S. customary units of measure and another set with metric units. These curves and tables were designed for use in the field by forest managers.

**Keywords:** Site index, increment (height), stem analysis, stand age, altitude (-site, Douglas-fir (coast), Oregon (Cascade Range), Washington (Cascade Range).

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