United States
Department of
Agriculture

Forest Service

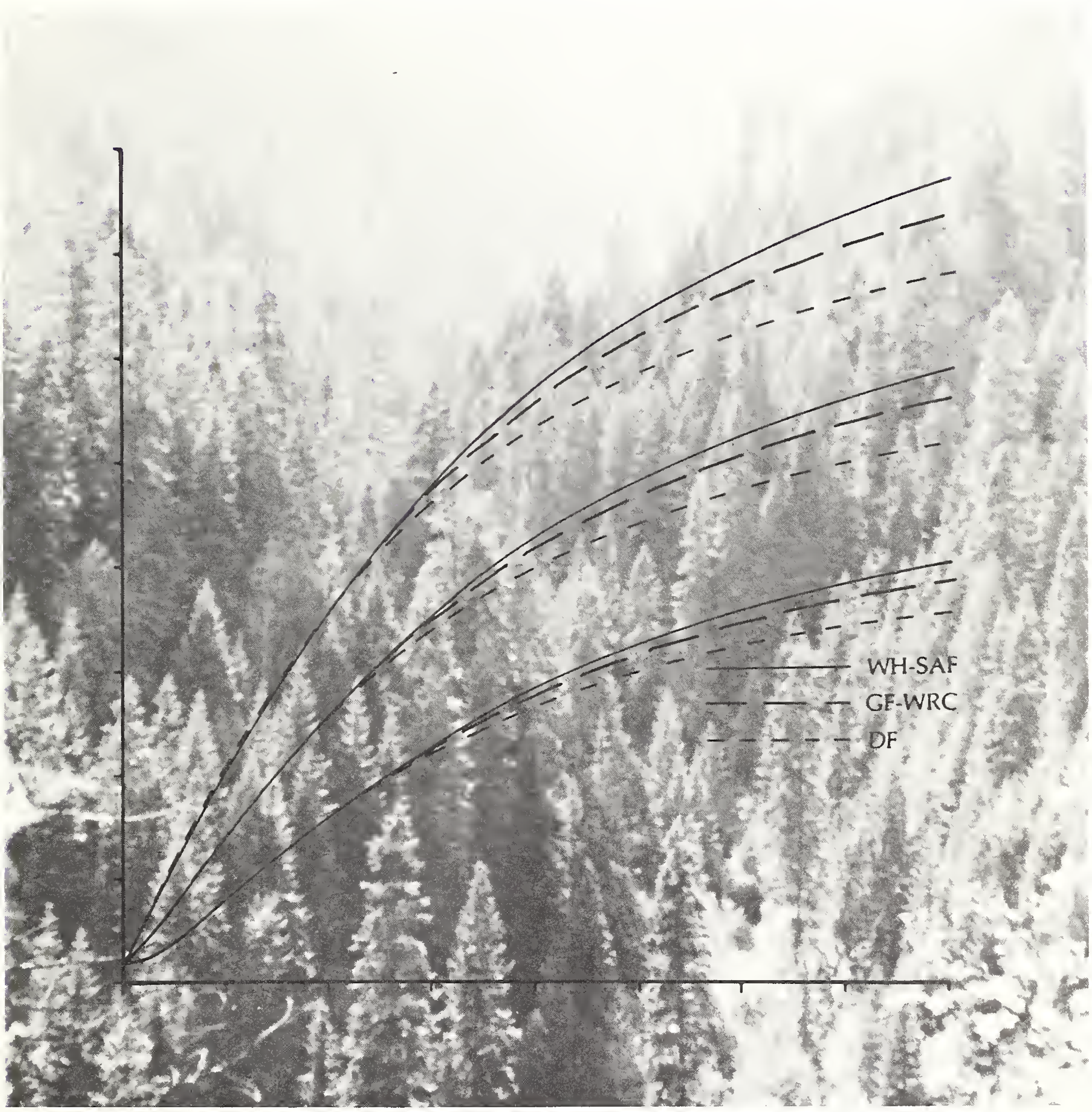
**Intermountain
Research Station
Ogden, UT 84401**

Research Paper
INT-347

July 1985

Applying Height Growth and Site Index Curves for Inland Douglas-fir

Robert A. Monserud



THE AUTHOR

ROBERT A. MONSERUD is principal mensurationist, Intermountain Research Station, at the Forestry Sciences Laboratory, Moscow, ID. Dr. Monserud is assigned to the Quantitative Analysis of Forest Resources research work unit at Moscow. He earned a B.A. degree in mathematics in 1968 from the University of Iowa, and taught mathematics for 3 years. In 1971, he enrolled at the University of Wisconsin-Madison, where he earned an M.S. degree in forest management in 1973 and a Ph.D. in forest mensuration and biometrics in 1975. Since joining the Intermountain Station in 1975, his research has primarily dealt with modeling stand dynamics in uneven-aged and mixed-species forests. He is currently working on projects in site productivity and the time series analysis of tree ring data.

RESEARCH SUMMARY

Methods for estimating both site index and dominant height growth for inland Douglas-fir in the Northern Rocky Mountains are presented and discussed. The methods should be applicable over a wide range of stand conditions because no restrictions were placed on species composition, stand density, spacing, or age structure in the original stem analysis sample. Increased accuracy can be obtained if habitat type is considered, because the shape of the site index curves varied with respect to three major habitat series groupings. Results are summarized in the form of equations, tables, and graphs. Precision curves are used to illustrate the relationship between expected standard error and both age and sample size.

The research reported here was financed in part by the USDA Expanded Douglas-fir Tussock Moth Research and Development Program and by the Intermountain Research Station, USDA Forest Service.

Applying Height Growth and Site Index Curves for Inland Douglas-fir

Robert A. Monserud

INTRODUCTION

In **Forest Science**, Monserud (1984) developed height growth and site index curves for inland Douglas-fir (*Pseudotsuga menziesii* Franco var. *glauca* [Beissn.] Franco) growing in the Northern Rocky Mountains. That paper emphasized model development and analysis. The purpose of this subsequent report is to provide additional information and instructions for applying these curves.

METHODS

Plot Selection.—Monserud's (1984) selection criteria were both simple and nonrestrictive: any plot containing suitable dominant Douglas-fir site trees was acceptable. No requirements were placed on species composition, stand density, spacing, or age structure. Thus both even and uneven-aged stands were selected, as well as pure and mixed species stands. Suitable site trees were the best-growing dominants (based on increment cores) on an approximately half-acre plot that was representative of the growing conditions in the stand. Site trees had no observable top damage, had well developed and healthy appearing crowns, and a history of regular radial growth with no indication of suppression or damage; no wolf-trees or super-dominants were sampled, however. One hundred forty-one such plots (fig. 1) were established throughout the seven National Forests in northern Idaho and northwestern Montana (the Nezperce, Clearwater, St. Joe, Coeur d'Alene, and Kaniksu in Idaho, and the Lolo and Kootenai in Montana).

Forest habitat typing has been widely accepted as a useful management tool in the Rocky Mountains because of its sound ecological base (Pfister and Arno 1980). Because the factors that determine the habitat type of a site might also affect the shape of the growth curves, habitat type was expected to be a useful concomitant variable in this study. Plot selection was therefore stratified by habitat type (using Daubenmire and Daubenmire 1968, Pfister and others 1977, and Steele and others 1976), with the result that all five major habitat series that contain Douglas-fir were well represented in the sample. The five series are (1) the Douglas-fir series; (2) the grand fir (*Abies grandis*) series; (3) the western redcedar (*Thuja plicata*) series; (4) the western hemlock (*Tsuga heterophylla*) series; and (5) the subalpine fir (*A. lasiocarpa*) series. These five habitat series will be abbreviated as follows in this paper: DF, GF, WRC, WH, and SAF, respectively.

Height Growth and Site Index Curves.—Fitting height as a function of site index and age and then solving for site index will always result in a different (and inferior) model than if site index is fit as a function of height and age. This results from minimizing two different sum of squares surfaces (see Draper and Smith 1981, p. 6). It is thus necessary for the researcher to develop separate models for both height growth and site index (Curtis and others 1974). If the average height growth pattern of the best-growing dominants in a stand of known site index is desired, then a height growth model should be used; if the site index for a stand with site trees not at index age is needed, then a site index model is necessary. And both site index and height growth models are needed to estimate the average height development of the best dominants for a stand with site trees not at the index age.

Site index was defined to be the average total height of the three best site trees (per one-half acre) at an index age of 50 years at breast height. Because the length of time it takes a seedling to reach breast height may be strongly influenced by factors that are poorly related to site quality—such as animal damage, snow damage, and plant competition in the immediate vicinity of the seedling (Cochran 1979; Curtis 1964)—index age was located at breast height rather than the base of the tree.

Stem analysis data were obtained from the three best-growing dominant site trees per plot; trees were sectioned at approximately every tenth whorl. After screening these data to eliminate trees that obviously underestimated the height growth potential of the site (based on graphs of height vs. age and diameter vs. age), 1,586 observations were available for analysis. The following models were determined by Monserud (1984) to best represent Douglas-fir height growth and site index:

$$\hat{H} = \frac{42.397 \bullet S^{(0.3197 \bullet Z_1 + 0.3488 \bullet Z_2 + 0.3656 \bullet Z_3)}}{1 + e^{9.7278 - 1.2934 \bullet \ln A - (1.0232 \bullet Z_1 + 0.9779 \bullet Z_2 + 0.9527 \bullet Z_3) \bullet \ln S}} \quad [1]$$

$$\hat{S} = [38.787 - 2.805 \bullet (\ln A)^2 + 0.0216 \bullet A \bullet \ln A + (0.4948 \bullet Z_1 + 0.4305 \bullet Z_2 + 0.3964 \bullet Z_3) \bullet H + (25.315 \bullet Z_1 + 28.415 \bullet Z_2 + 30.008 \bullet Z_3) \bullet H/A] \quad [2]$$

where

$$Z_1 = \begin{cases} 1 \text{ if habitat type is in the DF series, or} \\ 0 \text{ otherwise.} \end{cases}$$

$$Z_2 = \begin{cases} 1 \text{ if habitat type is in the GF or WRC series, or} \\ 1 \text{ if have no habitat type information;} \\ 0 \text{ otherwise.} \end{cases}$$

$$Z_3 = \begin{cases} 1 \text{ if habitat type is in the WH or SAF series, or} \\ 0 \text{ otherwise.} \end{cases}$$

H = total height − 4.5 ft.
S = site index − 4.5 ft.
A = age at breast height.
e = the base of natural logarithms.
lnx = the natural logarithm of argument x.

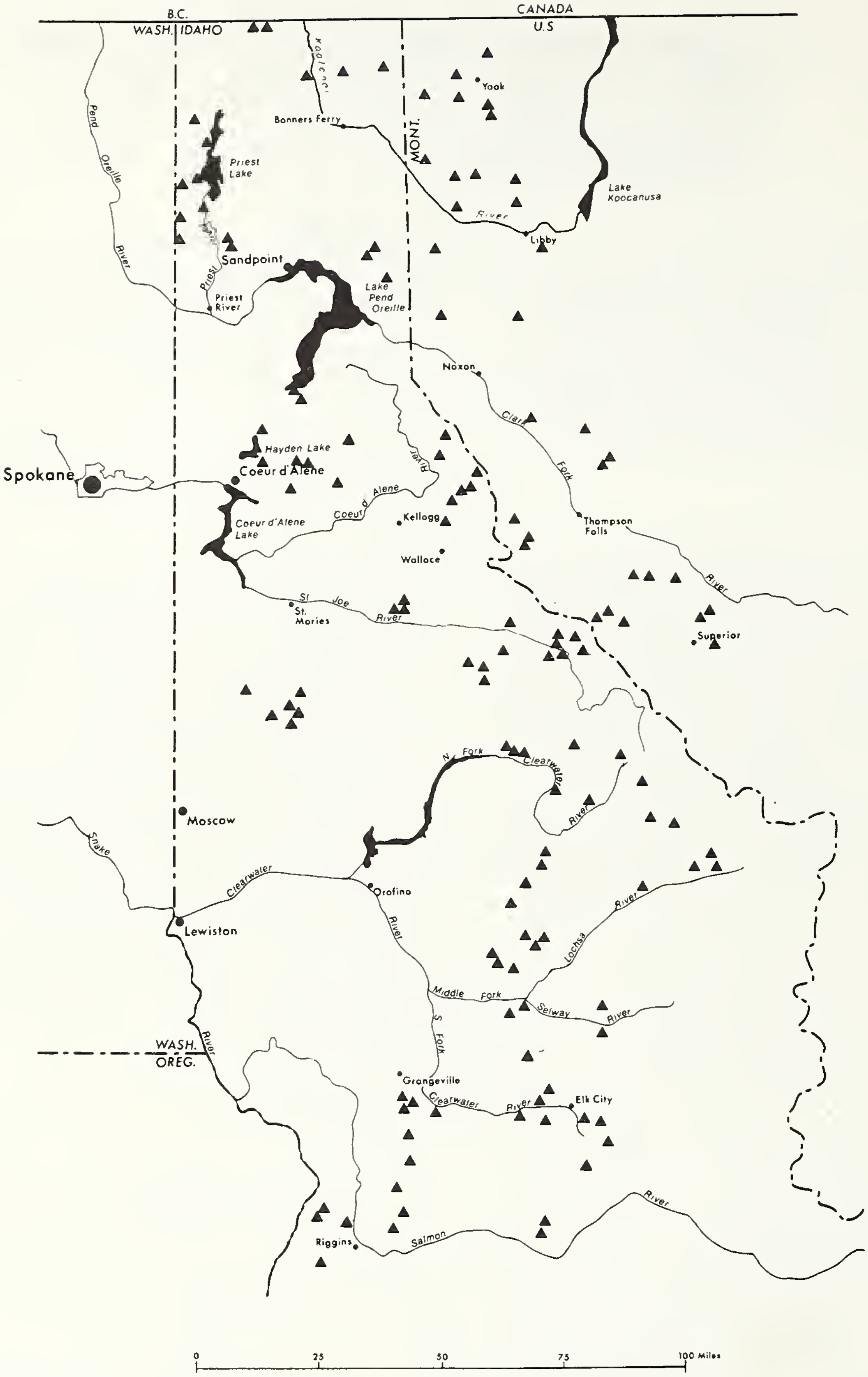


Figure 1.—Douglas-fir site index study plot locations.

The following equations can be used if metric units are preferred:

$$\hat{H}_m = \frac{12.923 \cdot (3.2808 \cdot S_m)^{(0.3197 \cdot Z_1 + 0.3488 \cdot Z_2 + 0.3656 \cdot Z_3)}}{1 + e^{9.7278 - 1.2934 \cdot \ln A - (1.0232 \cdot Z_1 + 0.9779 \cdot Z_2 + 0.9527 \cdot Z_3) \cdot \ln(3.2808 \cdot S_m)}} \quad [1m]$$

$$\hat{S}_m = [11.822 - 0.855 \cdot (\ln A)^2 + 0.0066 \cdot A \cdot \ln A + (0.4948 \cdot Z_1 + 0.4305 \cdot Z_2 + 0.3964 \cdot Z_3) \cdot H_m + (25.315 \cdot Z_1 + 28.415 \cdot Z_2 + 30.008 \cdot Z_3) \cdot H_m / A] \quad [2m]$$

where

H_m = total height − 1.37 m.
S_m = site index − 1.37 m.
1 m = 3.2808 ft.

Height growth model [1] and site index model [2] are graphed in figures 2 through 7—one graph for each of the three habitat groupings that significantly affect curve shape. Note that model [2] is graphed in conventional height versus age format, even though site index is the dependent variable. As an additional aid in applying models [1] and [2]—especially in the field—tables 1 through 6 list height by 5-year age and 5-ft site index classes. The range of data in Monserud's (1984) sample is indicated by light shading in tables 1 through 6, so that the user will know when the curves are being extrapolated. Note that height was not constrained to equal site index at the index age. Such a constraint not only gives undue importance to the index age (at the expense of the precision of the predictions at non-index ages), but is unnecessary. Tables 1 through 6 reveal that height at age 50 does not differ from site index as predicted by model [2], and site index rarely differs from height growth predictions at age 50 by more than 1 ft, and then only at or past the extremes of the sample data.

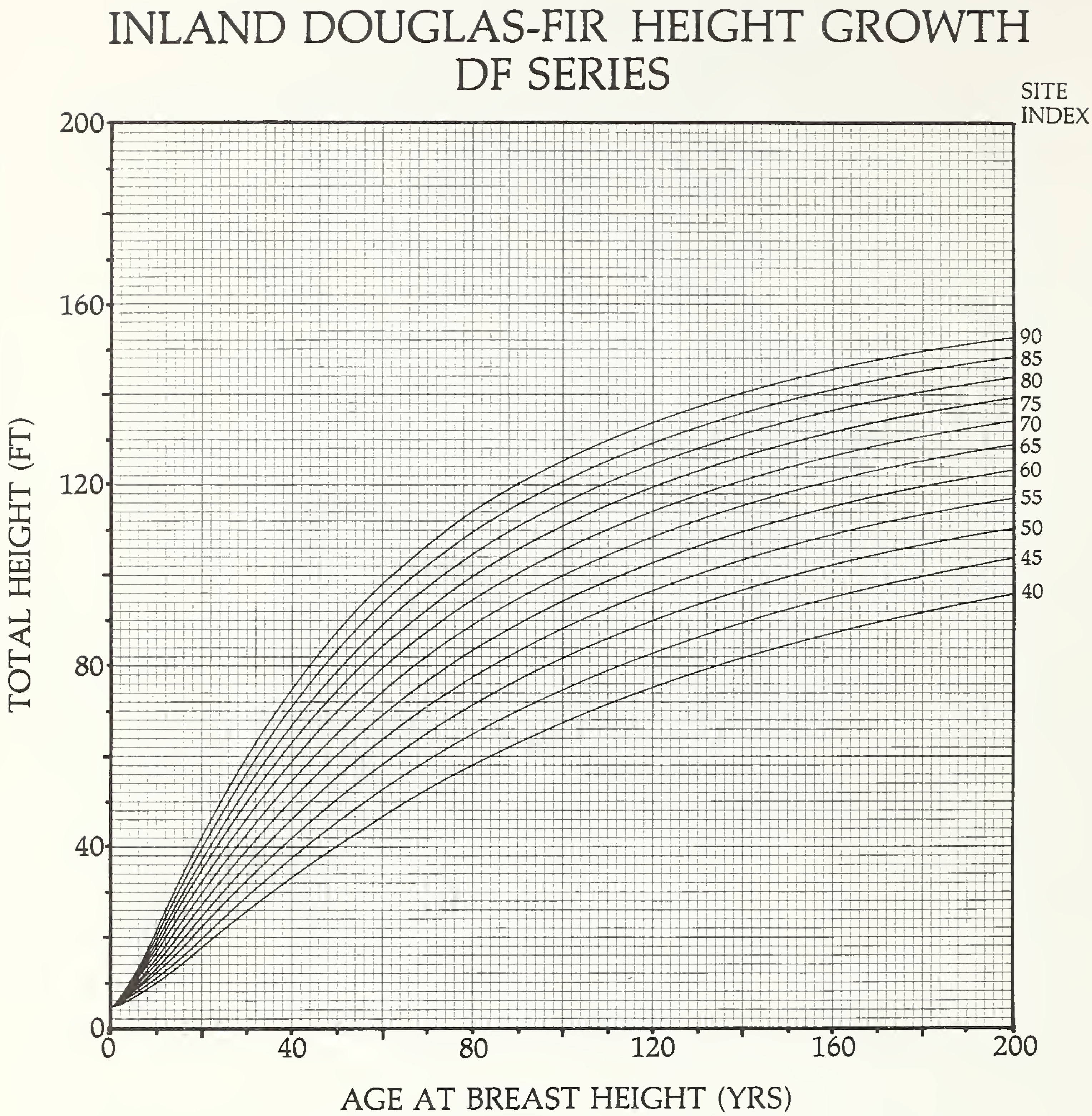


Figure 2.—Height growth from model [1], for the Douglas-fir (DF) series.

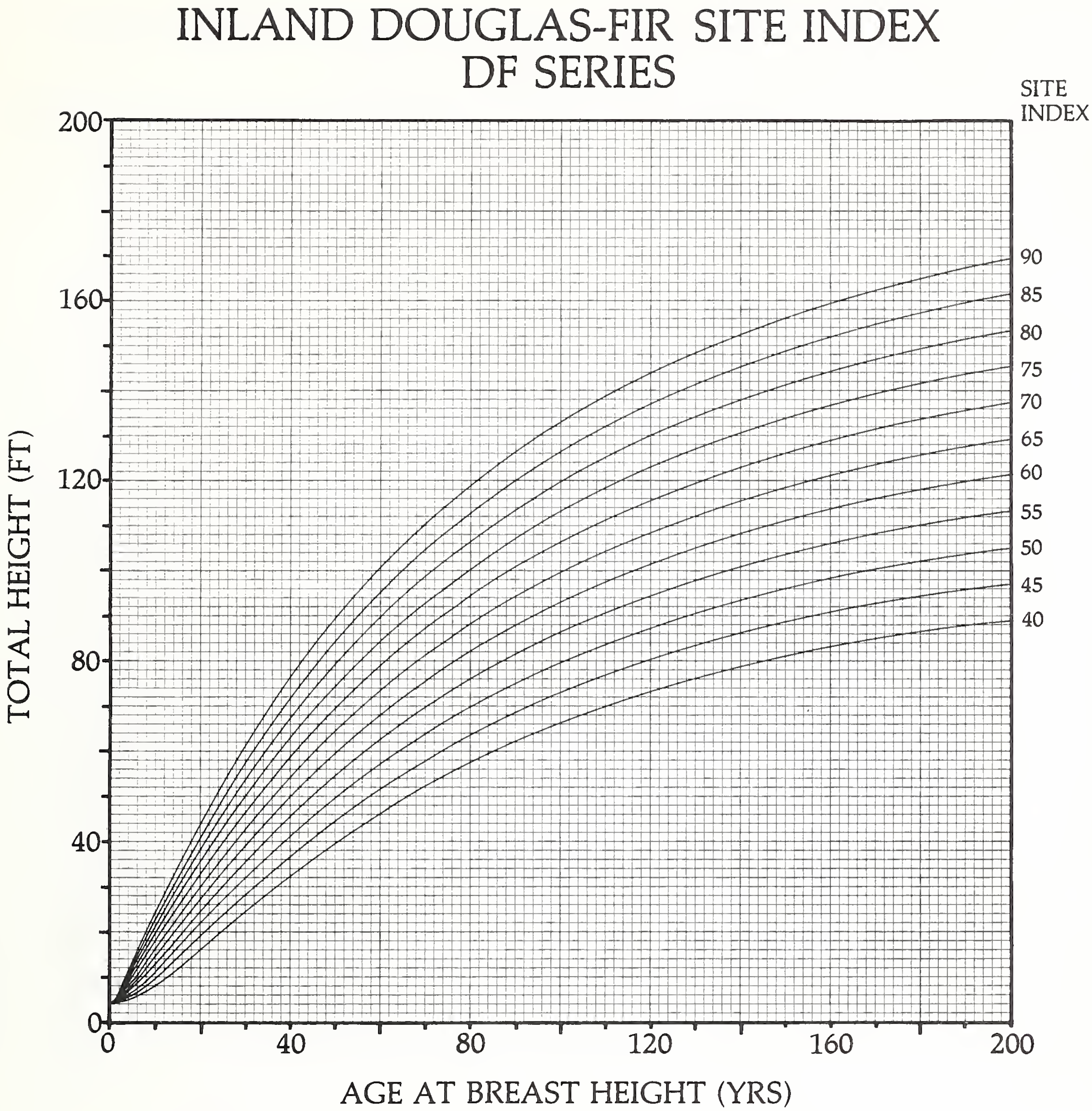


Figure 3.—Site index from model [2], for the Douglas-fir (DF) series.

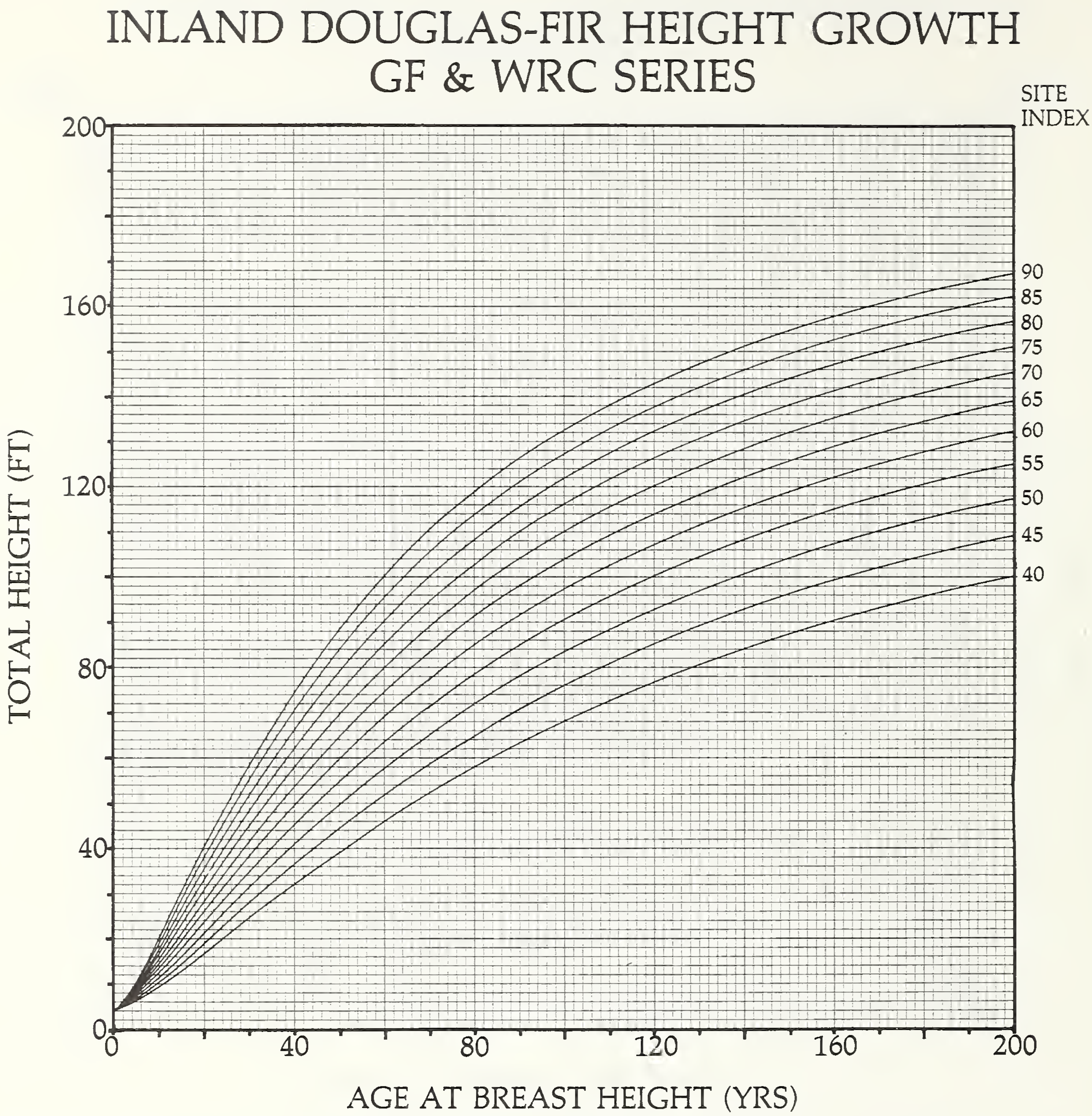


Figure 4.—Height growth from model [1], for the grand fir and western redcedar (GF-WRC) series, or if no habitat information is available.

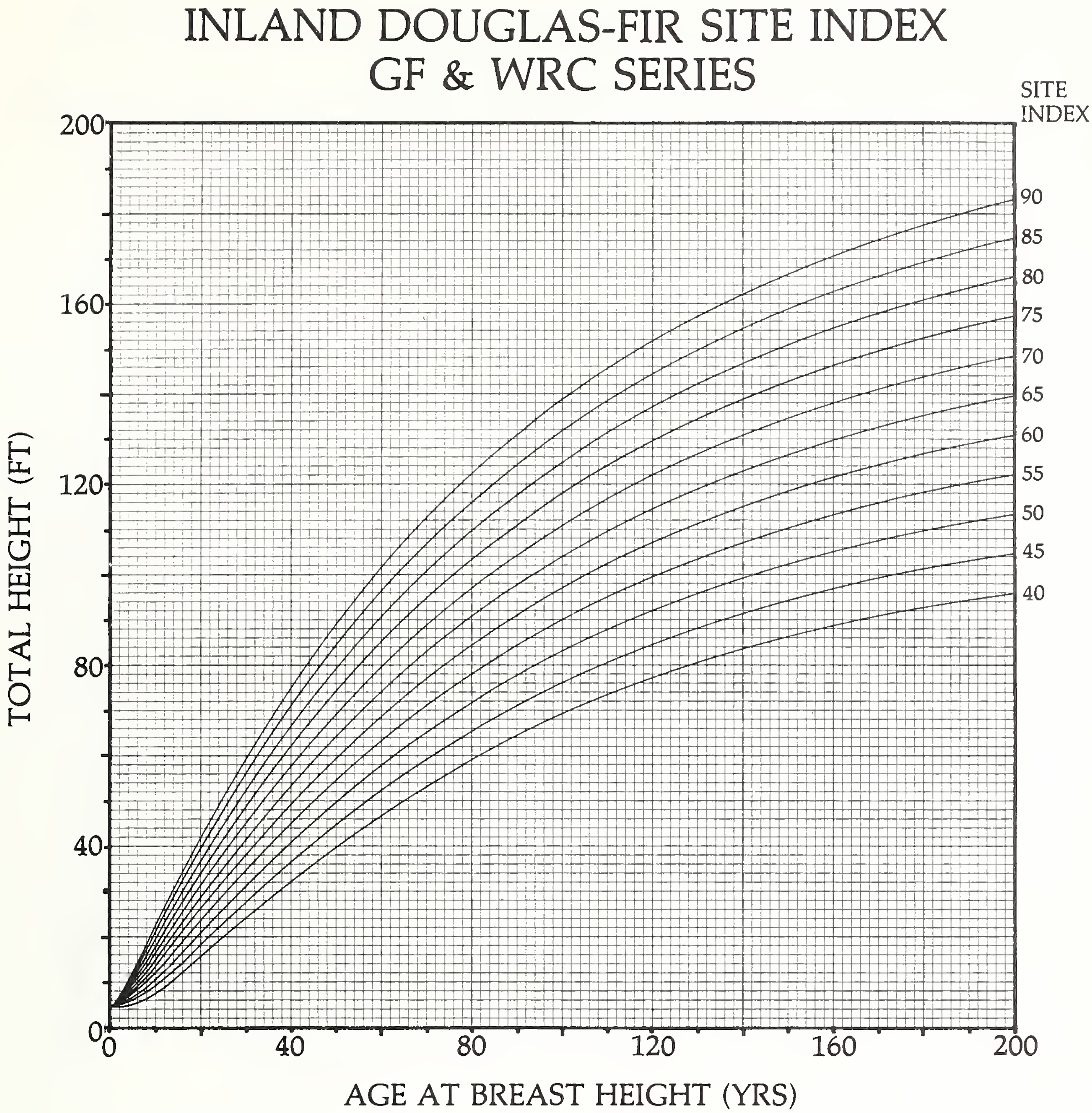


Figure 5.—Site index from model [2] for the grand fir and western redcedar (GF-WRC) series, or if no habitat information is available.

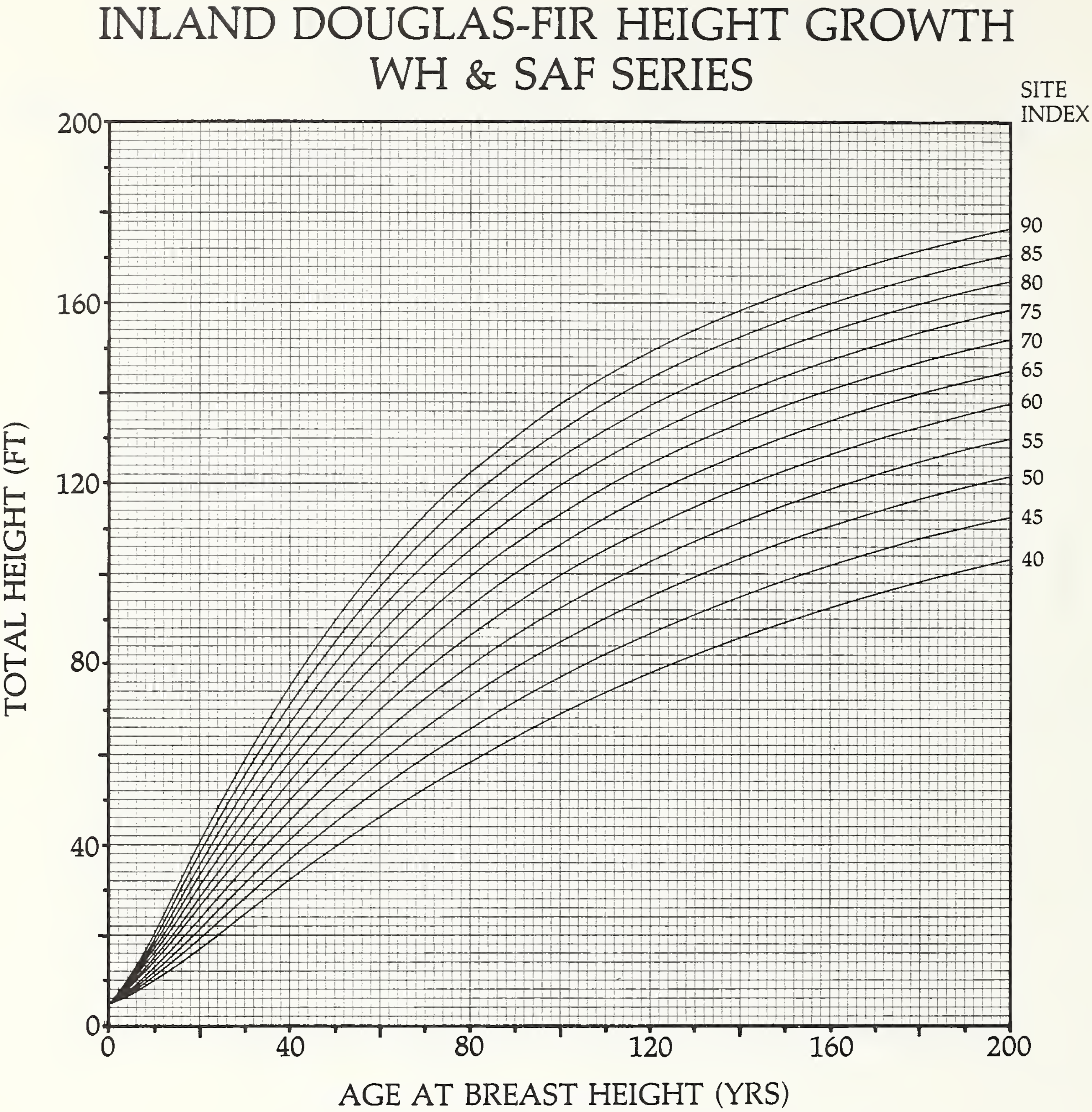


Figure 6.—Height growth from model [1], for the western hemlock and subalpine fir (WH-SAF) series.

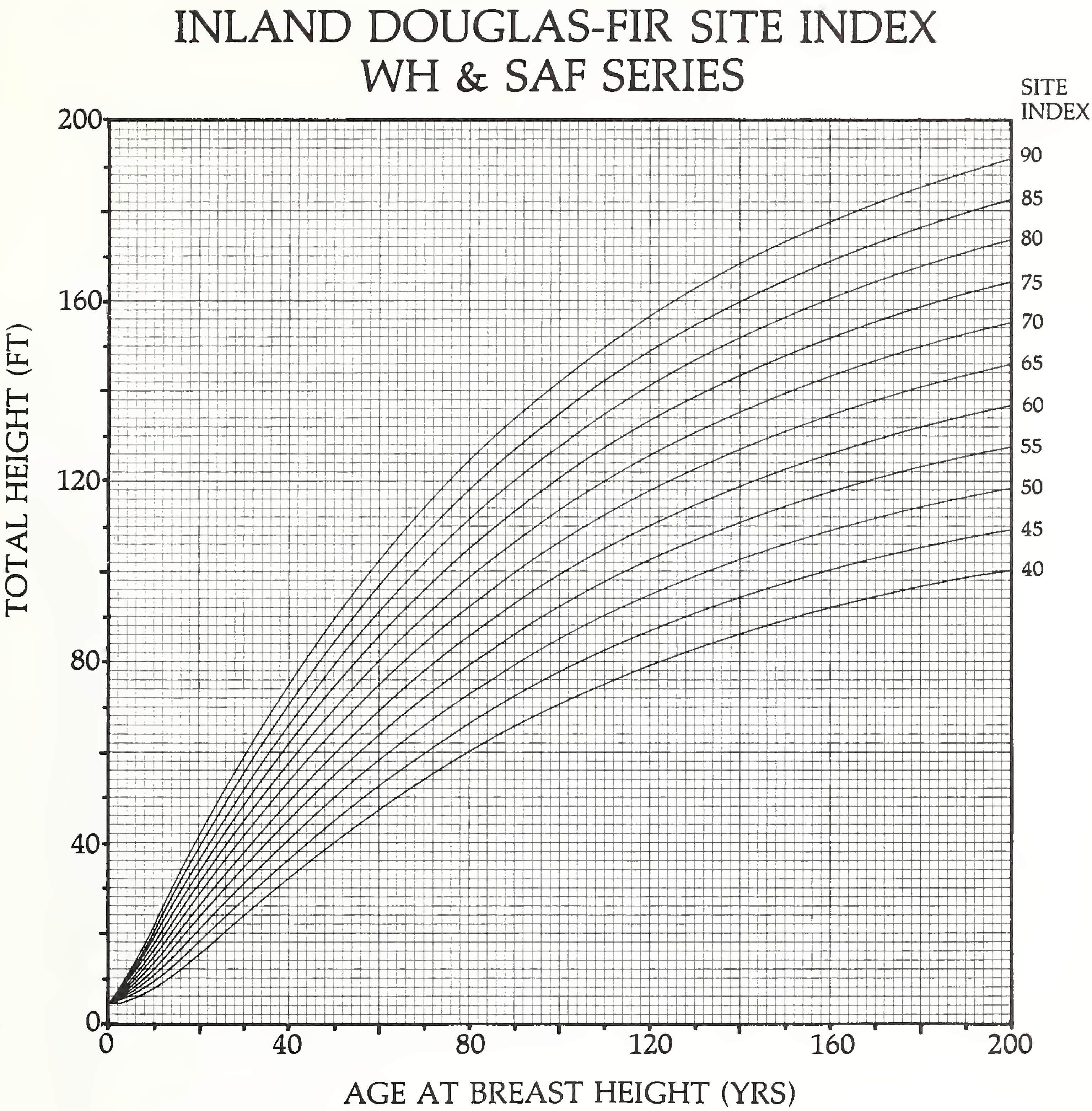


Figure 7.—Site index from model [2], for the western hemlock and subalpine fir (WH-SAF) series.

Table 1.—Height versus age for the following site classes, using the **DF series height growth** model; the range of Monserud's (1984) DF series data is indicated by light shading

B.H. AGE (YRS)	SITE INDEX 30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
	(HEIGHT IN FEET)														
5	6	6	7	7	8	8	9	9	10	10	11	12	12	13	13
10	8	9	10	11	12	14	15	16	17	18	20	21	22	23	25
15	11	12	14	16	17	19	21	23	25	27	29	30	32	34	36
20	13	16	18	20	23	25	27	30	32	35	37	40	42	45	47
25	16	19	22	25	28	31	34	37	40	43	46	49	52	54	57
30	19	22	26	29	33	36	40	43	47	50	53	57	60	63	67
35	21	25	29	33	37	41	45	49	53	57	61	64	68	72	75
40	24	28	33	37	42	46	51	55	59	63	67	71	75	79	83
45	27	32	37	41	46	51	56	60	65	69	73	78	82	86	90
50	29	35	40	45	50	56	60	65	70	75	79	83	88	92	96
55	32	38	43	49	54	60	65	70	75	80	84	89	93	97	101
60	34	40	46	52	58	64	69	74	79	84	89	94	98	102	106
65	36	43	49	56	62	67	73	78	84	89	93	98	103	107	111
70	39	46	52	59	65	71	77	82	87	92	97	102	107	111	115
75	41	48	55	62	68	74	80	86	91	96	101	106	110	115	119
80	43	51	58	65	71	77	83	89	94	100	105	109	114	118	123
85	45	53	60	67	74	80	86	92	97	103	108	113	117	122	126
90	47	55	63	70	77	83	89	95	100	106	111	115	120	125	129
95	49	57	65	72	79	86	92	98	103	108	113	118	123	127	132
100	51	59	67	75	81	88	94	100	106	111	116	121	125	130	134
105	53	61	69	77	84	90	97	102	108	113	118	123	128	132	136
110	55	63	71	79	86	92	99	105	110	115	121	125	130	134	139
115	56	65	73	81	88	95	101	107	112	118	123	127	132	136	141
120	58	67	75	83	90	96	103	109	114	120	125	129	134	138	142
125	59	68	77	84	92	98	105	111	116	121	126	131	136	140	144
130	61	70	78	86	93	100	106	112	118	123	128	133	137	142	146
135	62	72	80	88	95	102	108	114	119	125	130	134	139	143	147
140	64	73	82	89	97	103	110	115	121	126	131	136	140	145	149
145	65	75	83	91	98	105	111	117	122	128	133	137	142	146	150
150	66	76	84	92	100	106	112	118	124	129	134	139	143	147	151
155	68	77	86	94	101	108	114	120	125	130	135	140	144	149	153
160	69	78	87	95	102	109	115	121	126	132	136	141	145	150	154
165	70	80	88	96	103	110	116	122	128	133	138	142	147	151	155
170	71	81	89	97	105	111	117	123	129	134	139	143	148	152	156
175	72	82	91	99	106	112	119	124	130	135	140	144	149	153	157
180	73	83	92	100	107	113	120	125	131	136	141	145	150	154	158
185	74	84	93	101	108	114	121	126	132	137	142	146	150	155	158
190	75	85	94	102	109	115	122	127	133	138	142	147	151	155	159
195	76	86	95	103	110	116	122	128	134	139	143	148	152	156	160
200	77	87	96	104	111	117	123	129	134	139	144	149	153	157	161

Table 2.—Height versus age for the following site classes, using the **DF series site index** model; the range of Monserud's (1984) DF series data is indicated by light shading

B.H. AGE (YRS)	SITE INDEX 30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
	(HEIGHT IN FEET)														
5	3	4	5	6	7	8	9	10	11	11	12	13	14	15	16
10	5	7	8	10	11	13	15	16	18	20	21	23	25	26	28
15	7	10	12	14	17	19	21	23	26	28	30	33	35	37	40
20	11	13	16	19	22	25	28	30	33	36	39	42	45	47	50
25	14	17	20	24	27	30	34	37	40	44	47	50	54	57	60
30	17	21	25	28	32	36	40	43	47	51	55	58	62	66	69
35	20	25	29	33	37	41	45	49	53	57	62	66	70	74	78
40	24	28	33	37	41	46	50	55	59	64	68	73	77	81	86
45	27	32	36	41	46	51	55	60	65	69	74	79	84	88	93
50	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
55	33	38	43	48	54	59	64	69	75	80	85	90	96	101	106
60	36	41	46	52	57	63	68	74	79	85	90	96	101	106	112
65	38	44	49	55	61	66	72	78	83	89	95	100	106	112	117
70	41	46	52	58	64	70	76	81	87	93	99	105	111	116	122
75	43	49	55	61	67	73	79	85	91	97	103	109	115	121	127
80	45	51	58	64	70	76	82	88	94	101	107	113	119	125	131
85	47	54	60	66	73	79	85	91	98	104	110	117	123	129	136
90	49	56	62	69	75	82	88	94	101	107	114	120	127	133	139
95	51	58	64	71	77	84	91	97	104	110	117	123	130	137	143
100	53	60	66	73	80	86	93	100	106	113	120	126	133	140	147
105	55	61	68	75	82	89	95	102	109	116	123	129	136	143	150
110	56	63	70	77	84	91	98	105	111	118	125	132	139	146	153
115	58	65	72	79	86	93	100	107	114	121	128	135	142	149	156
120	59	66	73	80	88	95	102	109	116	123	130	137	144	151	158
125	61	68	75	82	89	96	104	111	118	125	132	139	147	154	161
130	62	69	76	84	91	98	105	113	120	127	134	142	149	156	163
135	63	70	78	85	92	100	107	114	122	129	136	144	151	158	166
140	64	71	79	86	94	101	108	116	123	131	138	145	153	160	168
145	65	73	80	88	95	102	110	117	125	132	140	147	155	162	170
150	66	74	81	89	96	104	111	119	126	134	141	149	157	164	172
155	67	75	82	90	97	105	113	120	128	135	143	151	158	166	173
160	68	76	83	91	99	106	114	122	129	137	144	152	160	167	175
165	69	76	84	92	100	107	115	123	130	138	146	154	161	169	177
170	69	77	85	93	101	108	116	124	132	139	147	155	163	170	178
175	70	78	86	94	101	109	117	125	133	141	148	156	164	172	180
180	71	79	87	94	102	110	118	126	134	142	150	157	165	173	181
185	71	79	87	95	103	111	119	127	135	143	151	159	166	174	182
190	72	80	88	96	104	112	120	128	136	144	152	160	168	176	183
195	73	81	89	97	105	113	121	129	137	145	153	161	169	177	185
200	73	81	89	97	105	113	121	129	137	145	153	162	170	178	186

Table 3.—Height versus age for the following site classes, using the **GF-WRC series height growth** model; the range of Monserud's (1984) GF-WRC series data is indicated by light shading, and the entire range of Monserud's data is indicated by both light and dark shading

B.H. AGE (YRS)	SITE INDEX 30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
	(HEIGHT IN FEET)														
5	6	6	7	7	8	8	9	9	10	10	11	11	12	12	13
10	8	9	10	11	12	13	14	15	16	18	19	20	21	22	24
15	10	12	14	15	17	19	20	22	24	26	28	29	31	33	35
20	13	15	17	20	22	24	27	29	31	34	36	39	41	44	46
25	16	18	21	24	27	30	33	36	39	42	45	48	51	53	56
30	18	21	25	28	32	35	39	42	46	49	53	56	59	63	66
35	21	25	29	33	37	41	45	48	52	56	60	64	68	71	75
40	23	28	32	37	41	46	50	54	59	63	67	71	75	79	83
45	26	31	36	41	46	51	55	60	65	69	74	78	83	87	91
50	29	34	39	45	50	55	60	65	70	75	80	85	89	94	98
55	31	37	43	49	54	60	65	70	76	81	86	90	95	100	104
60	34	40	46	52	58	64	70	75	81	86	91	96	101	106	110
65	36	43	49	56	62	68	74	80	85	91	96	101	106	111	116
70	38	45	52	59	65	72	78	84	90	95	100	106	111	116	121
75	41	48	55	62	69	75	82	88	94	99	105	110	115	120	125
80	43	51	58	65	72	79	85	91	97	103	109	114	119	124	129
85	45	53	61	68	75	82	89	95	101	107	112	118	123	128	133
90	47	55	63	71	78	85	92	98	104	110	116	121	127	132	137
95	49	58	66	74	81	88	95	101	107	113	119	125	130	135	140
100	51	60	68	76	84	91	98	104	110	116	122	128	133	138	143
105	53	62	70	79	86	93	100	107	113	119	125	131	136	141	146
110	55	64	73	81	89	96	103	110	116	122	128	133	139	144	149
115	57	66	75	83	91	98	105	112	118	124	130	136	141	146	151
120	58	68	77	85	93	101	108	114	121	127	133	138	144	149	154
125	60	70	79	87	95	103	110	116	123	129	135	140	146	151	156
130	62	72	81	89	97	105	112	119	125	131	137	143	148	153	158
135	63	73	82	91	99	107	114	121	127	133	139	144	150	155	160
140	65	75	84	93	101	108	116	122	129	135	141	146	152	157	162
145	66	76	86	95	103	110	117	124	131	137	143	148	153	159	163
150	68	78	87	96	104	112	119	126	132	138	144	150	155	160	165
155	69	79	89	98	106	114	121	128	134	140	146	151	157	162	167
160	71	81	90	99	107	115	122	129	135	142	147	153	158	163	168
165	72	82	92	101	109	117	124	131	137	143	149	154	160	165	169
170	73	84	93	102	110	118	125	132	138	144	150	156	161	166	171
175	74	85	95	103	112	119	126	133	140	146	151	157	162	167	172
180	76	86	96	105	113	121	128	135	141	147	153	158	163	168	173
185	77	87	97	106	114	122	129	136	142	148	154	159	165	169	174
190	78	88	98	107	115	123	130	137	143	149	155	160	166	171	175
195	79	90	99	108	117	124	131	138	144	150	156	161	167	172	176
200	80	91	100	109	118	125	132	139	145	151	157	162	168	173	177

Table 4.—Height versus age for the following site classes, using the **GF-WRC series site index** model; the range of Monserud's (1984) GF-WRC series data is indicated by light shading, and the entire range of Monserud's data is indicated by both light and dark shading

B.H. AGE (YRS)	SITE INDEX 30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
	(HEIGHT IN FEET)														
5	3	4	5	6	7	8	8	9	10	11	12	12	13	14	15
10	5	6	8	9	11	12	14	16	17	19	20	22	23	25	26
15	7	9	12	14	16	18	20	22	24	27	29	31	33	35	37
20	10	13	16	18	21	24	26	29	32	35	37	40	43	45	48
25	13	17	20	23	26	29	33	36	39	42	45	49	52	55	58
30	17	20	24	28	31	35	39	42	46	49	53	57	60	64	68
35	20	24	28	32	36	40	44	48	52	56	60	64	68	73	77
40	24	28	32	37	41	45	50	54	59	63	67	72	76	80	85
45	27	31	36	41	46	50	55	60	64	69	74	79	83	88	93
50	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
55	33	38	44	49	54	59	65	70	75	81	86	91	96	102	107
60	36	41	47	53	58	64	69	75	80	86	91	97	102	108	113
65	39	45	50	56	62	68	73	79	85	91	96	102	108	114	119
70	41	47	53	59	65	71	77	83	89	95	101	107	113	119	125
75	44	50	56	63	69	75	81	87	93	100	106	112	118	124	131
80	47	53	59	66	72	78	85	91	97	104	110	117	123	129	136
85	49	55	62	68	75	82	88	95	101	108	114	121	127	134	140
90	51	58	64	71	78	85	91	98	105	111	118	125	131	138	145
95	53	60	67	74	81	87	94	101	108	115	122	129	135	142	149
100	55	62	69	76	83	90	97	104	111	118	125	132	139	146	153
105	57	64	71	79	86	93	100	107	114	121	128	136	143	150	157
110	59	66	73	81	88	95	103	110	117	124	132	139	146	153	161
115	61	68	75	83	90	98	105	112	120	127	134	142	149	157	164
120	62	70	77	85	92	100	107	115	122	130	137	145	152	160	167
125	64	71	79	87	94	102	109	117	125	132	140	147	155	163	170
130	65	73	81	88	96	104	112	119	127	135	142	150	158	165	173
135	67	75	82	90	98	106	114	121	129	137	145	153	160	168	176
140	68	76	84	92	100	108	115	123	131	139	147	155	163	171	179
145	69	77	85	93	101	109	117	125	133	141	149	157	165	173	181
150	70	79	87	95	103	111	119	127	135	143	151	159	167	175	183
155	72	80	88	96	104	112	120	129	137	145	153	161	169	177	186
160	73	81	89	97	105	114	122	130	138	147	155	163	171	180	188
165	74	82	90	98	107	115	123	132	140	148	157	165	173	181	190
170	74	83	91	100	108	116	125	133	141	150	158	167	175	183	192
175	75	84	92	101	109	118	126	134	143	151	160	168	177	185	193
180	76	85	93	102	110	119	127	136	144	153	161	170	178	187	195
185	77	85	94	103	111	120	128	137	145	154	163	171	180	188	197
190	78	86	95	103	112	121	129	138	147	155	164	172	181	190	198
195	78	87	96	104	113	122	130	139	148	156	165	174	182	191	200
200	79	88	96	105	114	122	131	140	149	157	166	175	184	192	201

Table 5.—Height versus age for the following site classes, using the **WH-SAF series height growth** model; the range of Monserud's (1984) WH-SAF series data is indicated by light shading

B.H. AGE (YRS)	SITE INDEX 30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
	(HEIGHT IN FEET)														
5	6	6	7	7	8	8	8	9	9	10	10	11	11	12	12
10	8	9	10	11	12	13	14	15	16	17	18	20	21	22	23
15	10	12	13	15	17	18	20	22	23	25	27	29	31	32	34
20	13	15	17	19	21	24	26	28	31	33	36	38	40	43	45
25	15	18	21	24	26	29	32	35	38	41	44	47	50	53	56
30	18	21	24	28	31	35	38	42	45	49	52	56	59	62	66
35	21	24	28	32	36	40	44	48	52	56	60	64	68	71	75
40	23	27	32	36	41	45	50	54	59	63	67	71	76	80	84
45	26	31	36	40	45	50	55	60	65	69	74	79	83	87	92
50	28	34	39	44	50	55	60	65	71	76	80	85	90	95	99
55	31	37	43	48	54	60	65	71	76	81	86	91	96	101	106
60	33	40	46	52	58	64	70	76	81	87	92	97	102	107	112
65	36	42	49	56	62	68	74	80	86	92	97	103	108	113	118
70	38	45	52	59	66	72	79	85	91	97	102	108	113	118	124
75	40	48	55	62	69	76	83	89	95	101	107	112	118	123	129
80	43	51	58	66	73	80	86	93	99	105	111	117	122	128	133
85	45	53	61	69	76	83	90	97	103	109	115	121	127	132	137
90	47	56	64	71	79	86	93	100	107	113	119	125	131	136	141
95	49	58	66	74	82	89	97	103	110	116	123	128	134	140	145
100	51	60	69	77	85	92	100	107	113	120	126	132	138	143	149
105	53	62	71	80	88	95	103	110	116	123	129	135	141	146	152
110	55	65	73	82	90	98	105	112	119	126	132	138	144	149	155
115	57	67	76	84	93	100	108	115	122	128	135	141	147	152	158
120	59	69	78	87	95	103	110	118	124	131	137	143	149	155	160
125	61	71	80	89	97	105	113	120	127	134	140	146	152	157	163
130	62	72	82	91	99	107	115	122	129	136	142	148	154	160	165
135	64	74	84	93	101	110	117	124	131	138	144	151	156	162	167
140	66	76	86	95	103	112	119	127	134	140	147	153	158	164	170
145	67	78	87	97	105	113	121	129	135	142	149	155	160	166	172
150	69	79	89	98	107	115	123	130	137	144	150	157	162	168	173
155	70	81	91	100	109	117	125	132	139	146	152	158	164	170	175
160	71	82	92	102	111	119	127	134	141	148	154	160	166	171	177
165	73	84	94	103	112	120	128	136	143	149	156	162	167	173	178
170	74	85	95	105	114	122	130	137	144	151	157	163	169	175	180
175	75	87	97	106	115	123	131	139	146	152	159	165	170	176	181
180	77	88	98	108	117	125	133	140	147	154	160	166	172	177	183
185	78	89	100	109	118	126	134	141	148	155	161	167	173	179	184
190	79	90	101	110	119	128	135	143	150	156	163	169	174	180	185
195	80	92	102	112	121	129	137	144	151	158	164	170	176	181	186
200	81	93	103	113	122	130	138	145	152	159	165	171	177	182	188

Table 6.—Height versus age for the following site classes, using the **WH-SAF series site index model**; the range of Monserud's (1984) WH-SAF series data is indicated by light shading

B.H. AGE (YRS)	SITE INDEX														
	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
	(HEIGHT IN FEET)														
5	4	4	5	6	7	7	8	9	10	11	11	12	13	14	14
10	5	6	8	9	11	12	14	15	17	18	20	21	22	24	25
15	7	9	11	13	16	18	20	22	24	26	28	30	32	34	36
20	10	13	15	18	21	23	26	29	31	34	36	39	42	44	47
25	13	16	20	23	26	29	32	35	38	41	45	48	51	54	57
30	17	20	24	27	31	35	38	42	45	49	52	56	60	63	67
35	20	24	28	32	36	40	44	48	52	56	60	64	68	72	76
40	23	28	32	37	41	45	50	54	58	63	67	71	76	80	84
45	27	31	36	41	46	50	55	60	64	69	74	78	83	88	93
50	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
55	33	38	44	49	54	60	65	70	76	81	86	92	97	102	107
60	36	42	47	53	59	64	70	75	81	86	92	98	103	109	114
65	39	45	51	57	62	68	74	80	86	92	97	103	109	115	121
70	42	48	54	60	66	72	78	84	90	97	103	109	115	121	127
75	45	51	57	64	70	76	82	89	95	101	107	114	120	126	133
80	47	54	60	67	73	80	86	93	99	106	112	119	125	132	138
85	50	56	63	70	76	83	90	96	103	110	116	123	130	136	143
90	52	59	66	73	80	86	93	100	107	114	121	127	134	141	148
95	54	61	68	75	82	89	97	104	111	118	125	132	139	146	153
100	57	64	71	78	85	92	100	107	114	121	128	136	143	150	157
105	59	66	73	81	88	95	103	110	117	125	132	139	147	154	161
110	61	68	76	83	90	98	105	113	120	128	135	143	150	158	165
115	62	70	78	85	93	100	108	116	123	131	138	146	154	161	169
120	64	72	80	87	95	103	111	118	126	134	142	149	157	165	172
125	66	74	82	89	97	105	113	121	129	137	144	152	160	168	176
130	67	75	83	91	99	107	115	123	131	139	147	155	163	171	179
135	69	77	85	93	101	109	117	126	134	142	150	158	166	174	182
140	70	79	87	95	103	111	120	128	136	144	152	160	169	177	185
145	72	80	88	97	105	113	122	130	138	146	155	163	171	180	188
150	73	81	90	98	107	115	123	132	140	149	157	165	174	182	190
155	74	83	91	100	108	117	125	134	142	151	159	168	176	184	193
160	75	84	93	101	110	118	127	135	144	152	161	170	178	187	195
165	77	85	94	102	111	120	128	137	146	154	163	172	180	189	198
170	78	86	95	104	112	121	130	139	147	156	165	174	182	191	200
175	78	87	96	105	114	122	131	140	149	158	167	175	184	193	202
180	79	88	97	106	115	124	133	142	150	159	168	177	186	195	204
185	80	89	98	107	116	125	134	143	152	161	170	179	188	197	206
190	81	90	99	108	117	126	135	144	153	162	171	180	189	198	207
195	82	91	100	109	118	127	136	145	154	163	173	182	191	200	209
200	82	92	101	110	119	128	137	146	156	165	174	183	192	201	210

Figures 8 and 9 illustrate the importance of habitat type in determining the shape of the resulting curves. Note that differences among the three habitat-series curves are trivial before age 70; only when the trees begin to reach maturity do differences in habitat series become important. The habitat-specific curves illustrated in figures 2 through 9 conform rather well with ecological expectations. The habitat series group with the lowest curve (past index age) is also the driest: the Douglas-fir climax series (DF). Reduced moisture availability is likely the cause of the large reduction in height growth once the site becomes fully utilized, which occurs at a younger age in stands of higher site index. The western hemlock and subalpine fir series group (WH-SAF) exhibited the opposite effect: good height growth continued for a longer time than was observed on the other habitat series. Moisture is usually not very limiting on the western hemlock series; indeed, some of the wettest habitats are found in this series (Daubenmire and Daubenmire 1968). The subalpine fir habitats also receive considerable precipitation, but are colder than the other series in which Douglas-fir is found (Pfister and others 1977); a shorter growing period on an otherwise favorable site would tend to prolong the length of

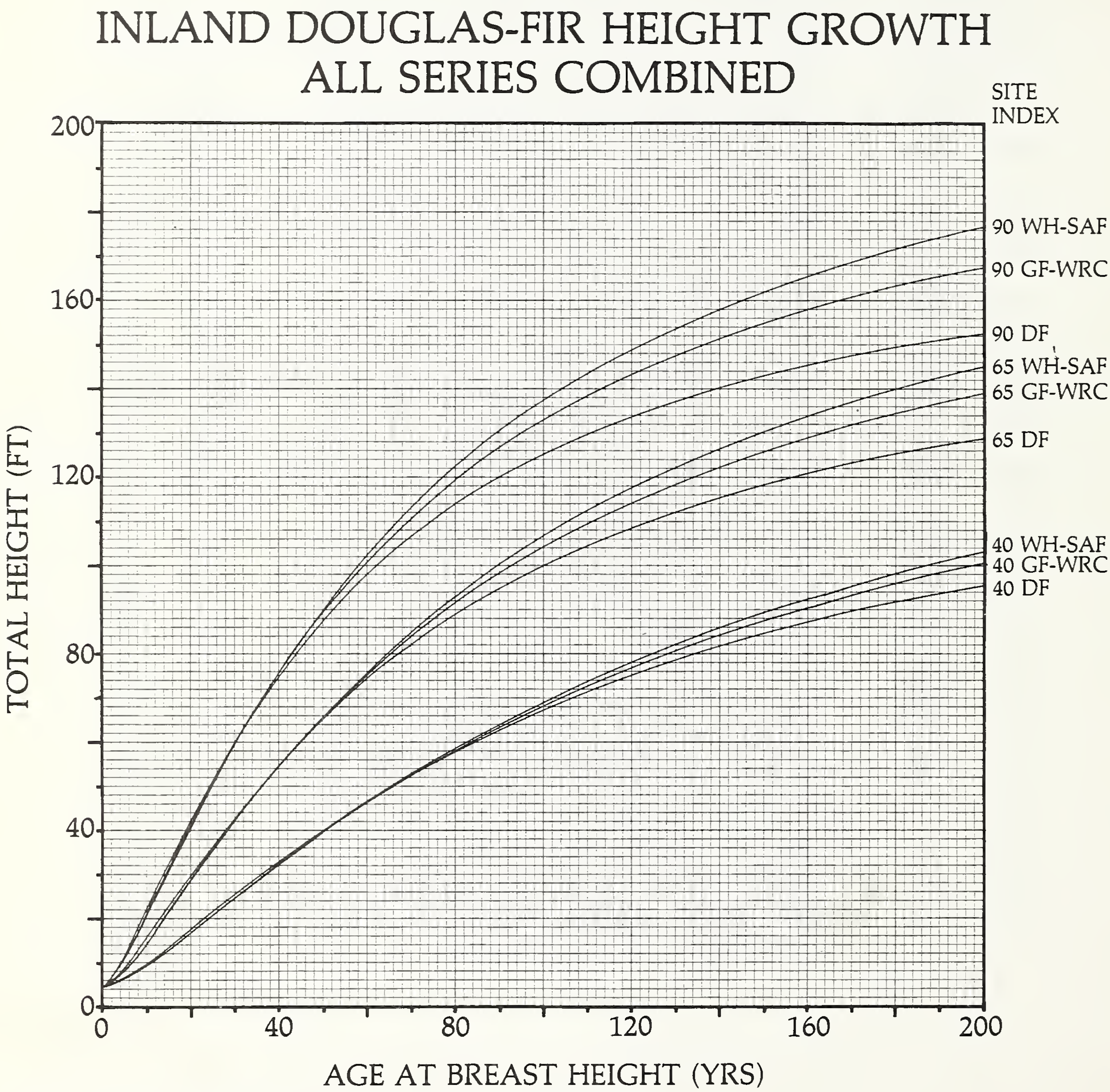


Figure 8.—Height growth model [1] versus age, for each of the three habitat series groups and for (approximately) the minimum (40), mean (65), and maximum (90) levels of site index sampled.

time required to approach the upper asymptote on the height growth curve. In general, these SAF series plots had a much lower average site index than the WH series plots (53 ft versus 66 ft), even though the curve shape for a given site index level was essentially the same for both series. The grand fir and western redcedar (GF-WRC) habitats are intermediate between the DF and WH-SAF habitats in both precipitation and temperature regimes; similarly, the GF-WRC curves in [1] and [2] are intermediate between the DF and WH-SAF series curves. In fact, the GF-WRC series curves are so intermediate that they are not significantly different from the overall all-series-combined curves. This result allowed Monserud (1984) to incorporate the simplification found in both [1] and [2]; the same site index and height growth equations can be used whether or not habitat type is known (as long as the dummy variables are coded accordingly). Although the GF-WRC series plots are intermediate in curve shape, they are not intermediate in height growth potential, for their average site index (72 ft) is 8 ft higher than the plots on the other three habitat series.

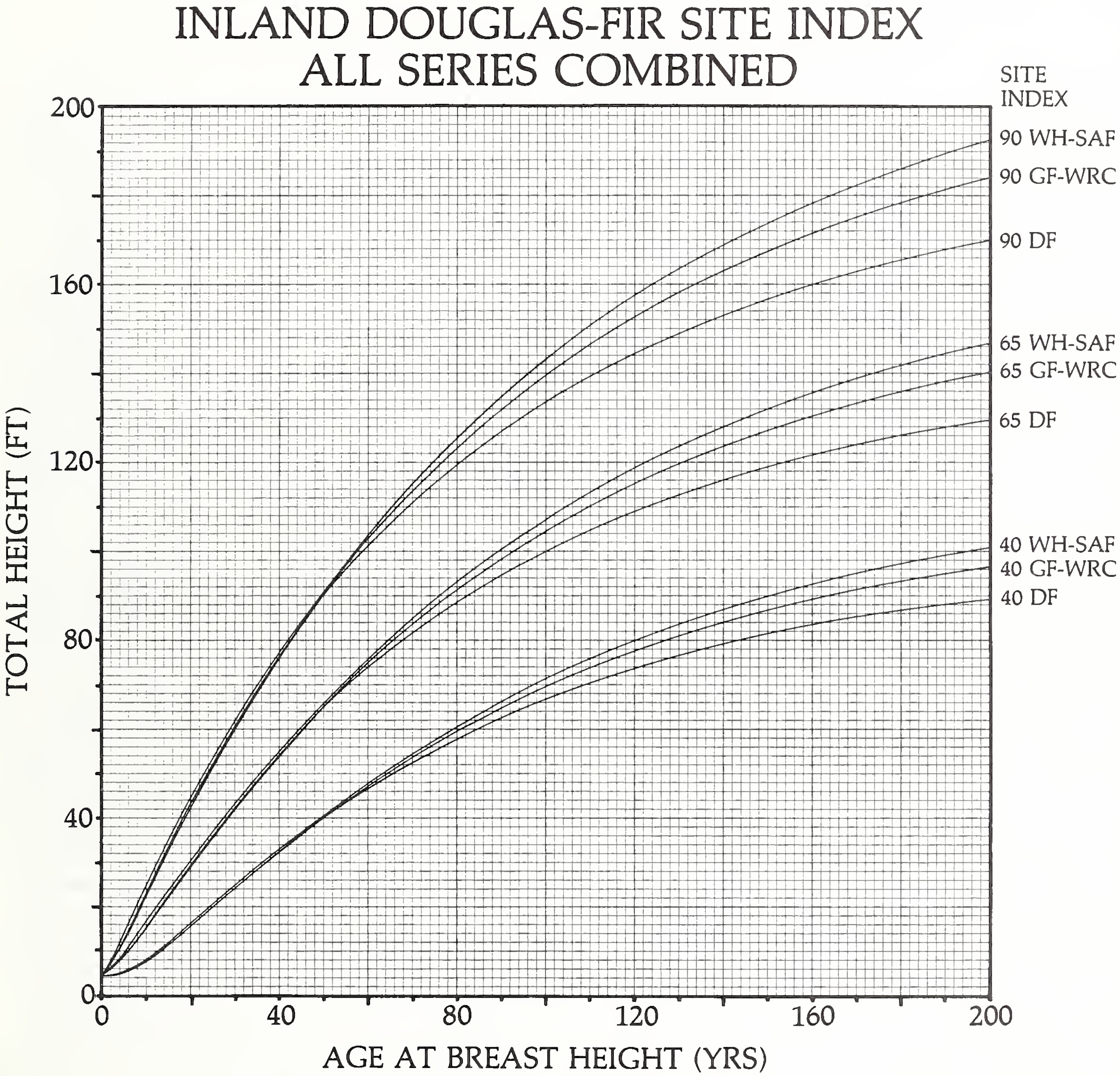


Figure 9.—Site index model [2] is plotted in conventional height vs. age format for each of the three habitat series groups and for (approximately) the minimum (40), mean (65), and maximum (90) levels of site index sampled.

Table 7.—Site index sample statistics by habitat series, from Monserud (1984; abbreviated RAM) and Cooper and others (in preparation; abbreviated CNS)

Habitat series	Mean		Minimum		Maximum		Standard deviation		Number of plots	
	RAM	CNS	RAM	CNS	RAM	CNS	RAM	CNS	RAM	CNS
	Feet									
Douglas-fir (DF)	64	67	41	44	85	96	13	11	27	29
Grand fir (GF)	70	69	44	46	100	104	12	11	33	95
Western redcedar (WRC)	72	74	41	52	100	102	14	14	33	21
Western hemlock (WH)	66	71	40	46	94	106	13	14	18	28
Subalpine fir (SAF)	53	54	28	32	76	79	10	12	24	25
Mountain hemlock (MH)	—	56	—	37	—	77	—	12	0	12
All plots combined	66	67	28	32	100	106	14	14	135	210

Table 7 summarizes the site index statistics by habitat series for the 135 sample plots that Monserud (1984) used. The overall average site index was 66 ft, with average site index ranging from 53 ft to 72 ft, for the SAF and WRC series, respectively. The variability of site index was large for all the habitat series, with the standard deviation ranging from 10 to 14 ft, again for the SAF and WRC series, respectively. There is clearly considerable overlap between habitat series, although the SAF series mean is significantly different than the other four series means according to most multiple comparison tests. Table 7 also summarizes the site index statistics of Cooper and others (in prep.), who used Monserud's curves to assess site productivity on their 210 northern Idaho plots that had suitable Douglas-fir site trees. The comparison of site index statistics from these two studies is extremely close. Generally, the statistics of Cooper and others were slightly larger than Monserud's, with very few differences greater than 10 percent. Such close correspondence between two independent studies with quite different objectives suggests that the statistics in table 7 are relatively unbiased regional estimates.

A final point concerns plot density. Monserud (1984) found no significant relations (past the 10 percent probability level) when site index was regressed on numerous measures of density (e.g., basal area per acre, trees per acre, crown competition factor). The differences in curve shape due to habitat series are not a result of habitat-specific density effects.

DISCUSSION

Sample Size Considerations.—Some error, of course, will be associated with any application of models [1] and [2], even if measurement error is ignored. This error arises from two sources: the variability among plots unaccounted for by the models, and the variability within plots (among trees) unaccounted for by the models. Monserud (1984) quantified these errors and produced precision curves that illustrate the relationship between expected standard error and both age and sample size (figs. 10 and 11).

One of the most important points shown in figures 10 and 11 is that the standard error of estimating either height growth or site index cannot be driven to zero by sampling more and more trees on a plot (unless they are all at index age 50). Even with an arbitrarily large sample size, the resulting estimates cannot be more precise than the underlying models, which contain unaccounted for among-plot error.

The difference between the minimum and maximum precision is rather small past age 100, whereas the greatest differences are in the vicinity of the index age. Thus the marginal value of sampling an additional site tree (i.e., reduction in standard error) is much greater for a tree near the index age than for an old-growth tree. For any given age, this marginal value is a decreasing function of sample size (e.g., measuring the fourth site tree on a plot always reduces the standard error by a smaller amount than measuring the third site tree did, and so on). Note that a sample of size 3 is about midway between the smallest ($n=1$) and largest ($n \rightarrow \infty$) standard errors possible, regardless of tree age.

Height growth (fig. 10) is most predictable (i.e., low standard error) at young ages and gets less predictable as age increases. Site index (fig. 11), on the other hand, is difficult to predict at young ages, but the curves of standard error versus age become relatively flat after age 100. Trees that are between 100 and 200 years old provide roughly equal amounts of information for predicting site index, for the associated standard error is mostly between 4 and 6 ft, regardless of sample size.

It is clear from figure 11 that site index is quite difficult to predict precisely at very young ages. Trees younger than 5 years (at breast height) provide very little information about site index, for all trees—regardless of site—begin their theoretical height growth curves at the same origin. Young trees make very poor phytometers, for they have had so little time to integrate the myriad of factors determining site productivity into an accurate index. As long as the trees on a plot are approximately 5 years old or less, simply using the mean site index (table 7) for the appropriate habitat series will give a more precise estimate of plot site index than model [2]. If the plot contains trees that are at least 10 years old, these habitat series means can always be improved upon by using the site index model [2]. A further comparison of table 7 and figure 11 reveals that measuring (without error) only one site tree older than age 25 will produce a

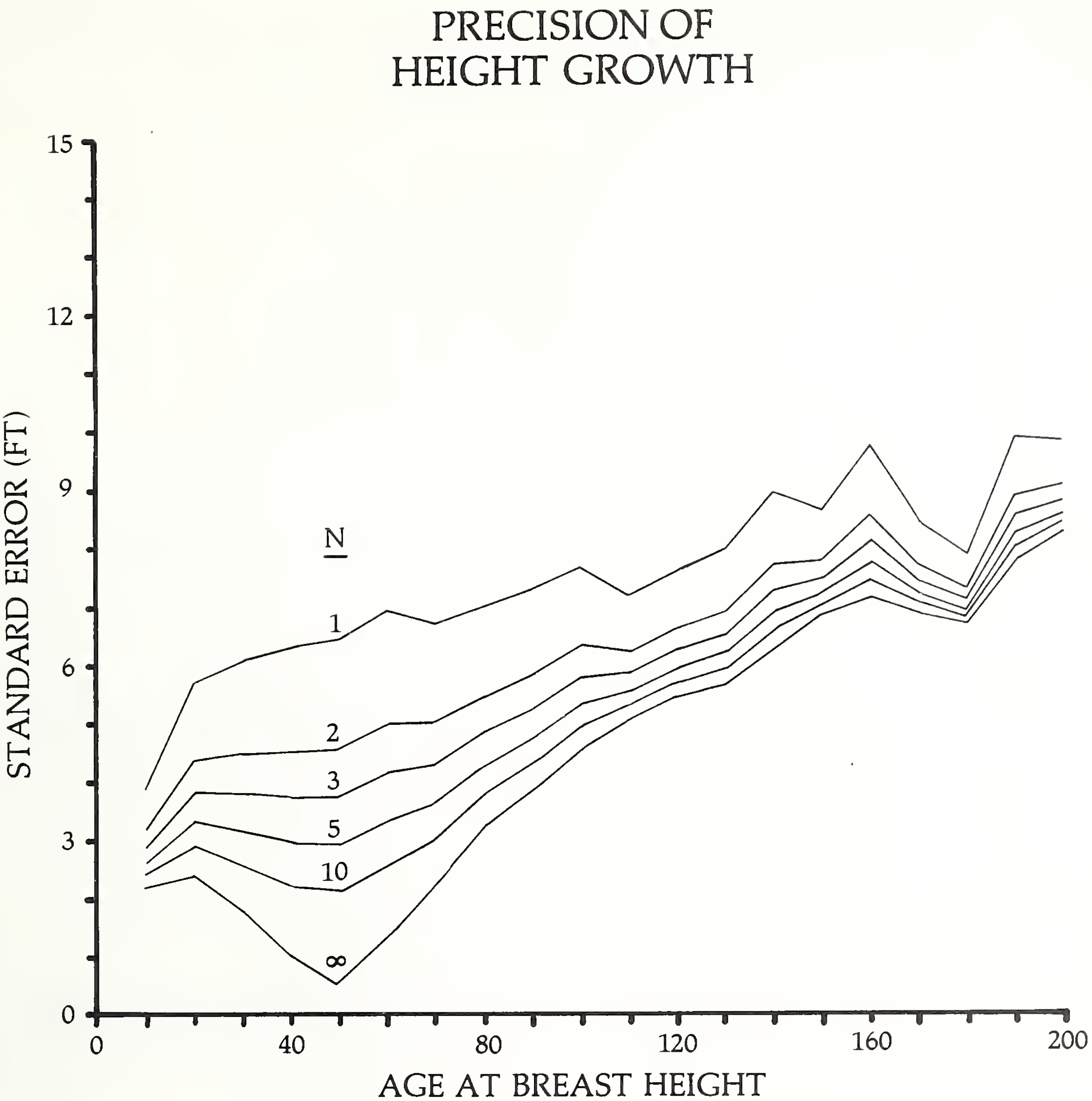


Figure 10.—Precision curves for estimating the expected standard error of applying height growth model [1], by both age and sample size (N).

more precise estimate of site index than using the habitat series mean. There is a danger, however, in measuring only one site tree per stand, for in hunting for this best tree the forester may unwittingly be searching out a microsite that is not representative of the growing conditions in the stand. For this reason at least two site trees per plot should be measured.

Note the variability with respect to age in the sample size required to predict site index to a fixed or constant level of precision. If a standard error of 7 ft is desired, then figure 11 indicates that sampling only one site tree between ages 45 and 200 will meet this goal and will provide the same amount of site index information as two 30-year-old site trees, or four 20-year-old site trees; furthermore, not even an infinite number of 10-year-old (or younger) trees will provide enough information for the site index prediction from model [2] to have a standard error of 7 ft or less. And if the desired precision is 2 ft, then the only trees that contain sufficient site index information are between 35 and 70 years old (and at least 10 of those per plot must be measured). An alternative (albeit, expensive) does nevertheless exist for estimating site index more precisely than model [2] allows: stem analysis, provided the site trees are close to or older than the index age of 50.

And a final note: the user should, of course, regard the curves of standard error in figures 10 and 11 as estimates. Clearly the dip in standard error at age 180 is a result of sampling variability in the original study, for there certainly is no biological reason why height growth or site index should be noticeably more predictable at age 180 than it is at age 160 and age 190.

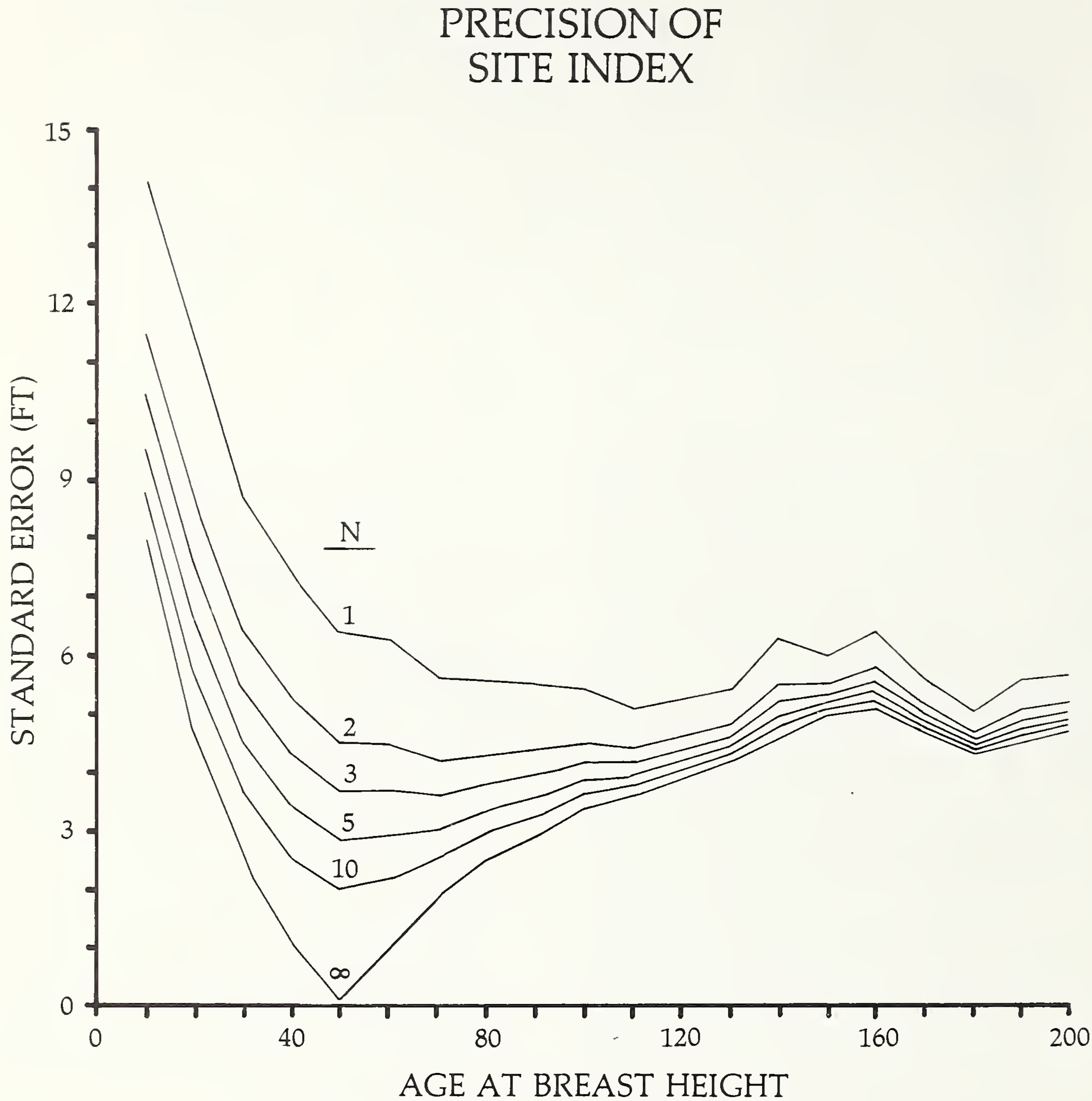


Figure 11.—Precision curves for estimating the expected standard error of applying site index model [2], by both age and sample size (N).

Directions for Field Use.—

1. Using figure 11, determine the number of site trees (N) necessary to meet the predetermined precision requirements.
2. Because site trees should (by definition) be chosen at the rate of three per one-half acre, the corresponding plot size is N/6 acres. For example, if N from step 1 is six trees then plot size is 1 acre; if N is two trees then plot size is one-third acre.
3. Select an N/6-acre plot that is representative of the growing conditions of the stand; clearly the plot must contain dominant Douglas-fir for these methods to be applicable.
4. Identify the habitat type.
5. Identify the potential site trees: they are the dominant Douglas-fir with no observable top damage and with healthy appearing crowns.
6. Obtain and examine complete increment cores (at breast height on the uphill side of the tree) for each potential site tree. Reject all trees with cores that show signs of suppression (or damage), release, or irregular growth histories. Count the rings at breast height for each of the remaining trees. These trees should all have regular radial growth histories that would be expected for trees that have always been either dominant or free to grow to the site's potential.
7. Select the N best-growing site trees from the remaining list. If the list of potential site trees at this point contains fewer than N trees, the user must then decide either to proceed with the reduced list or to begin again with a new plot.
8. Measure total height for each site tree and count rings at breast height (4.5 ft) if age has not already been determined.

9. Estimate a site index for each site tree, using any of three methods: equation [2]; tables 2, 4, or 6; figures 3, 5, or 7. Remember to add 4.5 ft to the estimate of S if equation [2] is used, and remember to use the correct habitat series model.

10. Plot site index is the average of these N estimates.

11. Dominant height growth at a desired age can then be estimated using this site index estimate and equation [1] or the appropriate tables (1, 3, or 5) or graphs (figs. 2, 4, or 6).

Given that the number of site trees (N) has been determined to meet stated precision requirements, then the average of these N site index estimates will be biased if the plot area remains fixed (e.g., average SI must decrease as N increases on a fixed-area plot). This bias can be removed only by increasing plot size proportional to N; the factor of proportionality is 1/6 because Monserud (1984) sampled at the rate of three trees per one-half acre. This results in sampling the population at the same rate or intensity, regardless of sample size. Thus you need to search for site trees over larger areas to increase the precision of the resulting site index estimate.

The selection of the "best" site trees in step 7 is somewhat subjective, more subjective than determining the largest or tallest site trees. But because dominant Douglas-fir commonly occur in uneven-aged stands in the Northern Rocky Mountains, the tallest or largest trees may possibly underestimate the site potential if they are released remnants from a previous stand. The user nevertheless has a more objective alternative to the selection of site trees in step 7, one that was not available to Monserud (1984): measure total height and breast high age for **all** potential site trees, and average the N largest site index estimates. This procedure requires measuring height and age of more potential site trees, but it is less subjective. Note that vigorous codominants could safely be included as potential site trees with this alternate selection procedure without risking the underestimation of site index. The rejection of trees with irregular radial growth (in step 6) should always be carried out, however.

Potential Problems.—One of the most common problems with successfully applying this or any site index system is the failure to select suitable site trees. Trees suspected of having suffered suppression, defoliation, or top damage should not be used as site trees, for the user runs the risk of underestimating site index. Such trees are often not easily identified decades after the damage or growth reduction has occurred, however, because forest trees have a remarkable ability to maintain their form. Monserud was forced to reject roughly one potential site tree in six based on evidence that was apparent only after stem analysis was completed. The ability of inland Douglas-fir to occasionally survive and grow well after being suppressed or seriously damaged will certainly be a factor that will complicate the selection of suitable site trees. It will be imperative that complete increment cores be extracted and examined for all potential site trees before determining the best site trees on a given plot; trees with increment cores indicating irregular growth, suppression (or damage), or later release should not be used as site trees.

Even though Monserud's (1984) selection requirements are far more liberal than most, there will still be candidate stands that do not contain suitable site trees. This will primarily be a problem in areas that have been host to severe or chronic outbreaks from defoliators such as Douglas-fir tussock moth (*Orgyia pseudotsugata* McDunnough) or western spruce budworm (*Choristoneura occidentalis* Freeman). Although it can rightly be argued that such indigenous pests are as important a determinant of the potential height growth on a site as are moisture and nutrient availability, defoliated trees were nevertheless avoided in Monserud's sample.

The second potential problem is extrapolating past the range of conditions represented in the underlying sample. Monserud's sample was chosen to try to minimize this problem. Well represented were both even- and uneven-aged stands, both pure and mixed species stands, and both young growth and old growth. In addition, all five major habitat series that contain Douglas-fir were adequately sampled. Nevertheless, there are some conditions that were not sampled, conditions that could result in an extrapolation of models [1] and [2]. Monserud sampled no stands with mountain hemlock (*T. mertensiana*) as the climax overstory species, sampled only two stands drier than Douglas-fir/ninebark (*P. menziesii/ Physocarpus malvaceus*), and sampled only five stands colder and harsher than subalpine fir/clintonia (*A. lasiocarpa/Clintonia uniflora*). If Monserud's curves are used for Douglas-fir habitats drier than ninebark, or for subalpine fir habitats harsher than clintonia, then it is possible that height growth will be overestimated (and the corresponding site index therefore underestimated), especially in old-growth stands. This possible bias is expected to be small because the height growth differences between habitat types are quite small when site index is low—as it is likely to be on such dry or harsh habitat types (figs. 8 and 9). A recent study by Kelsey Milner (1984) in western Montana indicates that such a reduction in height growth might indeed be the case on harsh or dry habitats; Milner found that this bias was significant but very small—less than 3 ft for all age classes.

Some users will find site trees that are older than Monserud's maximum for a given site index. For example, Monserud found only one old-growth stand near the upper extreme of site index (recall that the range in ages sampled is delineated by site index and habitat series in tables 1 through 6). The greatest possibility for bias due to extrapolation is in this high site/advanced age region, so users should be cautious of predictions made by models [1] and [2] for such conditions.

Extrapolation can also occur if the curves are used outside Monserud's geographic study area (fig. 1). Monserud's (1985) comparison with other Douglas-fir site index curves from the Northwest addresses this source of bias. Monserud (1985) found that the differences in the shape of the height growth curves increased with increasing distance between regions (which were both east and west of his study area). Height growth differences were extremely small between the Northern Rockies and the east side of the Cascades and were rather large between the Northern Rockies and the west side of the Cascades. The relatively small differences between the Northern Rockies and the Cascade crest fell between these two extremes. Within the Northern Rockies, very small differences were found between Montana and northern Idaho. Inland Douglas-fir has an enormous range, which extends almost the complete length of the Rocky Mountain chain, from Mexico through Canada. Little is known of the magnitude of the differences in Douglas-fir height growth between the Northern Rockies and the rest of the Rockies, so users should be cautious of applying these curves outside northern Idaho and northwestern Montana. Considering the variability in curve shape due to habitat type within this study area (figs. 8 and 9), there can be little doubt that the shape of the site index and height growth curves will change in other regions of Douglas-fir's range.

REFERENCES

Cochran, P. H. Site index and height growth curves for managed, even aged stands of Douglas-fir east of the Cascades in Oregon and Washington. Research Paper PNW-251. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; 1979. 16 p.

Cooper, S. V.; Neiman, K.; Steele, R. Forest habitat types of northern Idaho. Missoula, MT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station, Forestry Sciences Laboratory; [in preparation; review draft dated May 1983]. 210 p.

Curtis, R. O. A stem analysis approach to site index curves. For. Sci. 10: 241-256; 1964.

Curtis, R. O.; DeMars, D. J.; Herman, R. F. Which dependent variable in site index-height-age regressions? For. Sci. 20: 74-87; 1974.

Daubenmire, R.; Daubenmire, J. B. Forest vegetation of eastern Washington and northern Idaho. Tech. Bull. 60. Pullman, WA: Washington Agricultural Experiment Station; 1968. 104 p.

Draper, N. R.; Smith, H. Applied regression analysis. 2d ed. New York: John Wiley and Sons; 1981. 709 p.

Milner, K. Personal communication (12/18/84) and paper presented (1/23/85) at annual meeting, Inland Empire Growth and Yield Cooperative, Spokane, WA; 1984. [Further discussion can be found in Monserud (1985).]

Monserud, R. A. Height growth and site index curves for inland Douglas-fir based on stem analysis data and forest habitat type. For. Sci. 30: 943-965; 1984.

Monserud, R. A. Comparison of Douglas-fir site index and height growth curves in the Northwest. Can. J. For. Res. 15(4); 1985. [In press; accepted for publication 3/18/85.]

Pfister, R. D.; Arno, S. F. Classifying forest habitat types based on potential climax vegetation. For. Sci. 26: 52-70; 1980.

Pfister, R. D.; Kovalchik, B. L.; Arno, S. F.; Presby, R. C. Forest habitat types of Montana. General Technical Report INT-34. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1977. 174 p.

Steele, R.; Arno, S. F.; Pfister, R. D. Preliminary guide to habitat types on the Nezperce National Forest. Boise, ID: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1976. 71 p. Mimeographed.

Monserud, Robert A. Applying height growth and site index curves for inland Douglas-fir. Research Paper INT-347. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station; 1985. 22 p.

Methods for estimating both site index and dominant height growth for inland Douglas-fir in the Northern Rocky Mountains are presented and discussed. Results are summarized in the form of equations, tables, and graphs.

KEYWORDS: *Pseudotsuga menziesii*, site productivity, precision, stem analysis, habitat type, Northern Rocky Mountains

☆U.S. GOVERNMENT PRINTING OFFICE:1985—576-040 / 20007