HEIGHT-AGE CURVES FOR PLANTED STANDS OF DOUGLAS FIR, WITH ADJUSTMENTS FOR DENSITY

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STAND MANAGEMENT COOPERATIVE
SMC WORKING PAPER NUMBER 1
JANUARY 2001

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ABSTRACT

The objective of this study was to develop site index curves for young plantations of coastal Douglas-fir (*Pseudostuga menziesii* (Mirb) Franco). To accomplish this, a set of height-age equations were developed which incorporate an adjustment for stand density, expressed in trees per acre. A reference site index system, based on age from seed of 30 years and 300 trees per acre was developed. Equations to adjust to other stand densities and to convert to the King 50 year site index system for natural stands were also developed. Software implementation of the site index system developed in this report can be obtained at:

http://www.cfr.washington.edu/research.smc/pubs.htm

ACKNOWLEDGMENTS

This project was initiated when, in 1997, members of the Stand Management Cooperative identified and prioritized research topics of common interest, requested competitive proposals from the scientific community, and selected this project along with five others for funding during 1998/99. The members of the SMC are to be thanked for contributing their support and data. In addition to the standard series of SMC installations, much of the planation data that had been used in the SMC ORGANON growth modeling project was also used. That included data contributed by the British Columbia Ministry of Forests (Experimental Project 703), Washington State Department of Natural Resources, Forestry Canada, the USFS Pacific Northwest Forest Experiment Station and Weyerhaeuser Company. Gary Ritchie provided information on current and historical tree sizes typically used for planting. Dave Hyink provided valuable critiques on several modeling issues. Fred Martin, Washington State Department of Natural Resources, and Bob Curtis, USDA Forest Service, retired, assisted in the review process.

INTRODUCTION

For even-aged natural and planted stands, site curves are typically used to describe the development of dominant height or top height. For Douglas fir in the Pacific Northwest, the commonly used site curves are by King (1966) and Bruce (1981). In developing his curves, King used a data base of dominant height versus age for individual plots; past dominant heights were obtained by averaging measured heights to whorls at 5-year increments. Bruce fitted equations to increment in top height using data obtained from the remeasurement of permanent plots. The major difference between the resultant curves is at the youngest ages. Bruce extended the curves to ages prior to breast height, and considered the effect of fertilization upon height growth.

Stand density affects height growth. This effect is generally believed to be small and is usually not considered in the development of site curves. Reduced growth at low densities is expected for species with weak epinastic control (Oliver and Larson, 1996); this density effect has also been noted for Douglas fir (Isaac, 1937, Scott et al., 1998). Conversely, very high densities can produce marked reductions in height growth; and these effects are sometimes modeled. Examples for lodgepole pine are from Alexander et al. (1967), and Cieszewski and Bella (1993). In the former, CCF (crown competition factor) is formally brought into the site curve formulation; in the later a crowding index affects annual growth in a dynamic fashion. Similarly in managed stands, it is not uncommon to model the effect of a silvicultural treatment upon height growth; an example is Pienaar and Rheney (1995).

The objective of this site-curve project was to derive site curves for plantations of Douglas fir. Site curves are viewed as a family of height over age curves that typify height development. The SMC Type III installations had shown earlier that high densities could dramatically increase height growth (Scott et al., 1998). Hence it was anticipated that stand density should affect the site curves. The SMC installations, supplemented with other research installations used in developing the SMC variant of ORGANON, were available for use in developing site curves. Data availability and the anticipated usage of the site curves together suggested that the dependent variable should be top height as defined in the next section. Hence the felling and sectioning of trees was not required.

DEFINITIONS

Three measured variables require definition: top height, age, and density. The definitions and estimation procedures given here reflect what was appropriate for the fitting data set. Variables measured in exact conformance with these definitions may not be available in inventory applications. The use of slightly different definitions for top height or density will usually not pose a problem - as long as the users are consistent in their usage.

Total age (AGE) is defined as the number of elapsed growing seasons from germination. Most plantations now use 2-0 stock; therefore age at planting is 2 years; age at the end of the first field growing season is 3 years. Interpolation of age within a growing season is not addressed.

Top height (HTOP) is defined as the mean height of the largest 40 trees per acre (tpa) by DBH. All species are considered when defining the largest 40 *tpa*. However, the mean computation uses only the subset of trees which are Douglas fir; in a mixed-species stand, fewer than 40 *tpa* may be used. In very young stands, trees taller than breast height are considered first, and then the smaller trees ranked from tallest to shortest. Observed tree heights are used in the top height computation when they are available; otherwise heights come from height-diameter curves fitted to other trees measured on the same plot at the same time. With good local height-diameter curves, differences between computations from observed tree heights and predicted tree heights should be trivial. The use of predicted heights from regional height-diameter curves would be inappropriate. A usable definition of top height should include a sampling protocol. The expectation of top height will vary with plot size. Accordingly, for inventory work, it may be useful to adapt a sampling protocol and computational scheme similar to that used on permanent plots, or to quantify the difference in expectation that might arise from differing protocols (Rennolls, 1978; Garcia, 1998). The protocol for top height computation in the permanent sample plots was to simply accept existing plot sizes; these were generally 0.2 acres or slightly larger.

An example of a top height computation from a 0.2 acre plot follows. The targeted number of top height trees is $40 \times 0.2 = 8$. From a complete tree list, identify the eight trees with the largest DBH's. From that set, exclude non-planted trees and trees with broken tops. Thus the number of acceptable trees will be eight or fewer. In practice, non-planted trees may not be identifiable unless they are of another species. The broken-top exclusion is necessarily subjective; if there was a break many years ago it may not be readily detectable. With locally fitted height-DBH curves, trees with broken tops are usually excluded from the fitting data set; if that is the case, the decision on whether or not to include those trees in the top height, using equation-predicted heights, will have a minimal impact on the value of top height. The targeted number of trees may sometimes be a non-integer; for example a 0.19 acre plot would target 7.6 trees. The suggested procedure would be to use a weighted average with the largest seven trees given weights of 1.0, and the eigth given a weight 0.6. Equivalently, assign to each sample tree the number of trees per acre that it represents; sort by descending DBH, and cumulate to 40 trees per acre; the final included tree has its tpa factor reduced so that the total does not exceed 40. The later procedure is commonly used within growth models based on DBH classes or cohort lists.

In inventories, stands are typically sampled with many small plots, often prism plots. This poses two problems. First, a decision must be made as to whether the site curves, and any related growth models, are to be applied to the plots individually, or to an average stand condition. The usual decision for growth modeling of plantations is to calculate the average stand condition, and grow that forward. Given that the growth models, including the site curves, are constructed from small permanent plots, their application to stand average values may be biased. The computation of top height using a whole-stand diameter distribution table is definitely biased. An aggregate stand table is wider than would be found on any individual plot. Hence the average diameter of the largest 40 *tpa* from the aggregate stand table is larger than the average diameter of the top height trees that would have been selected on individual plots. We have not studied these differences, but expect they could be on the order of several percentage points; this leads to a small systematic difference - a bias - between top heights calculated from plots and from aggregate stand tables. One way to avoid that bias would be to calculate a top height at each sample plot, and average those values. The second problem is that for samples from small fixed-area plots or prism plots, the calculated top heights may be too low - compared with what would have been obtained from 0.2 acre plots. Here, the use of adjustments for plot size should be considered. Garcia (1998) gives general methodologies for the calculation of adjustment factors, and some results for Douglas fir. For any particular inventory methodology, it should be possible to derive simple -to-apply adjustment factors.

Trees per acre (TPA) is the measure of density used here. For plantations with no ingrowth, density refers to live planted trees. However, ingrowth trees are often present, and are sometimes indistinguishable from planted trees. Where non-planted trees are present and identifiable, the following formula is used to calculate an effective density as a function of planted-tree density (TPA_p), planted-tree basal area (BA_p), and total basal area (BA).

$$TPA = TPA_p \times (BA / BA_p) \qquad (1)$$

All subsequent references are to this effective density. The case where ingrowth is easily distinguished is where the ingrowth is of a different species, most commonly western hemlock. In that case, or any case with many ingrowth trees that are much smaller than the planted trees, it is important that Eqn. 1 be applied. If the ingrowth trees are about the same size as the planted trees, the effective trees per acre (Eqn. 1) is approximately equal to total trees per acre. At very young ages, especially if the planted trees are at or below breast-height, formulas with BA_p in the divisor should not be used. Accordingly, at the very youngest ages, use total trees per acre regardless of species.

POPULATION

The population of interest are Douglas fir plantations that have not suffered from extreme ingrowth, have not suffered severe wind damage or pathogen damage, and have not been pruned or fertilized, and do not have a significant component of advance regeneration or "leave" trees from a previous stand. The height - age data from the permanent sample plots used in this study for fitting the site curves are shown in Figure 1. Note that none of the observed top heights reach 125 *ft.*; ages do not exceed fifty years on good quality sites, and are lower on the very best sites. The fitting data set had excluded plots which were less than seventy percent Douglas fir by basal area.

BASE SITE CURVES

"Base" site curves refer to curves derived from equations that do not have density as an independent variable. Mathematically they are structured like most other site curves. They may be thought of as being in this form:

$$\text{HTOP} = g_1(\text{AGE}, \text{SI}) \qquad (2)$$

where site index (SI) is top height at a reference age, in this case, total age 30. The software developed by this project (see Appendix C) allows the above formulation to be used. However, the closed-form solution is actually:

$$\text{HTOP} = g_2(\text{AGE}, \Psi) \qquad (3)$$

where Ψ, or PSI, is a parameter used in defining a particular site curve; Ψ is the maximum derivative (*ft./yr.*) for a particular site curve. For every value of Ψ, there is a unique site index calculated as:

$$\text{SI} = g_2(30, \Psi) \qquad (4)$$

Similarly, for every value of site index, there is a unique value of Ψ. The user of the site curves will generally not be concerned with Ψ. However, an awareness of this under-lying parameter will facilitate an understanding of the software and of the underlying equations (Appendix A).

The base site curves are tabulated for a limited set of site index values in Table 1. Annual increments in HTOP at various ages are shown in Table 2. Figures 2 and 3 are another representation of the same information: top height and top height increment. These base curves are not functions of density; however they apply to one particular density regime. That density is a constant 300 *tpa*. For comparison, King's(1966) site curves are shown in Figure 4.

DENSITY EFFECTS

The mathematical formulation of the base curves has no explicit tie to density. Density-dependent curves are constructed upon the base curves. Each annual increment is increased or decreased depending upon the current density. Thus

$$(\Delta \text{ HTOP})' = (\Delta \text{ HTOP}) \times d(\text{ AGE, TPA}) \tag{5}$$

where (Δ HTOP) is the annual increment of the base curves AGE to AGE + 1, *d*( ) is a function of age and density, and (Δ HTOP)' is the density-dependent increment. The density function, *d*( ), which is applied as a multiplier, is shown in Table 3, and described in Appendix B.

The form of the density function for any given age is that of a quadratic equation in the logarithm of density, subject to the density limits in the data base. For each age there is a maximum value of *d*( ). At young ages, the maximum value of *d*( ), occurs at densities above 1600 *tpa*. At age 20, the maximum predicted growth occurs at about 600 *tpa*. At age 40, the maximum predicted growth occurs at about 100 *tpa*.

DENSITY-ADJUSTED SITE CURVES

Density-adjusted site curves are created by applying the density-effect model to the base site curves. This computation requires that a particular base curve and density regime be specified. The base curve can be specified by its site index, the underlying value of Ψ, or the height at any age. The density regime is specified by the array of densities from the planting age to one year shy of the final age of interest.

An example of a density-adjusted curve is presented in the following tabulation for a constant density of 1200 *tpa*, and a base site index of 75 *ft*. at age 30. The computations for the first few years are shown, using base values (HTOP) from Table 1, and density effects from Table 3. Starting at age 2 with HTOP = 1.40 *ft*., the base height versus age curve indicates that HTOP will grow to 1.63 *ft*. in a year - a height increment of 0.23 *ft*. Height increment at a density of 1200 *tpa*, rather than 300 *tpa*, is greater by a factor of 1.299, making the density adjusted increment 0.30 *ft*., and the age 3 density-adjusted HTOP 1.70 *ft*.

Age	HTOP (ft)	Δ HTOP	Density Effect	Δ HTOP '	HTOP' (ft)
2	1.40	0.23	1.299	0.30	1.40
3	1.63	0.64	1.220	0.78	1.70
4	2.27	1.02	1.167	1.19	2.48
5	3.29	1.39	1.130	1.57	3.67

Curves for site index 75, for the base 300 *tpa* and for 1200 *tpa*, are shown in Figure 5. The two curves cross at age 32. The assignment of a site index to the adjusted curve poses a dilemma. The assignment could be that of the base curve (75.0 *ft*.), or could be the predicted height at age 30 (75.9 *ft*.). The convention we use is to always refer to the site index of the base curve. Hence both curves in the figure are SI 75 curves; one is for a constant 300 *tpa*, and the other for a constant 1200 *tpa*.

Other density regimes will exhibit different patterns. To gain perspective on this, density-adjusted site curves were constructed for a set of four diverse regimes, all with a base SI of 75 feet:

1. Constant 1200 *tpa*
2. Constant 400 *tpa*
3. Constant 100 *tpa*
4. 1200 *tpa* through age 17; 300 *tpa* from age 18 through age 34, 100 *tpa* after age 34

The differences between these four curves and the base curve are shown in Figure 6. The first regime (high density) is predicted to be ten feet below the base curve at age 50. The fourth regime is predicted to be five feet above the base curve at age 50. In considering radically different density regimes, the density effect model will significantly impact predictions. However, in applying the curves to individual stands which are not subjected to extreme densities, predictions are unlikely to be radically different whether the density effect model is used or not.

In a growth modeling context, the calculation of density-adjusted site curves may have an additional complication due to model interactions. Many growth models use height from site curves as a driving variable. As such, height growth affects diameter growth and mortality. Mortality in turn affects height growth. Still, the annual computations are straight forward. The height increment in going from AGE to AGE + 1 is affected by the density at the first of the first of this pair of ages. The mortality prediction equation for that one-year period may use as input the density-adjusted height increment. Though annual computations are required, each year's computations are tractable and do not require simultaneous solutions for height growth and mortality.

RELATIONSHIP BETWEEN NATURAL-STAND SITE INDEX AND PLANTED SITE INDEX.

It has often been noted that "exhibited" site indices of young Douglas-fir plantations, calculated with standard site curves, sometimes exceed the highest natural-stand sites indices observed at breast height age 50. It is reasonable to believe that plantations will exhibit faster height growth than natural stands at the same location. The site indices (natural and planted) are correlated. This section quantifies this relationship. The resultant equations may be useful in predicting planted site index for newly planted areas, or in extrapolating the new curves to heights beyond the plantation data.

The available data are shown in Appendix D. These include all of the planted installations for which a natural stand site index was available in the SMC data base. The natural stand site index values, with an index age of 50 years at breast-height, came from a variety of sources; they were assembled by Bill Bennett while he was on the SMC staff. The plantation site index values came from the application of the density-adjusted site curves to the final measurement on each of the plots.

The geometric mean regression relating the site index values of the installations is:

$$SI_{planted} = -13.6 + 0.7955 \times SI_{natural} \tag{6}$$

Further exploration of the data indicated a relationship between planted SI and birth year (BIRTHYR): the more recently planted stands tended to have higher site indices. These was confirmed through linear regression analysis, adding one term to the regression:

$$SI_{planted} = -13.6 + 0.7955 \times SI_{natural} + 0.40 \times (BIRTHYR - 1980) \tag{7}$$

Birth year is defined as the calendar year in which the seeds have germinated; thus 2-0 stock planted in the winter of 1999-2000 would have birth year 1998. In applying the above regression, BIRTHYR should not exceed the range of the data: 1955 to 1993; a more conservative approach might be recommending: limiting the application to the range 1970 to 1990. Presumably this effect is due to better planting stock, better handling, and better genetics. The difference in predicted planted site index between 1970 and 1990 would be 8 feet.

OTHER APPLICATION ISSUES

One assumption that is needed is height at time of planting. In model application, we assume that planting age (AGE_p) is 2 years. Top height at the time of planting ($HTOP_p$) has been estimated for each plantation; in modeling this is set to a reference value, fixed at 1.4 feet. This is perhaps a bit lower than current standards, and a bit higher than in past decades.

The data at the very youngest ages (age less than five) is sparse, and includes few annual remeasurements. Accordingly the distribution of growth in the first three years after planting should be viewed as soft predictions. The annual growth predictions from the curves should not be used as a benchmarks for new plantations at those very young ages.

At any age, an "exhibited" site index can be calculated from the age, observed top height, and density regime. If at a young age an exhibited site index has a very low value, chances are that at later ages, new calculations will yield higher values for exhibited site index. Similarly, stands that initially have very high exhibited site index values will tend to have lesser exhibited site index values at older ages. The explanation for this tendency with traditionally fit curves is explained by Curtis et al. (1974); such a tendency probably exists with the present curves - but to a lesser degree. The present curves, and most curves fit to growth data such as those of Garcia (1983) or Bruce (1981), would be expected to produce distributions of exhibited site indices that do not vary much with age. Such exhibited site indices are suitable for most forest-wide planning analyses; distributions will be correct, even if individual predictions are not optimal.

For any particular young plantation it should be possible to obtain a more precise estimate of site index than the exhibited site index discussed in the previous paragraph. An obvious strategy is to make a weighted mean estimator where one of the inputs is exhibited site index, and the other input is either an overall mean site index or perhaps the plantation site index predicted by applying Equations 6 or 7 to the site index from the previous natural stand. No precise guidance on weights is being given. At ages 30 and above, the exhibited site index should probably be accorded complete control. At ages 10 to 30, the exhibited site index should be accorded no more than half of the total weight, and at younger ages, even less.

The data do not extend to the heights where most current plantations will be harvested. Extrapolations to those heights may not be warranted; some users may prefer more conservative alternatives. For example, King's natural stand site curves could be invoked at the older ages. One way to do this would be based on the planted - natural SI relationship developed in the previous section. Using Eqn. 6, selected site index values in the plantation site curves (Figure 2, SI = 35 to 95), are translated to a set of natural stand site index values: 61 to 136. The King site curves for these four values are plotted in Figure 4. The major differences between these and the plantation curves (Figure 2) are the overall higher level of the plantation curves, and a much faster start for the plantation curves. A possible way to switch from the plantation curves to the natural curves is to match the curves at a particular height. For example, the plantation height curve for SI = 75 feet could be used to age 49, where the predicted top height is 120.8 feet. The plantation site curves would predict growth for the next decade as 17.8 feet. The corresponding natural stand curve has $SI_{natural}$ = 111 feet. That curve reaches the same height (121 *ft*.) at total age 65 (breast height age 58). The natural stand curve predicts growth for the following decade as 11.4 feet. This is a typical result. If the site curves are matched on height at the extremes of the fitting data (120 feet or 75 years whichever comes first), the natural stand curves predict ongoing growth about a third less than the predictions from the plantation curves. Adopting the lower estimates of subsequent growth would be conservative. The right choice is unknowable at present.

DISCUSSION

The fitting procedures, which have not been presented here, have produced curves which are in good agreement with the observed growth rates. However the data does not represent a single population. Growth at the oldest ages is entirely from early plantations for which there was no genetic improvement. Growth at young ages is from a mixture of early measurements on early plantations, and recent measurements on recent plantations. Possibly the resultant curves are not representative of any constant population. At present, there can be no evidence that the site curves will correctly predict future conditions on recently established plantations.

The validity of extrapolation to older heights is best addressed by continued data collection, and eventual refitting of the curves. That, plus the incorporation of a genetic gain model, and the development of SI - biogeoclimatic relationships, would seem to be a more satisfying approach than resolving the natural-planted conversion relationships. Still, it would be possible to improve upon the conversion relationships presented here. A good starting point would be using historical inventory data to find natural stand site indices on a large sample of stands that have since been planted.

REFERENCES

Alexander, R. R., D. Tackle and W. G. Dahms. Site index for lodgepole pine with corrections for stand density: methodology. U.S. For. Serv Research Paper RM-29.

Bonnor, G.M., R. J. de Jong, P. Boudewyn, and J.W. Flewelling, 1995. A guide to the STIM growth model. Natural Res. Canada, Pacific Forestry Centre, Victoria. Information Report BC-X-353.

Bruce, D., 1981. Consistent height-growth and growth-rate estimates for remeasured plots. Forest Sci. 27: 711-725.

Cieszewski, C.J. and I.E. Bella, 1993. Modeling density-related lodgepole pine height growth, using Czarnowski's stand dynamics theory. Can. J. For. Res. 23: 2499-2506.

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

Garcia, O., 1983. A stochastic differential equation model for the height growth of forest stands. Biometrics 39: 1059-1072.

Garcia, O., 1998. Estimating top height with variable plot sizes. Can. J. For. Research 28: 1509-1517.

Isaac, L.A. 1937. 10 years' growth of Douglas-fir spacing-test plantations. USDA For. Serv. Res. notes 23.

King, J.E., 1966. Site index curves for Douglas-fir in the pacific northwest. Weyerhaeuser Forestry Paper No. 8, Centralia.

Oliver, C.D., and B. C. Larson, 1996. Forest stand dynamics. John Wiley and Sons, New York, 520 p.

Pienaar, L.V. and J. W. Rheney, 1995. Modeling stand level growth and yield response to silvicultural treatments. Forest Sci. 41: 629-638.

Rennolls, K., 1978. "Top height"; its definition and estimation. Commonwealth Forestry Review 57(3): 215-219.

Scott, W., R. Meade, R. Leon, D. Hyink and R. Miller. 1998. Planting density and tree-size relations in coast Douglas-fir. Canadian Journal of Forest Research 28: 74-78 (1998).

TABLE 1: SITE CURVES: TOP HEIGHT (FT.) FOR SELECTED VALUES OF SITE INDEX.

Total Age (Years)	Site Index = HTOP at Total Age 30						
	35	45	55	65	75	85	95
2	1.40	1.40	1.40	1.40	1.40	1.40	1.40
3	1.46	1.49	1.52	1.56	1.63	1.80	2.29
4	1.64	1.75	1.88	2.01	2.27	2.71	3.81
5	1.94	2.18	2.47	2.76	3.29	4.09	5.89
6	2.35	2.78	3.29	3.79	4.68	5.92	8.47
8	3.51	4.45	5.56	6.64	8.45	10.73	14.84
10	5.12	6.74	8.64	10.44	13.39	16.81	22.09
15	10.93	14.86	19.29	23.26	28.89	34.03	40.41
20	18.92	25.39	32.06	37.65	44.90	51.36	58.72
25	27.26	35.60	44.04	51.66	60.37	68.54	77.04
30	**35.00**	**45.00**	**55.00**	**65.00**	**75.00**	**85.00**	**95.00**
35	42.19	53.65	65.00	77.50	88.61	100.34	111.85
40	48.86	61.60	74.12	89.07	101.11	114.33	127.14
45	55.06	68.92	82.45	99.66	112.48	126.91	140.71
50	60.81	75.66	90.05	109.28	122.73	138.06	152.52
55	66.15	81.85	96.99	117.96	131.91	147.86	162.68
60	71.11	87.56	103.32	125.74	140.07	156.39	171.31
65	75.71	92.80	109.09	132.68	147.30	163.76	178.57
70	79.98	97.63	114.37	138.84	153.67	170.10	184.65

TABLE 2. ANNUAL INCREMENTS IN TOP HEIGHT (FT.) FOR SELECTED VALUES OF SITE INDEX

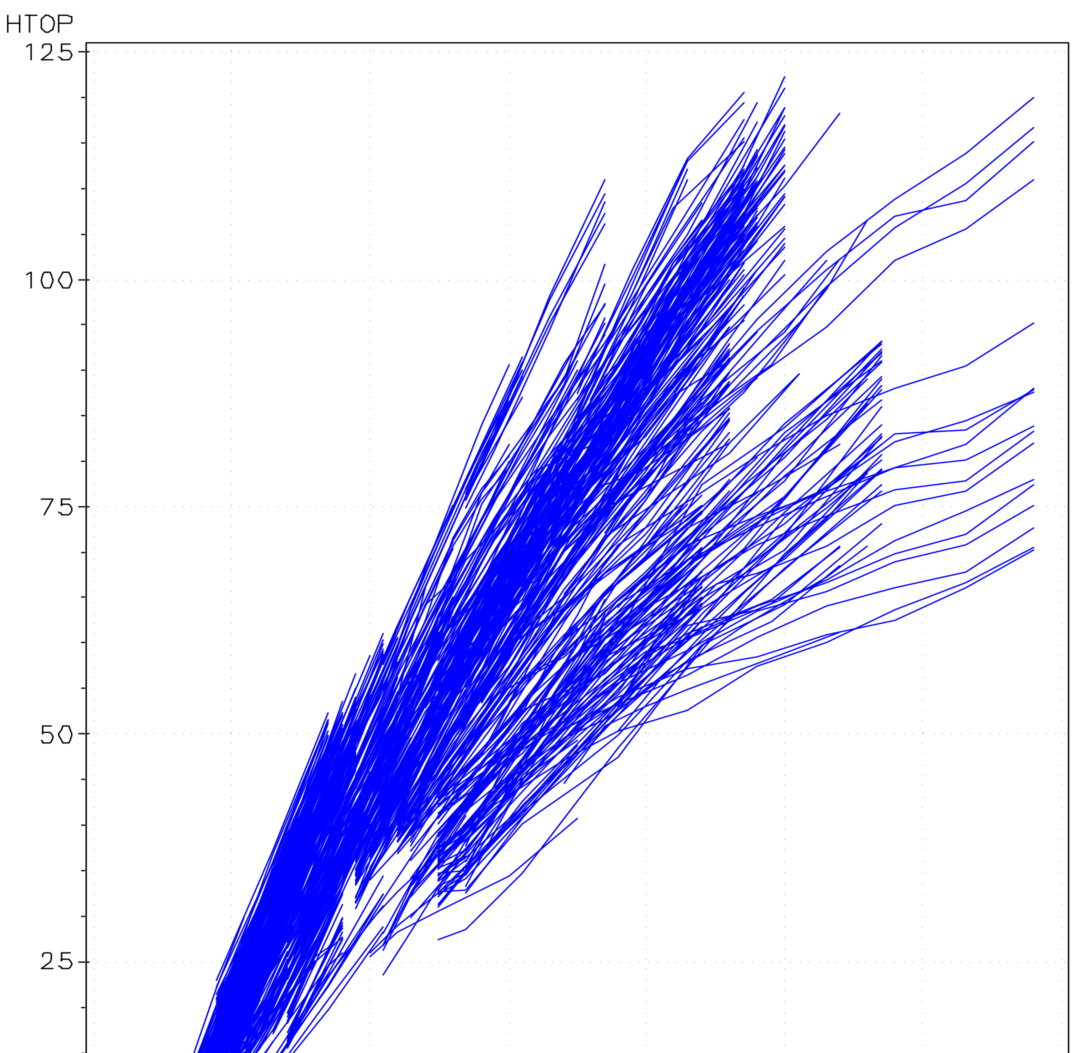
Total Age (Years)	Site Index = HTOP at Total Age 30						
	35	45	55	65	75	85	95
2	0.06	0.09	0.12	0.16	0.23	0.40	0.89
3	0.18	0.26	0.36	0.46	0.64	0.91	1.52
4	0.30	0.43	0.59	0.75	1.02	1.38	2.08
5	0.41	0.60	0.82	1.03	1.39	1.82	2.58
6	0.53	0.76	1.03	1.30	1.73	2.23	3.01
8	0.75	1.07	1.44	1.79	2.34	2.91	3.59
10	0.96	1.36	1.81	2.23	2.83	3.37	3.66
15	1.45	1.98	2.52	2.89	3.23	3.47	3.66
20	1.72	2.11	2.48	2.84	3.15	3.46	3.66
25	1.59	1.94	2.27	2.73	3.00	3.37	3.65
30	1.48	1.79	2.07	2.57	2.81	3.17	3.48
35	1.37	1.64	1.89	2.39	2.59	2.91	3.19
40	1.28	1.51	1.73	2.20	2.36	2.63	2.85
45	1.18	1.39	1.58	2.00	2.14	2.34	2.50
50	1.10	1.28	1.44	1.81	1.92	2.06	2.16
55	1.02	1.18	1.31	1.63	1.71	1.80	1.84
60	0.95	1.08	1.20	1.45	1.52	1.56	1.56
65	0.88	1.00	1.09	1.29	1.34	1.35	1.30
70	0.82	0.92	1.00	1.15	1.18	1.15	1.09

TABLE 3: DENSITY ADJUSTMENT MULTIPLIERS

Density function, a multiplier to be applied to top height increments from the base site curves. All total ages up to 10 are shown; then every fifth age. The density function has the value of 1.000 for 300 tpa at each age. The largest value on each row of the table is in bold type to indicate which of the tabulated densities has the highest growth rate.

d(AGE, TPA)

	TPA												
AGE	50	100	200	300	400	500	600	700	800	900	1000	1200	1600
2	0.650	0.714	0.899	1.000	1.068	1.118	1.158	1.191	1.219	1.243	1.264	1.299	**1.307**
3	0.737	0.785	0.925	1.000	1.050	1.088	1.117	1.141	1.162	1.179	1.194	1.220	**1.226**
4	0.795	0.833	0.942	1.000	1.039	1.067	1.090	1.108	1.123	1.136	1.148	1.167	**1.171**
5	0.834	0.865	0.953	1.000	1.031	1.053	1.071	1.085	1.097	1.107	1.116	1.130	**1.134**
6	0.861	0.887	0.961	1.000	1.025	1.044	1.058	1.069	1.079	1.087	1.094	1.106	**1.108**
7	0.880	0.903	0.967	1.000	1.022	1.037	1.049	1.059	1.066	1.073	1.079	1.088	**1.090**
8	0.892	0.913	0.971	1.000	1.019	1.032	1.043	1.051	1.058	1.063	1.068	1.076	**1.078**
9	0.901	0.920	0.973	1.000	1.017	1.029	1.038	1.045	1.051	1.056	1.060	1.067	**1.068**
10	0.906	0.925	0.975	1.000	1.016	1.027	1.035	1.041	1.046	1.050	1.054	1.060	**1.061**
15	0.878	0.936	0.980	1.000	1.011	1.018	1.023	1.026	1.028	1.030	1.031	1.032	**1.032**
20	0.891	0.948	0.987	1.000	1.006	1.008	**1.008**	1.007	1.005	1.003	1.001	0.996	0.986
25	0.915	0.968	0.996	**1.000**	0.998	0.993	0.987	0.980	0.973	0.967	0.960	0.947	0.923
30	0.951	0.996	**1.008**	1.000	0.987	0.974	0.960	0.947	0.934	0.922	0.910	0.888	0.848
35	0.996	**1.029**	1.022	1.000	0.976	0.952	0.930	0.909	0.890	0.871	0.853	0.821	0.763
40	1.047	**1.066**	1.038	1.000	0.963	0.929	0.898	0.869	0.842	0.817	0.793	0.749	0.674
45	1.101	**1.104**	1.054	1.000	0.950	0.906	0.865	0.827	0.793	0.761	0.731	0.676	0.582
50	**1.156**	1.143	1.071	1.000	0.937	0.881	0.831	0.785	0.743	0.704	0.668	0.602	0.489
55	**1.211**	1.182	1.087	1.000	0.924	0.858	0.798	0.744	0.694	0.649	0.606	0.529	0.397
60	**1.265**	1.221	1.103	1.000	0.912	0.834	0.765	0.703	0.646	0.594	0.545	0.457	0.307
65	**1.317**	1.258	1.119	1.000	0.899	0.812	0.734	0.664	0.600	0.541	0.486	0.388	0.220
70	**1.367**	1.293	1.133	1.000	0.887	0.790	0.703	0.626	0.555	0.490	0.430	0.321	0.136



(*ft*) versus Total Age

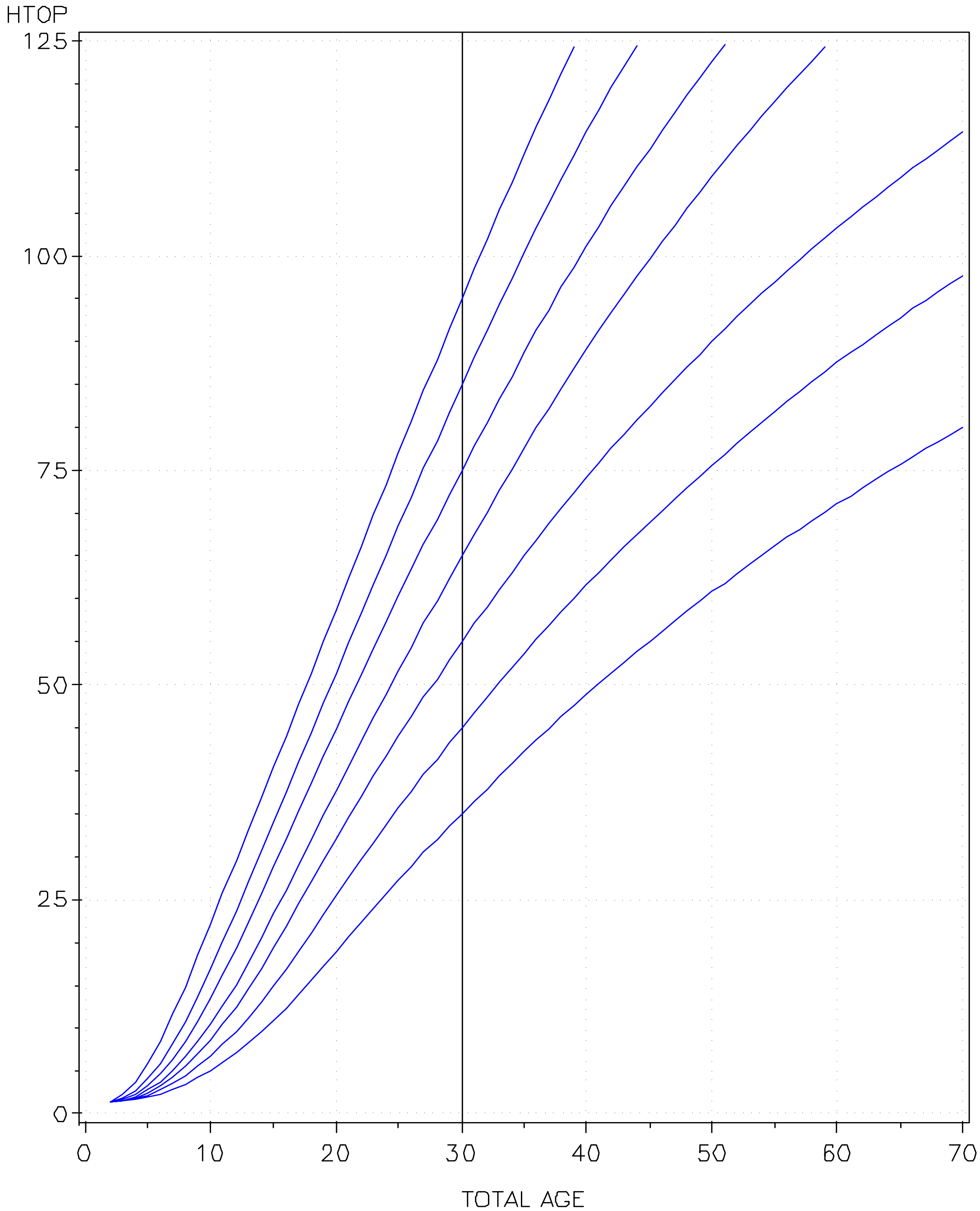


FIGURE 2. Base plantation site curves: top height (*ft.*) versus total age, for site index values 35, 45, 55, 65, 75, 85 and 95

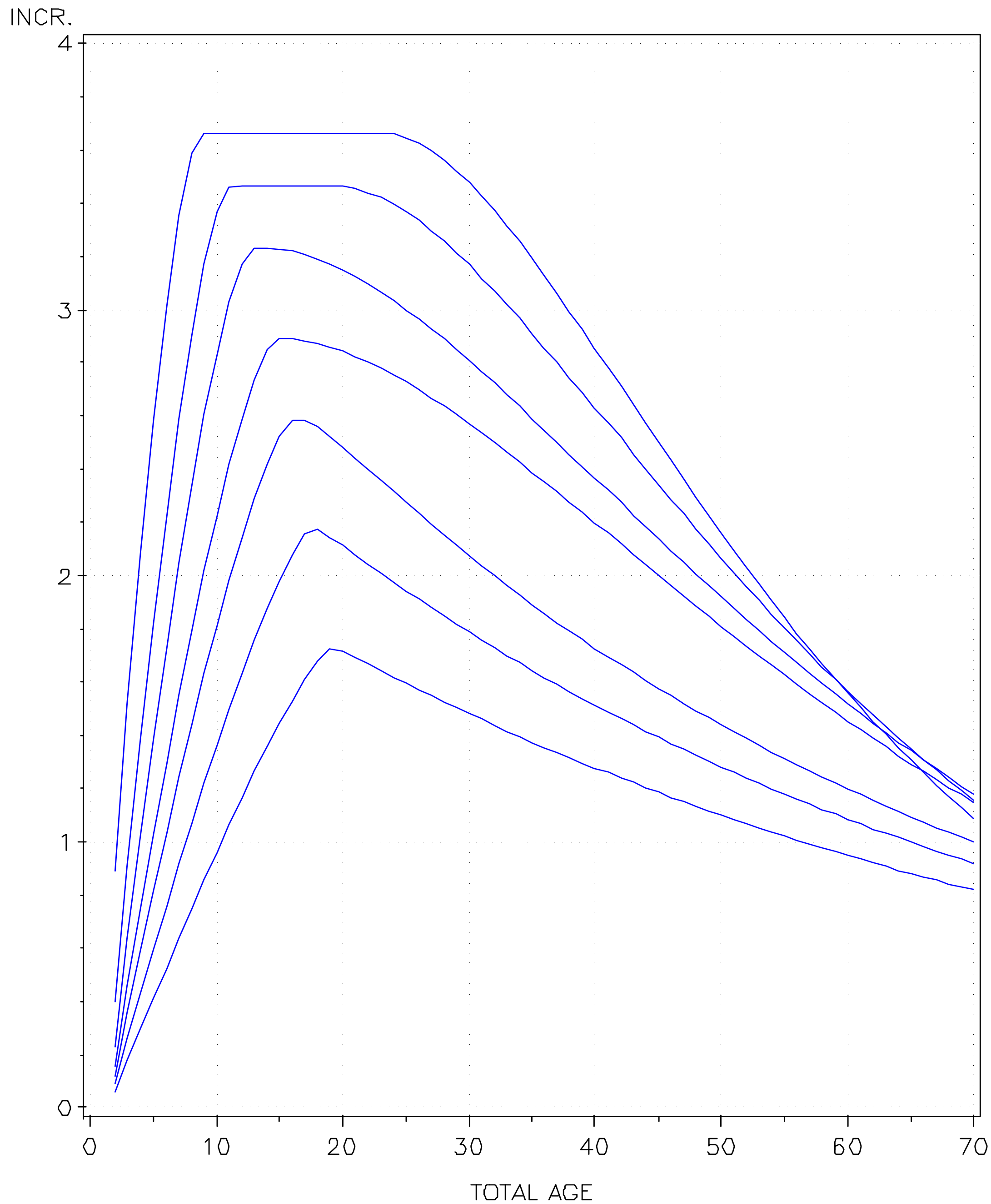


FIGURE 3. Annual increment in top height (*ft.*), for site index values 35, 45, 55, 65, 75, 85 and 95

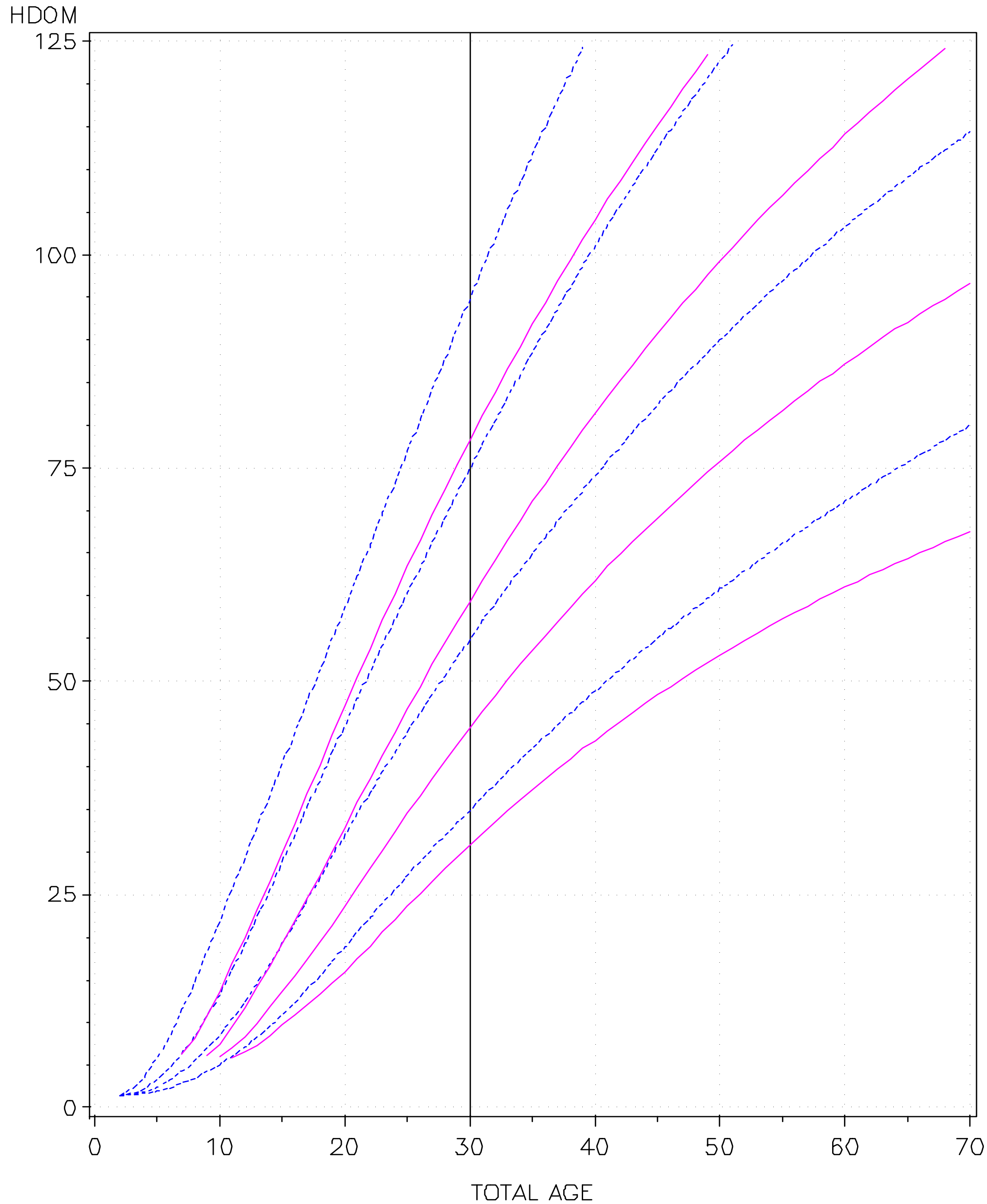


FIGURE 4. Comparison of Plantation and King (1996) Douglas-fir Site Curves [1]

[1] Douglas fir site curves from King (1966) are shown as solid lines: dominant height in feet (HDOM) versus total age for site index values 61, 86, 111,and 136 *ft.* (base age 50 years, breast height). The dashed lines show plantation curves for site index 35, 55, 75 and 95 *ft*.

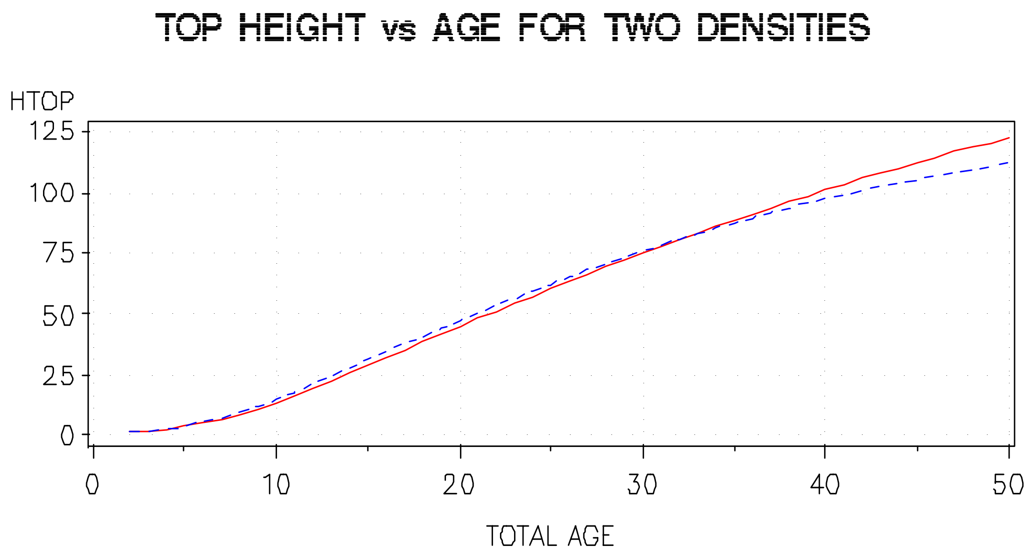


FIGURE 5. Top height *(ft.)* versus age for: 300 *tpa* (red solid), 1200 *tpa* (blue dashed).

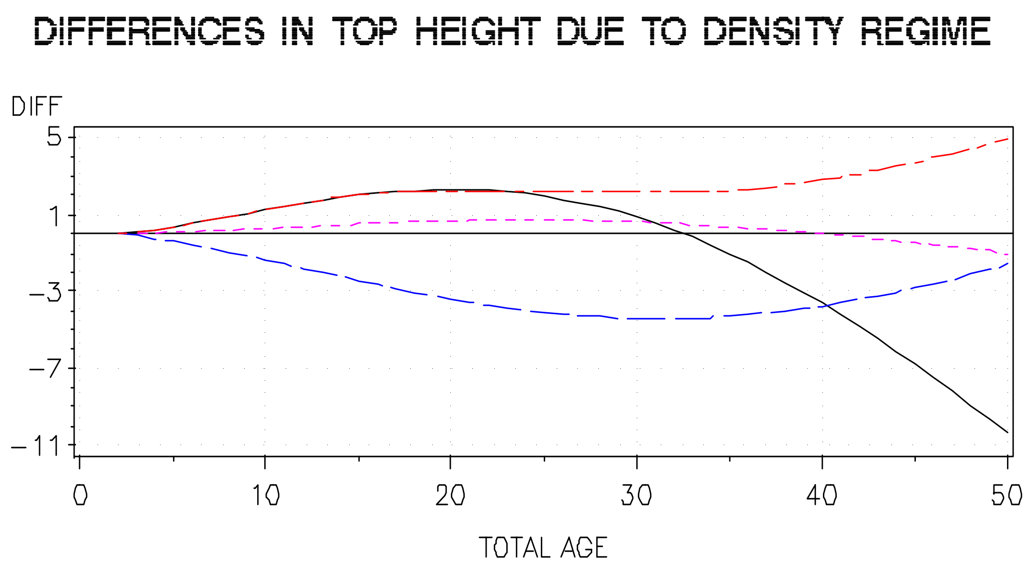


FIGURE 6. Differences in Top Height Due to Density Regime [2]

[2] Differences in top height *(ft.)* due to density for selected regimes. Values are density-adjusted top heights minus base top heights (300 *tpa*). Regime 1: 1200 *tpa* (black-solid line); 2: 400 *tpa* (magenta-short dashes); 3: 100 *tpa* (blue-long dashes), 4: 1200-300-100 *tpa*, at ages 2-17, 18-34, 35-50 (red-long and short dashes).

APPENDIX A: EQUATIONS FOR BASE SITE CURVES

The algebraic formulation of the base curves is a modification of that presented by Bonnor et al. (1995). These equations predict top height as a function of Ψ, total age (AGE), and several parameters which depend on Ψ through equations given here. Those parameters include ALPHA, b, c, λ_1, λ_2, x_1, x_2, $HTOP_1$, $HTOP_2$ and $HTOP_{max}$; the parameters have interpretations in terms of growth versus age graphs for a constant site index. The equations to predict these parameters involve thirteen coefficients, f_1 through f_{13}. The definition of the independent variable (x), and the initial value of top height ($HTOP_p$) are as follows:

$x = AGE - AGE_p$ where age at planting (AGE_p) is typically 2 years. (1)

$h_0 = HTOP_p$ (default value = 1.4 *ft*.) (2)

The steps in computing HTOP for a given value of x and Ψ follow. Each site curve is the integral of a growth versus age curve. The parameters of most interest are x_1: the value of x at the inflection point; x_2: the upper value of x for a age range where growth per year is constant; $HTOP_1$: the value of HTOP at $x = x_1$; $HTOP_2$ the value of HTOP at $x = x_2$; $HTOP_{max}$: the asymptote; b and c: shape parameters controlling the curve below the inflection; λ_1, λ_2, and ALPHA, shape parameters controlling the curve above the inflection. All of the parameters are algebraic functions of Ψ, which is the growth rate at the inflection.

For $x < x_1$:

$$HTOP = h_0 + \Psi \times \{ x + (1 - b) \times x_1/(c + 1) \times [(1 - x/x_1)^{(c+1)} - 1]\} \quad (3)$$

For $x = x_1$:

$$HTOP_1 = h_0 + x_1 \times \Psi \times [1 - (1 - b)/(c + 1)] \quad (4)$$

For $x_1 \le x \le x_2$:

$$HTOP = HTOP_1 + (x - x_1) \times \Psi \quad (5)$$

For $x > x_2$:

$$z = x - x_2$$

$$HTOP = HTOP_2 + ALPHA \times [(\lambda_1)^z - 1] + [HTOP_2 - HTOP_{max} - ALPHA] \times [(\lambda_2)^z - 1] \quad (6)$$

The parameters for the lower part of the curve (x_1, b, c) are determined as:

$$b = \text{logit}^{-1}(f_3 + f_4 \times \Psi)$$

$\text{logit}^{-1}(t) = \exp(t)/[1 + \exp(t)]$ with t constrained to [-8 , +8]

$$x_1 = [\,\text{Max}(1, f_1 + f_2 \times \Psi)\,]^{f_{13}}$$

$$c = f_5 + f_6 \times \Psi$$

The use of the inverse "logit" function does not imply logistic regression; this is simply one of several simple transforms that map from a domain of [-∞, +∞] to the range [0, 1]

The parameters for the middle (straight section) are:

$$x_2 = x_1 + \max(0, f_7 + f_8 \times \Psi)$$

$$HTOP_2 = HTOP_1 + (x_2 - x_1) \times \Psi$$

The parameters for the upper part of the curve (ALPHA, λ_1 and λ_2), are functions of Ψ and empirical coefficients f_9, f_{10}, f_{11}, f_{12} :

$$HTOP_{max} = f_{10} + f_9 \times \Psi$$

$$\lambda_1 = 0.05 + [\,\exp(2 \times \Psi/(HTOP_2 - HTOP_{max})) - 0.05] \times \text{logit}^{-1}(f_{11} + f_{12} \times \Psi)$$

where $\text{logit}^{-1}(t) = \exp(t)/[1 + \exp(t)]$ with t constrained [-8, 8]

$$ALPHA = -\Psi^2 / [\,\ln^2(\lambda_1) \times (HTOP_2 - HTOP_{max}) - 2 \times \ln(\lambda_1) \times \Psi\,]$$

$$\lambda_2 = \exp\{\,[\Psi - ALPHA \times \ln(\lambda_1)] / [HTOP_2 - HTOP_{max} - ALPHA]\,\}$$

The empirical coefficients are:

f_1	6464.0	f_7	-102.4
f_2	-1691.0	f_8	31.93
f_3	-29.23	f_9	39.67
f_4	7.510	f_{10}	66.58
f_5	0.9075	f_{11}	-42.79
f_6	0.1788	f_{12}	16.57
f_{13}	0.3505		

The following table shows parameter values for site indices 35 *ft*. through 95 *ft*.

Site Index	ψ	X_1	X_2	$HTOP_1$	$HTOP_2$	$HTOP_{MAX}$	b	c	λ_1	λ_2	ALPHA
35	1.73432	17.52	17.52	18.1	18.1	135.4	0.00034	1.218	0.0503	0.9853	0
45	2.18503	16.09	16.09	21.3	21.3	153.3	0.00034	1.298	0.0513	0.9835	0
55	2.59371	14.55	14.55	23.2	23.2	169.5	0.00034	1.371	0.5504	0.9819	0
65	2.89195	13.20	13.20	23.8	23.8	181.3	0.00055	1.425	0.9586	0.9681	224
75	3.23237	11.25	12.06	23.2	25.9	194.8	0.00700	1.485	0.9622	0.9628	5041
85	3.46601	9.43	17.70	21.7	50.3	204.1	0.03916	1.527	0.9556	0.9562	5414
95	3.66335	7.11	21.68	18.8	72.2	211.9	0.15210	1.563	0.9486	0.9492	5730

APPENDIX B: EQUATIONS FOR DENSITY ADJUSTMENTS

The adjusted top height increment for the a year is the base increment (ΔHTOP) times a density-effect function:

$$(\Delta HTOP)' = (\Delta HTOP) \times d(AGE, TPA) \quad (1)$$

The density-effect multiplier is a quadratic function in ln(TPA):

$$d(AGE,TPA) = 1 + F_1(AGE) \times [\ln(TPA) - \ln(TPA_{ref})] + F_2(AGE) \times [\ln^2(TPA) - \ln^2(TPA_{ref})] \quad (2)$$

$$TPA_{ref} = 300 \quad (3)$$

$$F_2(AGE) = p_1 + p_2 \times \ln(AGE + p_0) + p_3 \times [\ln(AGE + p_0)]^2 \quad (4)$$

$$F_1(AGE) = -2 \times F_2(AGE) \times F_3(AGE) \quad (5)$$

$$F_3(AGE) = p_5 + p_6 \times \ln(AGE + p_0) + p_7 \times [\ln(AGE + p_0)]^2 \quad (6)$$

If TPA is beyond the range of densities in the fitting data, it is recommended that TPA be moved into those ranges before being used in the above equations. Those ranges are:

80 to 1250 for ages up to 10

40 to 1900 for older ages.

The coefficients are:

p_0	7.00	p_1	-.2320	p_2	.1636	p_3	-.030128
p_5	34.636	p_6	-13.18	p_7	1.393		

The F_2 function controls the degree of concavity of the density function with respect to ln(TPA). The maximum value of the density function for a given age occurs where the logarithm of TPA equals $F_1/[-2 \times F_2]$, as can be inferred by differentiating Eqn. 2. The logarithm of that TPA value is referred to as F_3(AGE) and is empirically estimated (Eqn. 6). F_1 can be calculated from F_2 and F_3, as is shown in Eqn. 5.

APPENDIX C: SOFTWARE OVERVIEW

Callable software referred to as DFSITE has been made available to SMC members. The following is a partial reproduction of the user documentation. It's purpose here is to clarify what inputs are required to use these site curves. The specifications of the user calls may change over time; in preparing to use the software, documentation distributed with the program should be referred to. The software can be found at:

http://www.cfr.washington.edu/research.smc/pubs.htm

Overview of user calls

DFSITE1 Sets up any parameters that may affect operation of software.

DFSITE2 Initializes site operations. Specifies height at assumed planting age.

DFSITE3D Specifies a whole or partial density regime.

DFSITE3H Specifies a known height and age; calculates and sets SI and PSI (Ψ). Specified height may be a base height, or an adjusted height.

DFSITE3P Specifies Ψ (feet).

DFSITE4 Specifies an age. Returns "base" height.

DFSITE5 Specifies an age. Returns heights (base and adjusted) for multiple that age and earlier.

Typical usage:

DFSITE1 is called once per execution before any other call.

DFSITE2 is called multiple times. Call after DFSITE1, and for every new simulation -where a density regime is to be replaced or a new site curve is to be evaluated.

DFSITE3D may be called before or after a site curve is determined. It must be called before density-adjusted heights can be used or calculated. Multiple calls allowed.

DFSITE3H or DFSITE3P determine the site curve. Most often DFSITE3H will be used, but DFSITE3P is also a valid means of setting the curve. Multiple calls not allowed.

DFSITE4 and DFSITE5 can be called after the site curve has been determined.

Specification for user calls

SUBROUTINE DFSITE1(FVEC, NVEC, IER)

Purpose:

Establish control parameters

Inputs:

FVEC	REAL*4(10)	floating point control parameters
NVEC	integer(10)	integer control parameters

Outputs:

IER	integer	error code (0 for no error)

Notes:

NVEC (1) = Maximum age to ever use. Required: 30-100 or 0
0 will default to 100.
For current applications, suggest always using 100 (or 0)
Initialization would go a bit faster with lower values.
In the future, if age is ever used as an output, there
may be a reason to want lower values for NVEC(1)

NVEC (2) = 1 for English units (feet, TPA), 2 for metric (m., TPH)
affects all user input and output, except psi and fvec(*).

FVEC (1) = Convergence criterion used in matching to specified ht (ft)

FVEC (2) = Convergence criterion, fraction of targeted height.
If both FVEC(1) or FVEC(2) are <= 0, defaults are used.
If only one is positive, that one is used.
If both positive, then max error for a specified ht is:

MIN[FVEC(1), FVEC(2)*(specified height)]

Other array positions. Suggest that these be set to zero; for future use.

SUBROUTINE DFSITE2(Hplant)

Purpose:

Specify height at planting. Reinitializes site curve and density history.

Inputs:

HPLANT	Real*	height at planting. (ft or m); or 0 for default.

Note:

Planting age is presently hard-coded at two years. Hence the argument for this function should be height at two years. At a later date, planting age might become an input argument.

SUBROUTINE DFSITE3D(IAGE1, IAGE2, DENV, IER)

Purpose:

Specify a complete or partial density history.

Inputs

IAGE1	integer	1st age with new specification (>= 1)
IAGE2	integer	last age with new specification. (IAGE2 >= IAGE1)
DENV	REAL*4(100)	densities (array positions IAGE1 to IAGE2)

Output:

IER	intege	Error code (0=OK, 1= WRONG age range)

Notes:

TPA's's (or TPH's) must be in DENV(IAGE1) through DENV(IAGE2)

if IAGE1 > 2, the earlier ages must have been given in earlier call.

Generally, all ages from 2 to (final-1) are given; age 1 is irrelevant.

DENV(i) is the TPA (or TPH) in the stand growing from age i to i+1.

SUBROUTINE DFSITE3H(HT_R4, IHTYPE, IAGE, PSI_FEET, SI_R4, IER)

Purpose:

Specify a height (base or adjusted). Calculate psi and SI.

Inputs:

HT_R4	real*4	height (feet or meters)
IHTYPE	integer	1 if HT_R4 is a BASE height, 2 if density-adjusted
IAGE	integer	age from seed [> 2, <= NTROL(1)]

Outputs:

PSI_FEET	real*4	Ψ (psi) with units of feet.
SI_R4	real*4	site index (from base curve), feet or meters
IER	integer	error code (>0 indicates errors)

Notes:

Typically used to calculate exhibited site, or to specify a site index (with IAGE=30).

SUBROUTINE DFSITE3P(PSI_FEET, SI_R4)

Purpose:

Specify Ψ in feet. Determine a site curve.

Input:

PSI_FEET	real*4	Ψ in feet (metric NOT ALLOWED)

Output:

SI_R4	real	site index (feet or meters)

SUBROUTINE DFSITE4(IAGE, Hbase_R4, HADJ_R4)

Purpose:

Find base height at a given age.

Input:

IAGE	integer	total age from seed

Output:

HBASE_R4	real*4	base (unadjusted) height (ft or m)
HADJ_R4	real*4	Reserved for future use.

SUBROUTINE DFSITE5(IAGE, IFILLALL, HV_R4, HADJV_R4)

Purpose:

(1) Calculate base heights for ages through IAGE

(2) Calculate adjusted heights IF densities already specified.

Input:

IAGE	integer	total age (maximum age for which heights wanted)
IFILLALL	integer	1 if all ages through IAGE are wanted.
		0 if previously requested ages not needed.

Output:

HV_R4	real*4(100)	base (unadjusted) height (ft or m)
HADJV_R4	real*4(100)	adjusted heights (ft or m)

Notes:

In the case of multiple calls to DFSITE5, with increasing ages, previously returned heights may not be provided again IF IFILLALL has been set to zero. There is an interaction between which density histories have been provided, and which ages have been requested. Generally the user should not change the vectors between calls. Then the user can rely on HV_R4 always being complete through IAGE, and HADJV_R4 being complete through the lesser of IAGE, or 1 + the last age for which density was provided. [cell for age 1: reserved usage]

APPENDIX D: SMC INSTALLATIONS WITH BOTH PLANTED AND NATURAL SITE INDEX VALUES

(data are sorted by natural stand site index)

INST #	INST NAME	STATE PROV.	ELEV ft	BIRTH YEAR	# plots	FINAL AGE	Planted SI	Natural SI	Method
511	DOE - WTH - DF Low	WA	1000	1978	6	14.0	58	79	9
731	Dingle 4	WA	3800	1978	7	21.0	50	80	8
501	Last Creek	OR	3858	1973	1	25.0	57	90	8
705	East Twin Creek	WA	2700	1974	9	20.8	75	90	7
716	Quilla Creek	BC	760	1978	7	19.0	72	100	8
720	Horton	OR	1300	1978	7	20.0	76	100	7
502	Baldy B	OR	3200	1987	3	8.0	47	105	7
913	Nimpkish Road	BC	820	1987	12	11.0	66	108	9
739	Silver Panther II	OR	1150	1983	1	16.0	93	110	9
510	DOE - WTH - DF High	WA	1000	1978	6	14.0	77	111	9
802	Catt Creek	WA	2400	1959	5	40.0	65	112	7
935	Skidder Hill	WA	1000	1988	6	10.0	86	115	7
807	Viola	OR	500	1972	5	26.0	80	115	8
724	Vedder Mountain	BC	1770	1980	10	17.0	89	115	9
917	Cultus Lake	BC	1700	1987	12	11.0	91	115	9
918	Grimm Road A	OR	750	1988	6	11.0	88	115	9
938	Grimm Road B	OR	750	1988	6	11.0	82	115	9
709	Mill Cr. Mainline	OR	1950	1971	7	26.0	78	120	7
722	Silver Creek Mainline	OR	2200	1975	12	21.7	71	120	8
736	Twin Peaks	WA	600	1982	16	14.6	91	120	7
903	Prather Creek	OR	2000	1984	6	14.0	75	120	8
247	RADIO HILL	WA	2120	1967	6	30.0	83	120	7
725	Sandy Shore	WA	550	1980	12	18.3	88	120	9
932	Forks #3	WA	400	1987	6	12.0	87	120	9
910	King Creek	WA	550	1985	9	14.0	75	123	9
914	Lewisburg Saddle	OR	750	1987	6	11.0	88	123	9
937	Ames Creek	OR	1000	1993	6	6.0	93	123	7
940	Mowich	WA	1700	1993	6	6.0	85	123	7
717	Grant Creek #1	OR	1000	1981	10	15.9	96	124	9
708	Copper Creek	WA	900	1979	12	17.3	92	125	8
734	Upper Canada Creek	OR	1000	1978	7	18.3	72	125	9
919	Brittain Creek #1	WA	360	1988	6	10.0	90	125	7
706	B & U Plantation	WA	300	1975	12	20.1	90	125	7
718	Roaring River 100-REV	OR	1100	1979	12	18.1	86	128	6
915	Big Tree	OR	1600	1987	6	12.0	89	128	6
916	Bobo's Bench	OR	1100	1986	6	12.0	78	128	9
812	Panther Creek	WA	1363	1955	5	44.0	67	130	7
901	Lincoln Creek	WA	350	1983	6	13.0	94	130	7
806	Elk Creek	OR	750	1962	5	37.0	86	132	9
805	Pilchuck Bridge	WA	550	1968	5	31.0	86	135	7
726	Toledo	OR	300	1982	12	16.1	91	135	9
710	Trail Creek	OR	600	1976	9	21.0	73	138	7
723	Formader Ridge	OR	1250	1979	5	19.0	87	140	7
729	Gnat Creek	OR	500	1981	12	17.1	95	140	7
905	LaVerne Park	OR	15	1986	6	13.0	90	150	9
	Mean						81.5	119.5	
	Stardard Deviation						11.36	14.28	

Site indices are in feet. Natural site indices have basis breast-height age 50. The basis for the planted site indices are total age 30; these are weighted means of the plot "exhibited" site indices at the oldest age not influenced by fertization; plots with the older ages are given greater weight.

Natural stand site index methods are coded:

6: Estimated from habitat type.

7: From soil series.

8: From natural stand adjacent to plantation.

9: From previous natural stand.