Site Index Curves for White Fir in the Southwestern United States Developed Using a Guide Curve Method

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ABSTRACT: *Site index curves for white fir (*Abies concolor*) in Arizona, New Mexico, and southwestern Colorado were developed using height-age measurements and an estimated guide curve and 95% confidence intervals for individual predictions. The curves were developed using height-age data for 1,048 white firs from 263 study sites distributed across eight national forests. These site index curves can be used with standard inventory data for estimating potential site productivity for white fir in the southwestern United States. West. J. Appl. For. 21(2):87–93.*

Key Words: White fir, *Abies concolor*, site index, Southwest.

The height of dominant trees at a specified age in stands or forests, typically referred to as the site index, remains the most commonly applied method of estimating potential site productivity (site quality) for forested areas in the United States (Carmean 1975, Barnes et al. 1998, Carmean et al. 2001) and in Europe (Hagglund 1981). In addition, site index is also used in forest-growth projection models for estimating height growth and forest productivity in the western United States (Edminster et al. 1991b, Crookston 1997, Crookston and Havis 2002). In the eastern and southeastern United States, reference ages of 25 or 50 years are often used for tree species, whereas in the western and southwestern United States reference ages of 50 or 100 years are more commonly used because of the long lifespan of many western coniferous species and the longer rotation ages used there (Davis 1966, Barnes et al. 1998, Husch et al. 2003). Because site index curves continue to be used in forest management, site index curves have been developed for most commercial timber species in the United States (Davis 1966, Wenger 1984). Methodologies used to develop site index curves in the United States have been reviewed by Jones (1969), Carmean (1975), and Cieszewski et al. (2000).

White fir [*Abies concolor* (Gordon & Glend.) Lindl.] is a common and abundant species in mixed conifer forests of the southwestern United States (Jones 1974). White fir is a principal seral component of several mixed conifer habitat types (plant associations) described for Arizona and New Mexico as well as representing its own series of habitat types in which it is the climax species (Moir and Ludwig 1979, Alexander 1988, Stuever 1997). Although it is not considered as one of the most valuable commercial timber species in the southwestern United States (Southwest) because of its wood qualities and propensity for older trees (>150 years) to be decayed by rust-red stringy rot (*Echinodontium tinctorium* E. & E.) (Kimmey 1965, Smith 1982), it is still a valued species, along with Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco], for wildlife habitat (Franzreb 1977, Ganey 1988, Mollohan 1989), watershed protection (Jones 1974, Elias 1980, Agee 1982), and recreational uses (Agee 1982). Furthermore, past harvesting practices in combination with fire suppression policies in the Southwest have created many mixed conifer forests with higher densities of white fir than occurred historically (Barrett 1980, Hopkins 1982, Dahms and Geils 1997).

White fir site index curves are available for mixed conifer forests of the Sierra Nevada Mountains (e.g., Schumacher 1926, Biging and Wensel 1984, Dolph 1987) and for managed, even-aged stands of white fir on the east side of the Cascade Range (Cochran 1979). However, no site index curves have been developed for white fir in the Southwest. As a result, white fir site quality has typically been estimated using site index curves developed for Douglas-fir (Edminster and Jump 1976, Edminster et al. 1991a), a tree species with similar growth patterns as white fir and which often occurs in mixed conifer forests in association with

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white fir (Jones 1974, Moir and Ludwig 1979, DeVelice et al. 1986).

The objective of this study was to develop site index curves for white fir in the Southwest. We decided to use a modified guide curve methodology developed by Edminster et al. (1991a), which was used to develop site index curves for Douglas-fir for the Southwest. Using this methodology allowed us to use a height/age data collection procedure that was the most efficient and cost-effective method of sampling a large geographic area, such as the Southwest. It also allowed a wide range of tree ages, particularly older trees that are often difficult or impossible to sample for stem analysis, to be sampled quickly so that site index curves using a reference age of 100 years, which is most appropriate for Southwestern mixed conifers forests, could be constructed. In addition, the white fir site index curves developed using the modified guide curve method can be used with standard forest inventory data collected by agencies managing mixed conifer forests in the Southwest.

Methods

Data Collection

A total of 264 stands representing even-aged or uneven-aged, mixed conifer forests were sampled in the Apache-Sitgreaves, Coconino, and Kaibab National Forests in Arizona; the Carson, Gila, Lincoln, and Santa Fe National Forests in New Mexico; and the San Juan National Forest in Colorado (Table 1). Each study site was 0.25 to 1.0 acre in a mixed conifer stand that appeared to have a uniform site quality. Study sites were selected in an attempt to represent the range of site qualities on these national forests, where white fir is a common component of the mixed conifer forests (Table 2).

For each mixed conifer stand sampled, trees selected were in the dominant crown class if the stand was predominantly even-aged or the trees were dominants or potential future dominants in younger age classes if the stand was uneven-aged. Potential future dominants were selected based on their rapid and vigorous height growth. The number of trees sampled at a study site ranged from 1 to 10 trees, but most study sites had 3 to 6 trees sampled depending on the availability of suitable sample trees at each site. Total height of each tree was measured to the nearest foot with a clinometer using standard forestry procedures for height measurements (Avery and Burkhart 2002). Increment cores were extracted at breast height (4.5 ft above the ground on the uphill side of the tree) using an increment borer and age determinations were made in the field using a ×10 hand lens. A total of 1,054 age-height measurements were collected for dominant, co-dominant, and potential future dominant trees. Trees sampled were between 10 and 207 years old at breast height and heights ranged from 13 to 131 ft.

Table 1. Number of study sites and white fir site trees sampled by national forest in Arizona, New Mexico, and Colorado.

National forest	Number of study sites sampled	Number of white fir site trees sampled
Apache-Sitgreaves, AZ	65	333
Coconino, AZ	8	33
Kaibab, AZ	20	99
Carson, NM	40	111
Gila, NM	9	41
Lincoln, NM	17	82
Santa Fe, NM	46	149
San Juan, CO	59	206
Total	264	1054

Table 2. White fir site indexes sampled by 10-ft site index classes for study sites in Arizona, New Mexico, and Colorado.

Site index class	Number of study sites sampled
<60	11
61–70	28
71–80	49
81–90	90
91–100	60
101–110	19
>110	7
Total	264

Sampled site index trees had to possess good form, crown ratios >50%, no excessive sweep or logging wounds, and they had no visible evidence of crown damage such as top crooks, broken tops, or multiple tops. All sample trees had no decay in increment cores all the way to the pith; trees with conks or cracks were not cored. Sample trees also had to have increment cores that displayed a growth pattern with no evidence of extended past suppression (>5 years) in diameter increment that may have been the result of western spruce budworm (*Choristoneura occidentalis* Freeman) defoliation (Swetnam and Lynch 1989, 1993), or due to its being a suppressed understory tree when it was young. Some trees with slightly reduced growth increment for <5 years were included in the sample, but the annual rings of these trees were not tightly arranged, rather their growth rate was slightly slower than that expressed by the majority of annual rings of the increment core.

Data Analysis

We initially examined our white fir tree data for anomalous tree height relationships by plotting height on age. Six trees were identified as outliers and removed from the analyses because they exhibited extremely rapid height growth (two trees) or slow height growth (four trees) for their age when compared to other trees of the same age class. As a result, we used a total of 1,048 white firs from 263 study areas as the data set for the regression analyses and construction of the white fir site index curves. All data analyses were completed using SAS (SAS software, release 8.1; SAS Institute, Inc., Cary, NC) and NCSS (NCSS Software, NCSS, Kaysville, UT).

To account for nonhomogeneous variance, we fit a height variance model to the white fir age-height data using a Chapman-Richards height model (Ratkowsky 1990). All height-age measurements were reviewed using box plots, violin plots, and scatter graphs to determine the feasibility of collapsing tree age data into 5-, 10-, or 20-year age classes. This analysis indicated that 10-year age classes best represented height variance behavior in contrast to alternative age class sizes. Therefore, height variance was calculated using the midpoints of 10-year age classes in the Chapman-Richards model:

$$\text{HTVAR} = b1 * (1 - \exp(b2 * A10)) ** b3, \quad (1)$$

where HTVAR = tree height variance (ft) calculated for 10-year age classes with midpoints specified in $A10$ and $A10$ = age class midpoints (15, 25, 35, ... 205 years).

The inverse of the height variance function (equation [1]) was used to weight the nonlinear regression using the Chapman-Richards height model for developing the final height growth guide curve:

$$\text{HG} = b1 * (1 - \exp(b2 * AGE)) ** b3, \quad (2)$$

where HG = total tree height (ft) on the guide curve.

The lower 95% prediction interval (HL) was constructed using the white fir height-age data and a modified Chapman-Richards model:

$$\text{HL} = b1 + b2 * (1 - b3 * \exp(-b4 * AGE)) ** b5, \quad (3)$$

where HL = height of the lower 95% confidence bound for individual predicted heights (ft) and AGE = age at breast height (yrs).

For each input observation, nonlinear regression output included corresponding height values for confidence intervals at discrete ages. To mathematically model the lower 95% bound for individual predicted values, the output data set was reduced to one observation for each discrete independent value of age, and nonlinear regression was used to fit the HL model as best possible.

Applying the method described by Edminster et al. (1991a), site index curves for white fir were then constructed by determining the distance from the guide curve to both the lower and upper 95% confidence bounds for the reference age of 100 years. The distance proportion (*P*) was calculated as the difference between the guide curve and decadal site index height values, divided by the difference between the guide curve and the lower 95% confidence bound for each height-age sample as represented by the equation:

$$\text{P} = (\text{HG} - \text{HT})/(\text{HG} - \text{HL}), \quad (4)$$

where HG = height (ft) of the guide curve at the sample age (yrs); HT = total height (ft) of the sample tree; and HL = height (ft) of the lower 95% confidence bound at the sample age (yrs).

Finally, given *P*, breast height age, and height for any measured site index tree, the equation for estimation of site index is represented by:

$$\text{SI} = \text{HG}_{100} - (\text{HG}_{100} - \text{HL}_{100}) * \text{P}, \quad (5)$$

where SI = site index; HG_{100} = height of the guide curve at age 100 years; HL_{100} = height of the lower 95% confidence bound at age 100 years.

Results

After fitting data to the height variance using the Chapman-Richards model (equation [1]), we obtained b1 = 180.8966, b2 = −0.0200, and b3 = 1.3603. Using these parameters we calculated the coefficients for the final guide curve equation (equation [2]) and obtained b1 = 117.5251, b2 = −0.122, and b3 = 0.9772. Regression results were significant ($p < 0.001$) with an approximate r^2 value of 0.88 and an approximate mean root square error of 1.01. Residuals from the guide curve regression were tested and accepted as normally distributed.

For the fitting of the lower 95% confidence interval in equation [3] b1 = −18.8943, b2 = 109.4977, b3 = 0.7802, b4 = −0.0122, and b5 = 1.2777. Regression results were again significant ($p < 0.0001$) with an approximate r^2 nearly equal to 1.00 and an approximate mean root square error of 0.0046. The height growth guide curve, bounds of the lower and upper 95% confidence intervals for individual predictions, and height-age data used to develop the white fir site index curves are illustrated in Figure 1.

At the reference age (100 years), the height of the guide curve was 83.6 ft. The height of the lower 95% confidence bound for an individual prediction at the reference age was 59.5 ft. The difference between the two heights was 24.1 ft. Therefore, using the guide curve method, and equation [5] with a reference age of 100 years, the site index equation was SI = 83.6 − 24.1 * P.

The source data used to construct the site index curves is illustrated with the curves in Figure 2. The site index curves for white fir constructed for ages 10 to 210 years and site indexes from 40 to 120 ft are polymorphic in that their form varies between the different site index classes (Figure 3). Estimated heights of dominant trees, corresponding to the site index curves in Figure 3, are presented in Table 3 by site index class and decadal ages.

Discussion

It should be noted that the site index curves for two extremes, 40 and 120 ft, were extrapolated slightly beyond the range of ages and heights by the 1,048 white fir site trees used in the data analyses. The need for using precaution regarding extrapolations for site index curves 40 and 120 due to a lack of height-age data for these curves is apparent in Figure 2. A larger sample may have resulted in a marginal increase in the number of observations at the more extreme site indexes for ages >160 years, but it is not possible to determine if a larger sample would have resulted in meaningful height variance changes at these older ages. If true height variance is greater for older trees than our sample indicated, the dispersion would have widened the 95% confidence intervals for the older ages. This would have increased the spread in the site index curves for older trees. However, we believe this to be unlikely because the increase in height variance by tree age was consistent when the trees >160 years old in our data set were included in the height variance analyses. An increased sample from older age-classes would, theoretically, correspond with a height

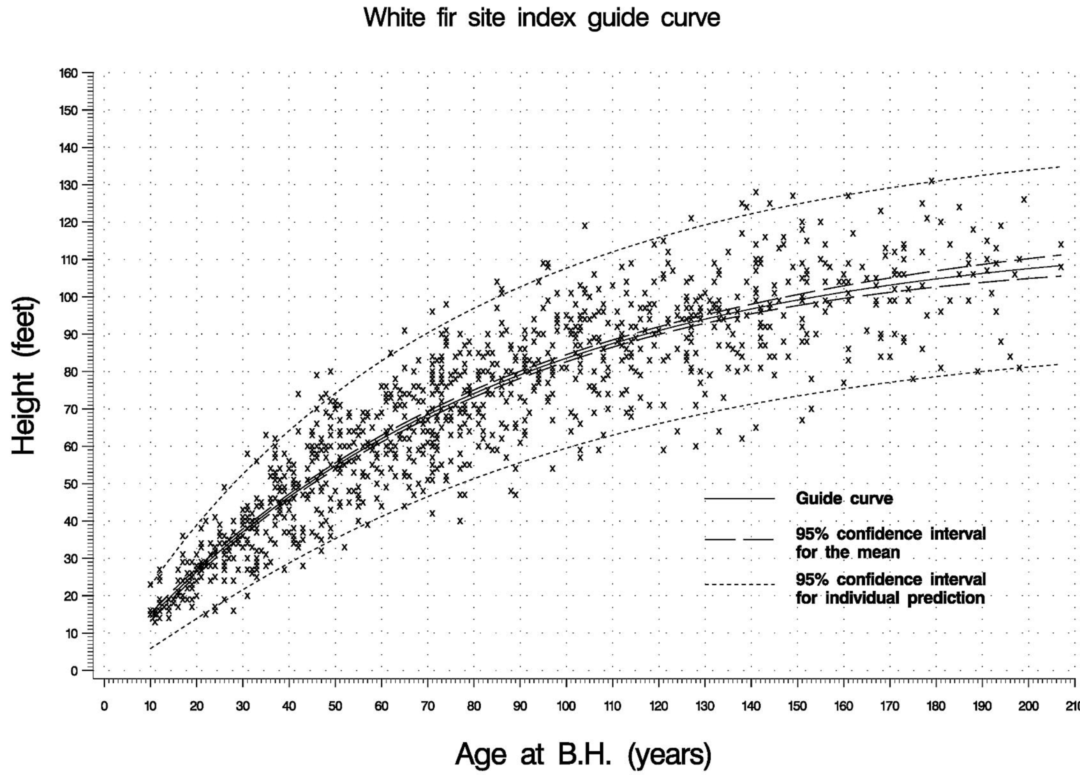

Figure 1. Guide curve and bounds for 95% confidence intervals for the mean and individual prediction in relation to the distribution of the white fir height-age data for 1,048 trees. Ages are for breast height (B.H.).

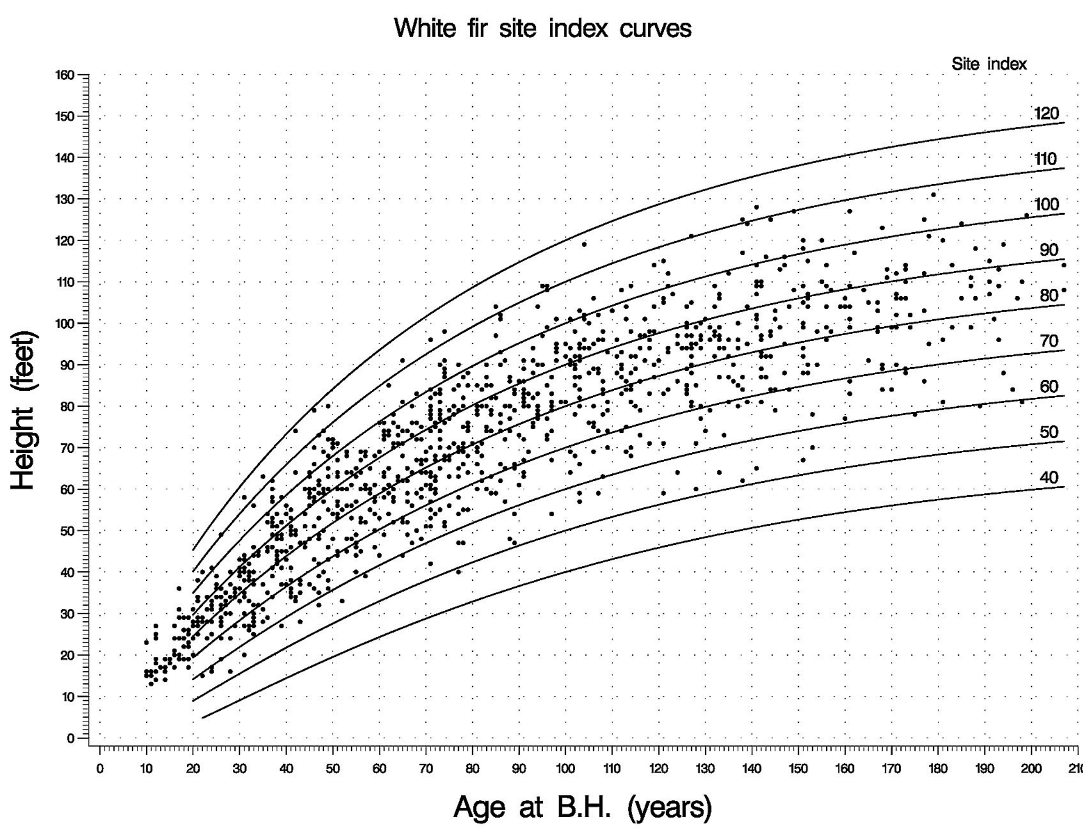

Figure 2. White fir site index curves with the height-age source data used to construct the curves. Ages are for breast height (B.H.).

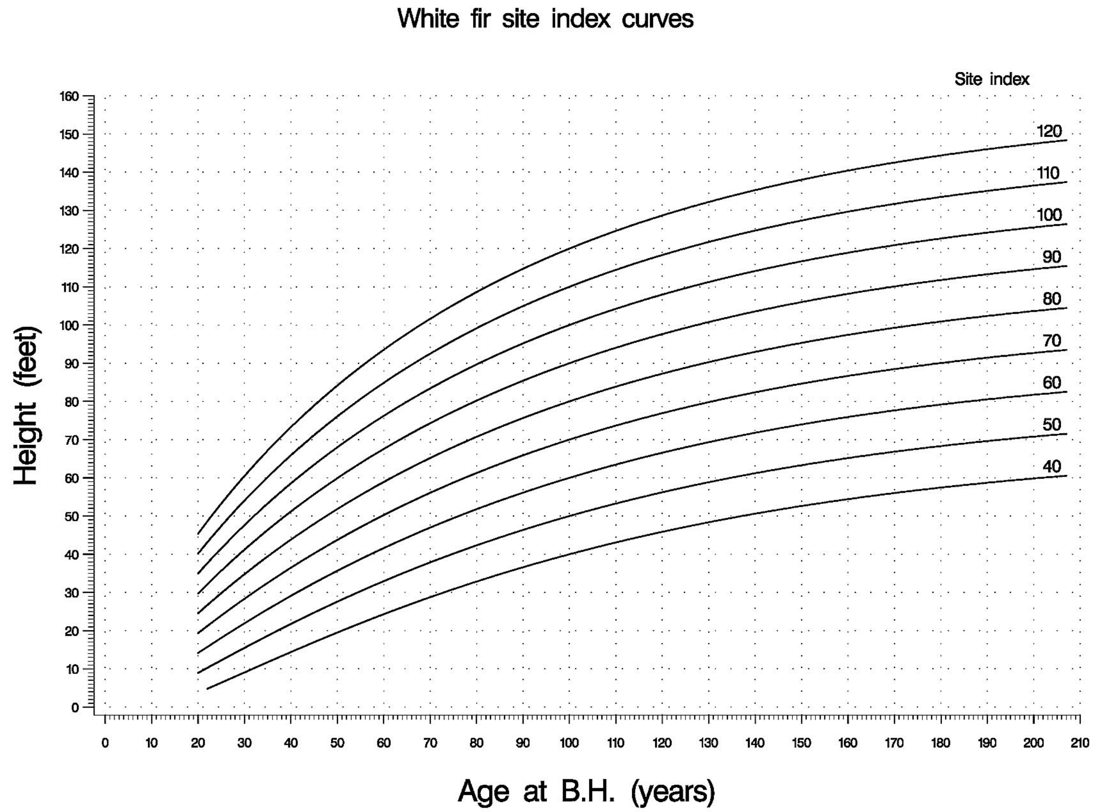

Figure 3. Site index curves for white fir in Arizona, New Mexico, and southwestern Colorado. Reference age 100 years, breast height (B.H.).

Table 3. Estimated total height (ft) of white fir trees in the dominant portion of the stand.

Breast height age (years)	Site index class								
	40	50	60	70	80	90	100	110	120
20	–	8.9	14.1	19.3	24.5	29.7	34.9	40.2	45.4
30	9.1	15.5	21.9	28.3	34.8	41.2	47.6	54.0	60.5
40	14.4	21.7	29.1	36.5	43.8	51.2	58.5	65.9	73.2
50	19.5	27.6	35.7	43.7	51.8	59.9	68.0	76.1	84.2
60	24.3	32.9	41.6	50.3	58.9	67.6	76.2	84.9	93.5
70	28.7	37.9	47.0	56.1	65.2	74.3	83.4	92.5	101.6
80	32.8	42.3	51.8	61.3	70.7	80.2	89.7	99.1	108.6
90	36.6	46.4	56.1	65.9	75.6	85.4	95.2	104.9	114.7
100	40.0	50.0	60.0	70.0	80.0	90.0	100.0	110.0	120.0
110	43.1	53.3	63.5	73.7	83.9	94.0	104.2	114.4	124.6
120	45.9	56.2	66.6	76.9	87.3	97.6	108.0	118.3	128.7
130	48.4	58.8	69.3	79.8	90.3	100.8	111.2	121.7	132.2
140	50.6	61.2	71.8	82.4	93.0	103.5	114.1	124.7	135.3
150	52.6	63.3	74.0	84.6	95.3	106.0	116.7	127.4	138.0
160	54.4	65.2	75.9	86.7	97.4	108.2	118.9	129.7	140.4
170	56.0	66.8	77.6	88.5	99.3	110.1	120.9	131.7	142.5
180	57.4	68.3	79.2	90.0	100.9	111.8	122.6	133.5	144.4
190	58.7	69.6	80.5	91.4	102.4	113.3	124.2	135.1	146.0
200	59.8	70.8	81.7	92.7	103.6	114.6	125.5	136.5	147.4
210	60.9	71.8	82.8	93.8	104.8	115.8	126.7	137.7	148.7

distribution relatively similar to our sample, and it would be difficult for increased sample size alone to meaningfully alter the height variance structure inherent in our data set.

It should also be noted that for ages >160 years, site indexes of 50 and 110 are extrapolations, but these curves are consistent with the height variance data used to weight the HG regression (equation [2]), and with derivation of the HL function (equation [3]). Extrapolations at site indexes 50 and 110 for older trees is of less concern than for site indexes 40 and 120 where available data is lacking across the range of sample ages (Figure 2).

Researchers attempting to use the guide curve method we used for constructing white fir site index curves in this study for other species should be aware that the statistics reported for the lower 95% confidence interval regression analysis (r^2 and root mean square error) were only approximations. The objective for fitting a regression model to the lower 95% confidence interval data reported in equation [3] was to develop a mathematical model that best represented the shape of the lower bound for HL. The data used for the HL regression was output from the nonlinear regression resulting in the HG function (equation [2]) and consisted of multiple observations for most discrete 1-year age observations. Therefore, for a single age value, multiple observations were output with identical values for the dependent variable (height). Reduction of this output data set to one observation for each discrete 1-year age class allowed the attainment of the best mathematical model that represented the lower 95% confidence bound. As a result, r^2 and mean root square error values reported for the HL function (equation [3]) do not represent meaningful statistical attributes. However, predicted values of HL were determined to be within 0.006 ft of height values output from the HG regression for all trees ages >25 years and within 0.019 ft for tree ages <25 years which is well within acceptable height measurement error estimations (Avery and Burkhart 2002).

Although the guide curve method we used for the development of site index curves for white fir in the Southwest has some limitations (Edminster et al. 1991a), it allowed us to use a white fir data set that represented a wide range of tree ages and heights collected from a large number of mixed conifer sites representing many site qualities and from several national forests in the Southwest (Tables 1 and 2). It also allowed us to sample older trees without destructive sampling so that a reference age of 100 years could be used. Because many white fir trees >150 years old are extensively decayed by rust-red stringy rot in the Southwest, it is frequently difficult to destructively sample an adequate number of dominant trees at a site for use in stem analysis. In addition, the moratorium on cutting trees larger than 24 in. in diameter in the Southwest prevents the use of many dominant white fir trees for stem analysis. Another advantage of the guide curve method is that it allowed the use of height-age data that is similar to that collected during typical stand inventories conducted by agencies managing mixed conifer forests in the Southwest.

Although site index curves have been developed for most western tree species, no curves have been available for white fir in the Southwest. Because the curves for white fir developed for other regions of the West used a reference age of 50 years, and were for regions with higher levels of precipitation, they are inappropriate for use in the Southwest. White fir is abundant and an important wildlife, watershed, and recreation species in Southwestern mixed conifer forests, so its management is still an important aspect of natural resource management in this region. Therefore, site quality estimation for white fir using the site index curves developed here will prove useful to forest managers working in the Southwest.

In a subsequent on-going analysis involving additional tree species from the same study data used for white fir site index, it was discovered just prior to publication of these results that an unintentional rounding anomaly may have occurred during field recording of breast height ages. A small proportion of decadal ages (10, 20, 30 years, etc.) may have been inadvertently rounded up, or down, into adjacent age classes. In consideration of these small rounding anomalies, the authors compared resulting site index curves with previously published work and believe the random nature of the field rounding had no discernible impact on guide curve and site index curve development, particularly with regard to the magnitude of variability associated with tree height measurements, site tree selection, and stand-level site index determination.

Summary

Site index for white fir in mixed conifer stands in the Southwest can be estimated using height-age measurements of carefully selected site trees and two-way interpolation in Table 3 or by plotting height-age measurements directly on the site index curves in Figure 3. Site indexes can be calculated directly by using the following equations:

1. For a measured white fir site index tree age (AGE), calculate the height of the guide curve (HG) using

$$HG = 117.5251 * [1 - \exp(-0.0122 * AGE)] ** 0.9772.$$

2. For the same AGE, calculate the height of the bound for the lower 95% confidence bound (HL) using

$$HL = -18.8943 + 109.4977 * [1 - 0.7802 * \exp(-0.0122 * AGE)] ** 1.2777.$$

3. Calculate the distance proportion (P) with P = (HG − HT)/(HG − HL) using the measured height (HT) of the site index tree and the values for HG and HL calculated using the AGE of the site index tree in steps 1 and 2.

4. Calculate the estimated site index for the tree using:

$$SI = 83.6 - 24.1 * P.$$

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