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Site Index Equations and Mean Annual Increment Equations for Pacific Northwest Research Station Forest Inventory and Analysis Inventories, 1985-2001

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Abstract

Site index equations and mean annual increment equations used by the Forest Inventory and Analysis Program at the Portland Forestry Sciences Laboratory, Pacific Northwest Research Station, Forest Service, U.S. Department of Agriculture. The equations are for 24 tree species in California, Oregon, and Washington.

Keywords: Site index equations, mean annual increment equations.

Introduction

The Forest Inventory and Analysis Program (FIA), a program within the Pacific Northwest Research Station (PNW), USDA Forest Service, is mandated to inventory, assess, and report on several forest characteristics, traditionally timberland area and volume, on all forested lands in the United States (public and private).This document presents the site index equations and mean annual increment equations used for tree species within the PNW-FIA forest inventory area of California, Oregon, and Washington in order to document the past and present inventories.

The PNW-FIA used equations from many documents to obtain a site index value and mean annual increment for every forested inventory plot. This set of equations has been used since the 1980s inventories; equations used before then are no longer used. Specifically, this set was used for periodic inventories in Oregon (1985, 1995, and 1998), Washington (1988, 1990, and 2000), and California (1991).

Site Index

What Is Site Index?

Site index is a measure of a forest's potential productivity. Site index is usually defined as the height of the dominant or codominant trees at a specified age in a stand. It is calculated in an equation that uses the tree's height and age. Site index equations differ by tree species and region.

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Forest mensurationists develop site index equations through fieldwork and analysis of data. First, they establish research plots in stands of a particular tree species covering a range of site conditions. They select representative dominant or codominant trees and measure their heights, ages, and diameters. Site index curves are constructed by using the tree heights at a base age, typically 50 or 100 years in the West, usually for trees in even-aged stands. An equation is derived from the curves to estimate the site index when an individual tree's age is not the same as the base age. Site index equations are developed either by following a stand through time (King 1966) or comparing several stands of different ages at a single point in time (McArdle and others 1961).

Using Site Index

Site index can help predict timber productivity, wood volume, and potential rate of growth of a forest. Forest managers use the site index to evaluate the quality of their land.

For PNW-FIA, the site index was used primarily as input to the mean annual increment (MAI) equations, which in turn were used to develop the site classes: six classes of volume growth per acre at culmination in fully stocked natural stands. The area was reported by site class in a table, "Area of timberland, by cubic-foot site class and owner class," in resource bulletins for each inventory (see Waddell and Bassett 1997 for an example). Another use was to separate "timberland" plots from "other forest-low productivity" plots (formerly called "noncommercial unproductive forest land"), based on whether the site can produce 20 cubic feet • acre^{-1} • year^{-1}. The PNW-FIA also used the site index to calculate annual squared diameter growth if the previous diameter was unavailable (to obtain annual volume growth), and to calculate projected and estimated tree heights (to obtain missing growth components). Other researchers used the PNW-FIA site index of plots for growth predictions.

Miscellaneous Notes on PNW-FIA Site Indexes

Some equations may have limitations owing to the method used to construct the site index curve or equation. Discussion of the different methods, and a summary of the modeling approach and number of trees sampled in most of these cited sources, can be found in Hann (1995).

Mixed conifer—Large areas of California forests had no main softwood tree species as the forest type, but instead were classified as mixed conifer. The PNW-FIA defined a mixed-conifer site as one within a certain region and capable of greater than 70 percent conifer stocking, and that had certain tree species predominating. In general, these plots had some mix of ponderosa pine, Jeffrey pine, sugar pine, Douglas-fir, red fir, Shasta red fir, incense cedar, and white fir (see app. 1 "Names of Trees" for scientific names). Mixed-conifer types grow on the east-facing slopes of the Coast Range, on the west-facing and higher elevation east-facing slopes of the Cascade Range and Sierra Nevada, and can extend into southern California.

Black cottonwood—No site index equation was available for black cottonwood, so a site index value for use in MAI equations and stocking values was developed in-house by using data from plots in cottonwood stands.

McArdle's and King's site index equations—In 1930, Richard E. McArdle and Walter H. Meyer published the first set of site index curves for Douglas-fir in the Pacific Northwest (McArdle and others 1961). In 1966, James E. King published a new set to account for changes since then: shorter rotations, younger trees, and improved methods of constructing curves (King 1966). In the coastal Douglas-fir region, PNW-FIA preferred the King site index equation for Douglas-fir. However, King's method required at least 25 mainstand trees within an area not larger than a 130-foot-diameter circle. If that amount of stocking was not present on or near the plot, the field crew used the McArdle site index equation and selection method.

- McArdle selection method for PNW-FIA: Select three dominant, suppression-free trees that were greater than 50 years old.
- King selection method for PNW-FIA: If the stand was over 30 years old, locate an area no greater than a 130-foot-diameter circle that contains 25 mainstand trees, not younger or shorter than the general canopy. From the 25 trees, select the 5 with the greatest diameter at breast height. If the stand is aged 15 to 30 years old, select the 10 with the largest diameter out of 50 trees. King's is only used in stands less than 130 years old and below 3,000 feet in elevation.

Dunning's site index conversion—The PNW-FIA used Dunning's site index for mixed-conifer plots in California. Other site index values used by PNW-FIA needed to be converted to Dunning's site index so they could be used as a variable in the plant stockability factor equations (see MAI section below). The following conversion equations were used if the site index taken for the plot was not Dunning's:

Site index equations	Conversion equations
1 (King) and 5 (Wiley)	$DSI = 3.07 \times (SI^{0.9})$
4 (Herman) and 8 (Barrett)	$DSI = 1.54 \times (SI^{0.98})$
7 (Krumland), 16 (M.C.), and 17 (Schumacher)	$DSI = 4.74 \times (SI^{0.82})$
9 (Dahms)	$DSI = 1.75 \times (SI^{0.96})$

where: DSI = Dunning's site index, and
SI = site index in feet.

Equations from other regions—Some equations were developed outside of the PNW-FIA region, such as site index equation no. 6 for Engelmann spruce in the northern and central Rocky Mountains (Brickell 1966). Because no similar site equation existed for Oregon or Washington, it was used for Engelmann spruce in this region.

PNW-FIA Site Tree Selection Procedures

Site trees were selected and measured on every forest land plot (10 percent or more stocked by trees), and when possible on "western woodland types" forest (5 percent or more stocked by juniper or other nontimber species). Since 1991, PNW-FIA mapped and collected plot data based on the "condition class" encountered on the plots. Although this sometimes resulted in more than one forested condition class on a single plot, site trees were collected across the plot, and only one site index was assigned to the plot. It was not believed that site varied over the area of the plot.

Table 1—Site index equation assignments

Site index equation group number	Species	Area
1	Douglas-fir	WOR except Jackson and Josephine Counties
1	Douglas-fir	WWA except in silver fir zone
1	Douglas-fir	CA except in mixed conifer
1	Grand fir	WOR except Jackson and Josephine Counties
1	Grand fir	WWA, CA
1	Western white pine	WWA
1	White fir	WOR except Jackson and Josephine Counties
2	Douglas-fir	Jackson and Josephine Counties in WOR
3	Grand fir	Jackson and Josephine Counties in WOR
3	White fir	Jackson and Josephine Counties in WOR
4	White fir	CA
4	Noble fir	All WOR, EOR, EWA, WWA, CA
4	Shasta red fir	All WOR, EOR
4	Pacific silver fir	All WOR, EOR, EWA, WWA, CA
4	Subalpine fir	All WOR, EOR, EWA, WWA, CA
4	Mountain hemlock	All WOR, EOR, EWA, WWA, CA
5	Western hemlock	All WOR, EOR, EWA, WWA, CA
5	Sitka spruce	All WOR, WWA, CA
6	Engelmann spruce	All WOR, EOR, EWA, WWA
7	Redwood	All WOR, CA
8	Ponderosa pine	All WOR, EOR, EWA, WWA, CA
8	Jeffrey pine	All WOR, EOR, EWA, CA
8	Coulter pine	CA
8	Bishop pine	CA
9	Lodgepole pine	All WOR, EOR, EWA, WWA, CA
9	Western white pine	All WOR, EOR, CA
10	Western red cedar	All WOR, EWA, WWA ,CA
11	Black cottonwood	All WOR, EOR, EWA, WWA, CA
11	Fremont poplar	All WOR, EOR, EWA, WWA, CA
12	Western larch	All WOR, EOR
13	Red alder	All WOR, EOR, EWA, WWA, CA
13	Other hardwoods	All WOR, EOR, EWA, WWA, CA
14	Douglas-fir	WWA in silver fir zone
14	Douglas-fir	EOR and EWA
14	Grand fir	EOR and EWA
14	White fir	EOR and EWA
15	Western larch	WWA and EWA
15	Western white pine	EWA
16	Mixed conifer	CA
17	Red fir, Shasta red fir	CA

WOR = western Oregon.
WWA = western Washington.
EOR = eastern Oregon.
EWA = eastern Washington.

On new plots, as of 2001, data from at least 3, and sometimes 5 or 10, site trees were collected, depending on the size of the trees and the selection method used.[2] On western woodland types, data from at least one were collected (if the species was juniper). When a crew revisited a plot, they measured one new site tree, and sometimes remeasured the previous site trees if they were in the lower age range, and a new site index was calculated for the plot.

A good site tree was a tree that was classified as a dominant within the stand (unless King's was used, which took the five with largest diameter), had never been suppressed, and had a normally formed top. The species should represent the forest within the sampled condition, with the preferred site species in western Oregon, western Washington, and northwestern California being Douglas-fir. Trees aged 50 years and older (King's method: 30 years) were desirable, but it was not always possible to obtain them, and younger trees could be measured. In California, the species and site equation also were determined by whether the plot was in the mixed-conifer type, which depended on the county, elevation, and percentage of conifer stocking of the stand.

Site Index Equations

Table 1 shows which site index equations were used for species and area.

For all equations:

H = height in feet,
EXP = natural exponent, and
Ln = natural log.

1. Douglas-fir and grand fir in western Oregon except for Jackson and Josephine Counties. Douglas-fir and grand fir in western Washington except in silver fir zone. Western white pine in western Washington. Douglas-fir (except in mixed-conifer stands) and grand fir in California (King 1966).

a. If King's selection method was used to select site trees (only Douglas-fir and grand

$$SI_k = \left[\frac{2500}{\left\{ \frac{\left[\frac{A^2}{(H-4.5) + 0.954038 - 0.0558178A + 0.000733819A^2} \right]}{0.109757 + 0.00792236A + 0.000197693A^2} \right\}} \right] + 4.5,$$

fir could be used), use:

where

SI_k = King's site index in feet for breast height age 50 years, and
A = breast-height age.

[2] Field instructions for the annual inventory of Oregon and California, 2001. Version 1.5. 342 p. On file with: USDA Forest Service, Pacific Northwest Research Station, Forest Inventory and Analysis Program, Forestry Sciences Laboratory, P.O. Box 3890, Portland, OR 97208-3890.

b. For Douglas-fir and grand fir, if King's selection method was **not** used **and** trees were < 40 years old, use the following to obtain McArdle's site index (equation derived from McArdle and others 1961). This equation also was used for western white pine in western Washington when age < 40 years.

$$SI_M = [EXP\ \{3.3 - [0.8Ln\ (A)]\}]\ (0.96H - 2.66)\ ,$$

where

SI_M = McArdle's site index in feet for breast-height age 50 years, and
A = breast-height age.

c. For Douglas-fir and grand fir, if King's selection method was **not** used **and** trees were ≥ 40 years old, use the following to obtain McArdle's site index (equation derived from McArdle and others 1961). This equation also was used for western white pine in western Washington when age ≥ 40 years.

$$SI_M = [EXP\ \{2.1 - [0.47Ln\ (A)]\}]\ (0.96H - 2.66)\ ,$$

where

SI_M = McArdle's site index in feet for breast-height age 50 years, and
A = breast-height age,

McArdle's site index was converted to King's site index by the equation from King (1966):

$$SI_K = 21.5 - 0.18127(A + 8) + 0.72114\ SI_M\ ,$$

where

A = breast-height age,
SI_K = King's site index, and
SI_M = McArdle's site index.

2. Douglas-fir in Jackson and Josephine Counties, Oregon (Cochran 1979b).

$$SI = 84.47 - AB + B(H - 4.5)\ ,$$

where

A = $EXP\ \{ -0.37496 + 1.36164Ln\ (a) - 0.00243434\ [Ln\ (a)]^4\}$,
B = $0.52032 - 0.0013194\ a + \frac{27.2823}{a}$,
SI = site index in feet for breast-height age 50 years, and
a = breast-height age.

3. White fir and grand fir in Jackson and Josephine Counties, Oregon (Cochran 1979c).

$$SI = (H - 4.5)\ EXP(X1) - EXP(X1 + X2) + 89.43\ ,$$

where

$X1$ = $3.8886 - 1.8017\ Ln(A) + 0.2105\ [Ln(A)]^2 - 0.0000002885\ [Ln(A)]^9 + 0.000000000000000001187\ [Ln(A)]^{24}$,

$X2$ = $-0.30935 + 1.2383\ Ln(A) + 0.001762\ [\mathrm{Ln}(A)]^4 - 0.0000054\ [Ln(A)]^9 + 0.0000002046\ [Ln(A)]^{11} - 0.000000000000404\ [Ln(A)]^{18}$,

SI = site index in feet for breast-height age 50 years, and
A = breast-height age,

4. Noble fir, Shasta red fir in Oregon, subalpine fir, white fir, Pacific silver fir, and mountain hemlock (Herman and others 1978).

Note: For California, when white fir was found in mixed-conifer stands, the mixed-conifer site index equation was used.

a. For site trees 100 years or less:

$$SI = [4.5 + 0.2145\ (100 - A) + 0.0089\ (100 - A)^2] + \left[\frac{1.0 + 0.00386\ (100 - A) + 1.2518\ (100 - A)^5}{10^{10}}\right] (H - 4.5)\ ,$$

where

SI = site index in feet for breast-height age 100 years, and
A = breast-height age.

b. For site trees > 100 years:

$$SI = \left[-62.755 + 672.55\left(\frac{1}{A}\right)^{0.5}\right] + \left[0.9484 + 516.49\left(\frac{1}{A}\right)^2\right](H - 4.5) + \left[-0.00144 + 0.1442\left(\frac{1}{A}\right)\right](H - 4.5)^2 ,$$

where

SI = site index in feet for breast-height age of 100 years, and
A = breast-height age.

5. Western hemlock and Sitka spruce (Wiley 1978).

a. For trees ≤ 120 years in age:

$$SI = 2500 \left\{ \frac{[(H - 4.5)(0.1394 + 0.0137A + 0.00007A^2)]}{[A^2 - (H - 4.5)(-1.7307 - 0.0616A + 0.00192A^2)]} \right\} + 4.5 ,$$

where

SI = site index in feet for breast-height age 50 years, and
A = breast-height age.

b. For trees > 120 years old, we used the 50-year index equation derived from Barnes (1962):

$$SI = 4.5 + 22.6EXP\,\{[0.014482 - 0.001162Ln\,(A)]\,(H - 4.5)\} ,$$

where

SI = site index in feet for breast-height age 50 years, and
A = breast-height age.

6. Engelmann spruce (Brickell 1966).

$$\begin{aligned} SI = H &+ 10.717283\,[Ln\,(A) - Ln\,(50)] \\ &+ 0.0046314777\left(\frac{10^{10}}{A^5} - 32\right) \\ &+ 0.74471147H\left(\frac{10^4}{A^2} - 4\right) \\ &- 26413.763H\,(A^{-2.5} - 50^{-2.5}) \\ &- 0.042819823H\,[Ln\,(A) - Ln\,(50)]^2 \\ &- 0.0047812062H^2\left(\frac{10^4}{A^2} - 4\right) \\ &+ 0.0000049254336H^2\left(\frac{10^{10}}{A^5} - 32\right) \\ &+ 0.00000021975906H^3\left(\frac{10^{10}}{A^5} - 32\right) \\ &+ 5.1675949H^3\,(A^{-2.75} - 50^{-2.75}) \\ &- 0.000000014349139H^4\left(\frac{100}{A} - 2\right) \\ &- 9.481014H^4\,(A^{-4.5} - 50^{-4.5}) , \end{aligned}$$

where

SI = site index in feet for total age 50 years, and
A = total age.

7. Redwood (table 2 is modified from Krumland and Wensel 1977).

Table 2—Average total height of dominant redwood sprouts by breast-height age and site index

Breast height age	Redwood site index											
	50	60	70	80	90	100	110	120	130	140	150	160
	Feet											
10	17	19	22	24	26	28	30	32	34	36	39	42
15	22	26	29	33	37	40	44	48	52	56	60	64
20	27	32	37	41	46	51	56	61	67	72	78	83
25	31	37	43	49	55	61	67	74	80	86	93	100
30	35	42	49	56	63	70	77	85	92	99	107	114
35	39	47	55	63	71	78	86	95	103	111	119	127
40	43	52	60	69	77	86	95	104	113	121	130	139
45	47	56	65	75	84	93	103	112	122	131	141	150
50	50	60	70	80	90	100	110	120	130	140	150	160
55	53	64	75	85	96	106	117	127	138	148	159	169
60	56	68	79	90	101	112	123	134	145	156	167	178
65	59	71	83	94	106	118	129	140	152	163	174	185
70	62	74	87	99	111	123	135	146	158	170	181	193
75	65	78	90	103	115	128	140	152	164	176	188	199
80	67	81	94	107	120	132	145	157	169	182	194	206
85	70	84	97	110	124	136	149	162	175	187	199	211
90	72	86	100	114	127	141	154	167	179	192	205	217
95	75	89	103	117	131	144	158	171	184	197	209	222
100	77	92	106	120	134	148	162	175	188	201	214	227
105	79	94	109	123	138	152	165	179	192	205	218	231
110	81	96	111	126	141	155	169	182	196	209	222	235
115	83	99	114	129	143	158	172	186	199	213	226	239
120	85	101	116	131	146	161	175	189	203	216	230	243
125	87	103	119	134	149	164	178	192	206	219	233	246
130	88	105	121	136	151	166	181	195	209	223	236	249
135	90	107	123	138	154	169	183	198	212	225	239	252
140	92	109	125	141	156	171	186	200	214	228	242	255
145	93	110	127	143	158	173	188	202	217	231	244	258
150	95	112	128	145	160	175	190	205	219	233	247	260
155	96	114	130	146	162	177	192	207	221	235	249	262
160	98	115	132	148	164	179	194	209	223	237	251	264
165	99	117	133	150	166	181	196	211	225	239	253	266
170	100	118	135	151	167	183	198	213	227	241	255	268
175	102	119	136	153	169	184	200	214	229	243	257	270
180	103	121	138	154	170	186	201	216	230	244	258	272
185	104	122	139	156	172	188	203	217	232	246	260	273
190	105	123	140	157	173	189	204	219	233	247	261	275
195	106	124	142	158	175	190	205	220	235	249	263	276
200	107	125	143	160	176	192	207	222	236	250	264	277

8. Ponderosa pine, Jeffrey pine, Coulter pine, and Bishop pine.
Note: For California, when these species were in mixed-conifer stands, we used the mixed-conifer equation.

a. For site trees < 130 years old breast-height age, site index was calculated from Barrett (1978).

$$SI = 100.43 - \left[1.198632 - 0.00283073A + \frac{8.44441}{A}\right] \{128.8952205 \left[1 - EXP\,(-\,0.016959A)\right]^{1.23114}\}$$

$$+ \left[\left(1.198632 - 0.00283073A + \frac{8.44441}{A}\right)(H - 4.5)\right] + 4.5\ ,$$

where

SI	=	site index in feet for breast-height age 100 years, and
A	=	breast-height age.

b. For ponderosa pine over 130 years old, we used the equation below, which approximates the site curves in Meyer (1961).

$$SI = [(5.328A^{-0.1} - 2.378)\,(H - 4.5)] + 4.5\ ,$$

where

SI	=	site index in feet at breast-height age 100 years, and
A	=	breast-height age.

9. Lodgepole pine in western Oregon, eastern Oregon, western Washington, eastern Washington, and California; and western white pine in western Oregon and California (Dahms 1975).

Site index was approximated from the equation:

$$SI = (72.68 - 8.8A^{0.45}) + 4.5 + \{2.2614 - 1.26489\,[1 - EXP\,(-\,0.08333A)]^{5}\}\,(H - 4.5)\ ,$$

where

SI	=	site index in feet at breast-height age 100 years, and
A	=	breast-height age.

10. Western red cedar (Kurucz 1987).

Although western red cedar was rarely chosen for a site tree, if it was chosen, we used the following equations adapted from Mitchell and Polsson (1987):

a. If age ≤ 50 years, then:

$$SI = \left(\frac{2500}{0.3048}\right)\left\{\frac{[(H - 1.3)\,(0.05027 + 0.01411A + 0.000097667A^2)]}{[A^2 - (H - 1.3)\,(-\,3.11785 - 0.02465A + 0.00174A^2)]}\right\} + 4.5\,,$$

where

SI = site index in feet for breast-height age 50 years, and
A = breast-height age.

b. If age > 50 years, then substitute H_a for variable H in the site index equation above.

$$H_a = H + 0.02379545H - 0.000475909AH\,,$$

where

A = breast-height age.

11. Black cottonwood, Fremont poplar.[3]

Site index = 92.0

12. Western larch in western Oregon and eastern Oregon (Cochran 1985).

$$\begin{aligned} SI = 78.07 &\\ &+ [(H - 4.5)\\ &\times (3.51412 - 0.125483A + 0.0023559A^2 - 0.00002028A^3 + 0.000000064782A^4)]\\ &- [(3.51412 - 0.125483A + 0.0023559A^2 - 0.00002028A^3 + 0.000000064782A^4)\\ &\times (1.46897A + 0.0092466A^2 - 0.00023957A^3 + 0.0000011122A^4)]\,, \end{aligned}$$

where

SI = site index in feet for breast-height age 50 years, and
A = breast-height age.

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[3] Bolsinger, C. 1974. Cottonwood MAI and stocking percent, California 1970-72 inventory units. Unpublished report. 6 p. On file with: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Forestry Sciences Laboratory, P.O. Box 3890, Portland, OR 97208-3890.

13. Red alder (and other hardwoods if needed except for black cottonwood) in western Oregon, eastern Oregon, western Washington, eastern Washington, and California (Worthington and others 1960).

$$SI = \left(0.60924 + \frac{19.538}{A}\right) H \ ,$$

where

SI = site index in feet for breast-height age 50 years, and
A = breast-height age.

14. Douglas-fir, grand fir, and white fir in eastern Oregon and eastern Washington. Douglas-fir in silver fir zone in western Washington (Curtis and others 1974). Silver fir zone had a plant association where the first two characters were CF or CM and the elevation was over 1000 meters.

a. Breast-height age 100 years or less:

$$SI = 4.5 + a + [b\ (H - 4.5)] \ ,$$

where

a = $0.010006\ (100 - A)^2$,
b = $1.0 + [0.00549779\ (100 - A)] + (1.46842 \times 10^{-14})\ (100 - A)^7$,
SI = site index in feet for breast-height age 100 years, and
A = breast-height age.

b. Breast-height age greater than 100 years:

$$SI = 4.5 + a + [b\ (H - 4.5)] \ ,$$

where

a = $7.66772 \left[EXP - 0.95 \left(\frac{100}{A-100}\right)^2\right]$,
b = $1.0 - [0.730948\ (LOG_{10} A - 2.0)^{0.8}]$,
SI = site index in feet for breast-height age 100,
A = breast-height age, and
LOG_{10} = logarithm to the base 10.

15. Western larch in western Washington and eastern Washington; and western white pine in eastern Washington (Brickell 1970).

These equations replaced Cochran (1985) equations for the same areas and species beginning in 1990.

$$SI = 0.37956H\ EXP\left(\frac{48.4372}{A + 8}\right),$$

where

SI	=	site index in feet for breast-height age 50 years, and
A	=	breast-height age.

16. Mixed conifer in California for all stands coded as mixed conifer. Note that as originally developed and published, this equation used a base age of 50 years, total age, and total height. The equations below were modified to accept breast-height age, the variable that our inventories normally measured.

Site species that could be used include: Douglas-fir, bigcone Douglas-fir, white fir, ponderosa pine, Jeffrey pine, Shasta red fir, red fir, and Coulter pine.

Site index equation derived from Dunning and Reineke (1933).

$$SI = H\left(0.25489 + \frac{29.377}{A}\right),$$

where

SI	=	site index in feet for breast-height age 100 years, and
A	=	breast-height age.

17. Red fir, Shasta red fir in California (Schumacher 1928).

Note that as originally developed and published, this equation used a base age of 50 years, total age, and total height. The equations below were modified to accept breast-height age, the variable that our inventories normally measured.

Note: For California, when Shasta red fir and red fir were in mixed-conifer stands, the mixed-conifer site index equation was used.

Site index approximated by equation derived from Schumacher (1928):

$$SI = H\ (0.1464 + 43.3273A^{-1.1}),$$

where

SI	=	site index in feet for breast-height age 50 years, and
A	=	breast-height age.

Mean Annual Increment

Foresters use MAI to describe the wood-growing capacity of a site, expressed by PNW-FIA as the average increase in cubic-foot volume per acre per year. As we used the term, it was defined as the increment (increase in volume) of a timber stand averaged over the period between age zero and the age at which MAI culminates, i.e., reaches its maximum value.

Mean annual increment equations, also called yield equations, were derived by PNW-FIA from yield data found in published normal yield tables. These normal yield studies were done for a particular species by taking tree measurements (diameter, height, and age, to determine individual tree volume) from many representative sample areas, and then computing basal area per acre, trees per acre, mean diameter, height and diameter of average tree, and volume. The result was a set of tables of growth and yield data representing a fully stocked stand.

The PNW-FIA bases the MAI equations on site index. This calculated MAI value is then modified by discount factors applicable to the plot or region.

MAI Discount Factors

Discount factors, also called weighted or stockability discount factors, were used by PNW-FIA when normal yield tables could overestimate productivity. This could happen if (1) the site would never be able to support normal stocking because of environmental factors such as poor soil types, yet the site index could imply normal productivity; (2) the resources of the site could support more trees than were present; or (3) when parts of the plot were nonstockable but still classed as forest land (rock outcroppings, small streams, etc.) and so appeared to be understocked. The PNW-FIA had two discount factors to adjust for this: plant stockability factor and nonstockable factor.

A discount factor of less than 1.0 indicated that the site was not capable of carrying normal levels of stocking as defined by the appropriate normal yield table.

Plant stockability factor was developed by PNW-FIA for use in regions where the potential stocking could vary widely owing to natural causes (MacLean and Bolsinger 1973). The field crew recorded the presence of certain plant species, called stockability indicator plants, in western Oregon (Douglas, Jackson, and Josephine Counties only), and California (except the north coast and central coast areas). In eastern Oregon and eastern Washington, the Pacific Northwest Region Forest Service plant association/ecoclass code was collected based on local plant association manuals classifying the plants found on the site (Hall 1998). All other regions had the plant stockability factor set to 1.0.

These stockability indicator plants indicated soil moisture problems and toxic (serpentine) soils. The plant data were used with other environmental variables, such as elevation, to compute the plant stockability factor for these plots.

Nonstockable factor was the percentage of nonstockable land estimated by the field crew for each subplot on the plot. Small streams, ponds, compacted landings, bedrock, and rock outcroppings are examples of areas that can prevent full stocking. (Also called "nonforest inclusions" and "nonstockable nonforest percent"). This was subtracted from the total subplot area to obtain the percentage of the subplot that is capable of full stocking.

Calculating Adjusted MAI

After the site index was calculated for the plot, the analyst selected the appropriate MAI equation based on the site species and geographic area (table 3) and calculated an unadjusted (unadjusted for discounts) MAI for each subplot in timberland. Then the nonstockable percentage was calculated and the plant stockability factor applied, if required. (This step also was called multiplying by the weighted plot discount factor). Finally, an adjusted MAI for the entire plot was made by averaging adjusted MAIs for all the subplots.

Since 1991, PNW-FIA mapped and collected plot data based on the "condition class" encountered on the plots. If there were two or more timberland condition classes, and only one had nonstockable area, then an MAI was calculated and reported for each condition class on the plot. If the nonstockable area occurred across the condition classes, the MAI was averaged over subplots as usual, and only one MAI was calculated and reported for the plot.

Using the MAI

In forestry, the MAI is used in economic analyses and determinations of forest policy because it can be associated with value and rate of return on investment. At PNW-FIA, the MAI was primarily used to develop the site classes: six classes of volume growth per acre at culmination in fully stocked natural stands. The site classes were in a standard table in resource bulletins, "Area of timberland by owner and site class" (for example, Bolsinger and others 1997).

The PNW-FIA also used the MAI to divide plots between "timberland" and "other forest low productivity" (formerly called "noncommercial forest land"), based on whether the site could produce 20 cubic feet • acre^{-1} • year^{-1}.

The Adjusted MAI

The adjusted MAI (adjusted for the two discount factors) was the MAI reported for the plot in the FIA national database and the published tables.

MAI Equations

The following equations express the yield in cubic feet per acre per year.

MAI = mean annual increment,
SI = site index for that species and area,
EXP = natural exponent, and
Ln = natural log.

1. Douglas-fir and grand fir in western Oregon (after 1984) except for Jackson and Josephine Counties, western Washington except in silver fir zone, California except in mixed-conifer stands (McArdle and others 1961).

$MAI = -60 + 1.71SI$ when site index < 75
$MAI = -81.3 + 2.02SI$ when site index ≥ 75, ≤130
$MAI = 22.9 + 1.21SI$ when site index > 130.

2. Douglas-fir in Jackson and Josephine Counties, Oregon (McArdle and others 1961).

$$MAI = 1.8SI - 57.12 .$$

Table 3—Mean annual increment (MAI) equation assignments

MAI equation number	Species	Area
1	Douglas-fir and grand fir	WOR (after 1984) except Jackson and Josephine Counties, WWA except in silver fir zone, CA except in mixed-conifer stands
2	Douglas-fir	Jackson and Josephine Counties in WOR
3	Grand fir and white fir	Jackson and Josephine Counties in WOR
4	Western hemlock and Sitka spruce	WOR, EOR, WWA, EWA, CA
5	Redwood	WOR, CA
6	Noble fir, Shasta red fir in OR, Pacific silver fir, subalpine fir, mountain hemlock	WOR, EOR, WWA, EWA, CA
7	Ponderosa pine, Jeffrey pine, Coulter pine, Bishop pine	WOR, EOR, WWA, EWA, CA
8	Douglas-fir	EOR, EWA
9	White fir and grand fir	EOR, EWA
10	Lodgepole pine, western white pine except in EWA	EOR, WWA, CA
11	Lodgepole pine	EWA
12	Western larch	EOR
13	Western larch	WWA, EWA
14	Engelmann spruce	EOR, WWA, EWA
15	Douglas-fir in silver fir zone	WWA
16	Western red cedar	WWA, WOR, CA
17	Western white pine	EWA
18	Mixed conifer	CA
19	Red fir, Shasta red fir in CA, white fir in CA	CA
20	All hardwoods	WOR, EOR, WWA, EWA, CA

WOR = western Oregon.
WWA = western Washington.
EOR = eastern Oregon.
EWA = eastern Washington.

3. Grand fir and white fir in Jackson and Josephine Counties, Oregon (Cochran 1979a).

$$MAI = 1.9407SI - 34 \ .$$

4. Western hemlock and Sitka spruce in western Oregon, eastern Oregon, western Washington, eastern Washington, and California (Barnes 1962).

$$MAI = 2.628SI - 49.8 \ .$$

5. Redwood in western Oregon and California (Lindquist and Palley 1963).

$$MAI = EXP\ (0.2995\ \sqrt{SI} + 2.404)\ .$$

6. Noble fir, Shasta red fir in Oregon, Pacific silver fir, subalpine fir, mountain hemlock in western Oregon, eastern Oregon, western Washington, eastern Washington, and California (Barnes 1962).

$$MAI = 1.6SI - 50 \ .$$

7. Ponderosa pine, Jeffrey pine, Coulter pine, and Bishop pine, in western Oregon, eastern Oregon, western Washington, eastern Washington, and California (Meyer 1961).

$$MAI = EXP\ (0.702695SI^{0.42} - \ 0.51367)\ .$$

8. Douglas-fir in eastern Oregon and eastern Washington (Cochran 1979a).

$$MAI = 0.00473\ SI^{2.04} .$$

9. White fir and grand fir in eastern Oregon and eastern Washington (Cochran 1979a).

$$MAI = EXP\ (\ 8.24227 - 23.53735\ SI^{-0.4})\ .$$

10. Lodgepole pine and western white pine in eastern Oregon, western Washington, and California (Dahms 1964).

$$MAI = 0.8594SI - 22.32 \ .$$

11. Lodgepole pine in eastern Washington (Brickell 1970).

$$MAI = 0.0122SI^2 - \ 0.2026SI + 7.4 \ .$$

12. Western larch in eastern Oregon (Cochran 1985).

$$MAI = EXP\left[0.05 - \frac{72.1299}{63.8 - 0.066SI} + 1.4\ Ln\ (SI - 20)\right].$$

13. Western larch in western Washington and eastern Washington (Brickell 1970).

$$MAI = -126.05 + (2.7974081SI) + \frac{1919.3157}{SI} \ .$$

14. Engelmann spruce in eastern Oregon, western Washington, and eastern Washington.[4]

$$MAI = (1.92SI) - 18.4 .$$

15. Douglas-fir in silver fir zone of western Washington (McArdle and others 1961).

$$MAI = 1.166SI - 50 .$$

16. Western red cedar in western Oregon, western Washington, and California (Barnes 1962).

$$MAI = 2.628SI - 49.8 .$$

17. Western white pine in eastern Washington (Brickell 1970).

$$MAI = 14.849891 + 1.7311563SI .$$

18. Mixed conifer in California (Dunning and Reineke 1933).

$$MAI = EXP\ (0.578265SI^{0.4} + 1.8108) .$$

19. Red fir, Shasta red fir in California, white fir in California (Schumacher 1928).

$$MAI = 48.278 + 0.23638SI^{1.6} .$$

20. All hardwoods (Worthington and others 1960).

$$MAI = (1.7102SI) - 53.1279 .$$

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[4] Teply, J. 1971. Mean annual increment equations. Unpublished document originally developed for eastern Oregon Blue Mountain inventory unit (1969), dated 12/71. 8 p. On file with: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Forestry Sciences Laboratory, P.O. Box 3890, Portland, OR 97208-3890.

Glossary

Codominant—The tree's crown is part of the general level of the canopy; it receives full light from above but little light from the sides. Crown is usually medium sized and somewhat crowded by other trees.

Condition class—a mapped area on a plot with a distinct land class (for example, timberland, oak woodland, nonforest) or a distinctive vegetative condition (for example, forest type, stand size). The condition class identified at a plot center is the only condition class that is remeasured and used for the analysis of periodic change.

Discount factor—An element of the MAI equation applied if one or both of the two PNW-FIA discount factors (plant stockability factor and nonstockable factor) are present on the field plot. It is also called weighted or stockability discount factor.

Dominant—The tree's crown extends above the general level of the canopy; it receives full light from above and some direct light from the sides (includes open-grown trees).

Forest land—A plot is established on the ground if the crew determines that the site meets the definition of "forest land." Forest land is land that is within the sampled area, is accessible, can be safely visited, and meets at least one of the following two criteria: (1) is (or has been) at least 10 percent stocked with trees of any size as well as not subject to nonforest use that would prevent regeneration, such as mowing, grazing, or recreation; or (2) has western woodland types (tree species not treated as timber species by PNW-FIA) and has (or previously had) at least 5 percent crown cover by trees of any size, and is not subject to nonforest use. In the PNW-FIA *National Core Field Guide* (used in the annual inventory starting in 2000), "forest land" is one of six kinds of condition status, which delineate the condition classes, and is the only one on which plots are measured for the inventory.

Mainstand—The stand that is currently available for management for timber production. All trees that are not understory seedlings or saplings, or residual overstory.

Mixed conifer—The PNW-FIA classifies some areas of California forests as mixed conifer if there is no main softwood tree species as the forest type. A mixed-conifer site is capable of greater than 70 percent conifer stocking, occurs in certain counties, and is further defined by the predominance of certain tree species. In general, these plots have some mix of ponderosa pine, Jeffrey pine, sugar pine, Douglas-fir, red fir, Shasta red fir, incense cedar, and white fir.

Mixed-conifer types grow on the east-facing slopes of the Coast Range, on the west-facing and higher elevation east-facing slopes of the Cascade Range and Sierra Nevada, and can extend into southern California.

Other forest-low productivity—Forest land capable of growing crops of trees to industrial roundwood quality but not able to grow wood at the rate of 20 cubic feet • $acre^{-1}$ • $year^{-1}$. Included are areas of low stocking potential or very low site index.

Silver fir zone in western Washington—The area in western Washington where the first two digits of the Pacific Northwest Region Forest Service plant association/ecoclass code are CF (silver fir, noble fir) or CM (mountain hemlock) and the elevation is over 1000 meters (3,000 feet).

Suppressed—A suppressed tree is completely overtopped by other trees and not free to grow.

Timberland—Forest land that is potentially capable of producing at least 20 cubic feet•acre^{-1}•year^{-1} at culmination in fully stocked, natural stands of continuous crops of trees to industrial roundwood size and quality. Industrial roundwood requires species that grow to size and quality adequate to produce lumber and other manufactured products (excluding fence posts and fuel wood, which are not considered manufactured). Timberland is characterized as having no severe limitations on artificial or natural restocking with species capable of producing industrial roundwood. "Timberland" is one of three categories of ground land class; the other two are "other forest" and "nonforest."

Western woodland types—Tree species designated in the PNW-FIA *National Core Field Guide* (used in the annual inventory since 2000) as those species for which diameter is measured at root crown: juniper, pinyon pine, mountain mahogany, etc.

Yield—The volume of wood that may be contained in a particular type of forest stand.

Metric Equivalents

1 foot = 0.3048 meter
1 acre = 0.405 hectare
1 cubic foot per acre = 0.07 cubic meter per hectare

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Appendix 1

Names of Trees

Common name	Scientific name
Bigcone Douglas-fir	*Pseudotsuga macrocarpa* (Vasey) Mayr
Bishop pine	*Pinus muricata* D. Don
Black cottonwood	*Populus balsamifera* ssp. *trichocarpa* (Torr. & Gray ex Hook.) Brayshaw
Coulter pine	*Pinus coulteri* D. Don
Douglas-fir	*Pseudotsuga menziesii* (Mirbel) Franco
Engelmann spruce	*Picea engelmannii* Parry ex Engelm.
Fremont poplar	*Populus fremontii* S. Wats.
Grand fir	*Abies grandis* (Dougl. ex D. Don) Lindl.
Incense cedar	*Calocedrus decurrens* (Torr.) Florin
Jeffrey pine	*Pinus jeffreyi* Grev. & Balf.
Lodgepole pine	*Pinus contorta* Dougl. ex Loud.
Mountain hemlock	*Tsuga mertensiana* (Bong.) Carr.
Noble fir	*Abies procera* Rehd.
Pacific silver fir	*Abies amabilis* (Dougl. ex Loud.) Dougl. ex Forbes.
Ponderosa pine	*Pinus ponderosa* P. & C. Lawson
Red alder	*Alnus rubra* Bong.
Red fir	*Abies magnifica* A. Murr.
Redwood	*Sequoia sempervirens* (Lamb. ex D. Don) Endl.
Shasta red fir	*Abies shastensis* (Lemmon) Lemmon
Sitka spruce	*Picea sitchensis* (Bong.) Carr.
Subalpine fir	*Abies lasiocarpa* (Hook.) Nutt.
Sugar pine	*Pinus lambertiana* Dougl.
Western hemlock	*Tsuga heterophylla* (Raf.) Sarg.
Western larch	*Larix occidentalis* Nutt.
Western red cedar	*Thuja plicata* Donn ex D. Don
Western white pine	*Pinus monticola* Dougl. ex D. Don
White fir	*Abies concolor* (Gord. & Glend.) Lindl. ex Hildebr.

Source: USDA NRCS 2001.

Appendix 2

Base age of original site index equation (whether it was based on 50- or 100-year age, and whether the equation was originally written with the individual tree's total or breast-height age [BHA]).

Table 4—Site index equation base age

Site index equation number	Source	Original equation age	Basis	PNW-FIA equation age
1	King 1966	50	BHA	50
	McArdle and others 1961[a]	100	Total	50
2	Cochran 1979b	50	BHA	50
3	Cochran 1979c	50	BHA	50
4	Herman and others 1978	100	BHA	100
5	Wiley 1978	50	BHA	50
	Barnes 1962[a]	50	BHA	50
6	Brickell 1966	50	Total	50
7	Krumland and Wensel 1977	50	BHA	50
8	Barrett 1978	100	BHA	100
	Meyer 1961	100	BHA	100
9	Dahms 1975	100	BHA	100
10	Kurucz 1987	50	BHA	50
11	Bolsinger 1974[b]	50	Total	50
12	Cochran 1985	50	BHA	50
13	Worthington and others 1960	50	BHA	50
14	Curtis and others 1974	100	BHA	100
15	Brickell 1970	50	Total	50
16	Dunning and Reineke 1933[a]	50	BHA	100
17	Schumacher 1928	50	BHA	50

[a] Some site index equations, for example no. 1: McArdle's Douglas-fir (McArdle and others 1961), were derived by PNW-FIA from the site index curves in the cited publication because there was no equation published. In these cases, the derived equation was sometimes written by using a different base age to better fit the available site trees. The citation reflects the publication that had the original curves.

[b] See footnote 3

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