# PREDICTING BASAL AREA INCREMENT FOR INDIVIDUAL NORTHERN ROCKY MOUNTAIN CONIFERS

by

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## SUMMARY

A model was developed to predict periodic basal area increment for individual trees. This model is independent of site index, age, and inter-tree distance and has been calibrated for 11 conifer species that occur in the northern Rocky Mountains. It has been tested extensively as a component in a growth-projection system that is used for management planning. Model parameters were estimated with linear regression using National Forest inventory data that represent mostly unmanaged stands. The model performed acceptably when evaluated using an independent data set that was collected from young managed stands. Model formulation, behavior, and evaluation are described.

Keywords: diameter increment, tree-growth modeling, stand projection, basal area increment

## INTRODUCTION

A model was developed to predict periodic basal area increments for 11 conifer species in the northern Rocky Mountains. This model is calibrated for eastern Washington, northern Idaho, and western Montana, a region that is known as the Inland Empire (fig. 1). The Inland Empire encompasses over 10 million hectares of commercial forest land, much of it mountainous (forests range from 0.4 to 2.5 km in elevation), with commensurate variability in the climate and in the structure of plant communities. At the climatic extremes, forests are relatively simple and growth is slow. At mid-elevations and along stream bottoms, however, there are moist sites with complex plant associations and highly productive forests. The biotic complexity has been heightened by large fires, pest and disease outbreaks, and questionable logging practices (Haig, Davis, and Weidman 1941). These factors have created forests in which nearly every stand is unique with regard to species composition, age classes, and stocking characteristics.

The model makes no explicit use of inter-tree distance, site index, or age. Most site index curves that are available for the Inland Empire assume that dominants are even-aged and were never suppressed. These conditions are not typical of Inland Empire stands. Further, many of the species that dominate the more productive sites are highly susceptible to heartrots, which makes it difficult to determine age. In general, the accepted inventory procedures do not produce reliable site index and age estimates.

The basal area increment model is the central component in a stand projection system, the Prognosis Model (Stage 1973; Wykoff, Crookston, and Stage 1982), that is used for silvicultural and management planning throughout the Inland Empire (Stage, Babcock, and Wykoff 1980). Because of the diversity of stand structures that is characteristic of the region, representation of stand development with a stand-level model was deemed infeasible. Instead, periodic increment predictions are made for individual trees, and stand statistics are compiled from updated tree records. The Prognosis Model is intended for use with actual stand inventories, and past diameter increment is an important input variable.

## METHODS

Independent models were fitted for each species using linear regression. Increment data were obtained from management planning inventories for the 10 National Forests in the Inland Empire. These inventories are stand oriented, and each inventory is intended to provide a representative sample of the stands that comprise a forest (Stage and Alley 1972). Within sampled stands, points were systematically located to represent approximately 2 hectares. At each sample point a small fixed area plot (approximately 0.00135 ha) was used to collect data on small trees (d.b.h. less than 12.7 cm) and a variable radius plot (usually basal area factor 9.18 $m^2$/ha) was used to collect data on larger trees. All trees within the plots were measured for d.b.h., crown ratio, and other characteristics that might influence management actions. A sub-sample, stratified by broad d.b.h. classes, was selected for measurement of height, age, and 10-year radial increment (USDA Forest Service, 1978). For each stand, slope, aspect, elevation, and habitat type (Pfister and others, 1977) were also recorded to reflect the general physiographic and ecological characteristics of the site. Prior to model fitting, all diameters and density measures were backdated to the start of the growth period. Only trees with backdated d.b.h. greater than 7.62 cm were actually used for parameter estimation. In all, slightly more than 44,000 usable increment records were available and they represented a broad spectrum of ecological conditions (Table 1).

## MODEL STRUCTURE AND BEHAVIOR

Although linear regression was used to estimate model parameters, the structure of the model is based on theoretical, as well as empirical considerations. The objective was to develop a model that not only fit well to the data but also extrapolated beyond the data in a biologically reasonable manner. The model predicts expected increments that are explicitly dependent on tree, stand, and site factors (eq. 1).

$$
\begin{aligned}
\ln(bai) \quad & HAB + LOC + b_1 \cdot \ln(D) + b_2 \cdot D^2 + b_3 \cdot BL \\
& + b_4 \cdot CR + b_5 \cdot CR^2 + b_6 \cdot CCF + \\
& + b_7 \cdot \cos(ASP) \cdot SL + b_8 \cdot \sin(ASP) \cdot SL + b_9 \cdot SL + b_{10} \cdot SL^2 \\
& + b_{11} \cdot EL + b_{12} \cdot EL^2 \qquad (1)
\end{aligned}
$$

where:

| | |
|---|---|
| bai | tree basal area increment inside bark, |
| HAB | intercept that is dependent on species and habitat type, |
| LOC | intercept that is dependent on species and location, |
| D | tree diameter at breast height, |
| BL | total basal area of all trees in the stand that are larger, |
| CR | ratio of live crown length to total tree height, |
| CCF | crown competition factor, |
| ASP | average angle of aspect for stand, |
| SL | average stand slope (percent), |
| EL | average stand elevation, |
| $b_i$ | species dependent regression coefficients. |

The variables in the model reflect size or maturity, site capability, tree vigor, and stand density. Tree vigor and stand density effects are most important for simulating response to thinning.

Table 1.--Distribution of diameter increment data by species and habitat type

| Habitat type[1] | Western white pine | Western larch | Douglas-fir | Grand fir | Western hemlock | Western redcedar | Lodgepole pine | Engelmann spruce | Subalpine fir | Ponderosa pine | Mountain hemlock | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SCREE | 0 | 0 | 36 | 0 | 0 | 0 | 1 | 3 | 3 | 22 | 0 | 65 |
| PIPO/AGSP | 0 | 0 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 10 | 0 | 13 |
| PIPO/PUTR | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 |
| PIPO/SYAL | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 2 |
| PSME/AGSP | 0 | 0 | 127 | 0 | 0 | 0 | 8 | 0 | 4 | 59 | 0 | 198 |
| PSME/FEID | 0 | 0 | 4 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 0 | 7 |
| PSME/VACA | 0 | 26 | 75 | 2 | 1 | 0 | 65 | 0 | 0 | 25 | 0 | 194 |
| PSME/PHMA | 26 | 236 | 1830 | 116 | 7 | 60 | 171 | 16 | 12 | 711 | 0 | 3185 |
| PSME/VAGL | 1 | 39 | 61 | 0 | 0 | 0 | 93 | 2 | 0 | 3 | 0 | 199 |
| PSME/LIBO | 0 | 86 | 140 | 2 | 0 | 0 | 115 | 4 | 2 | 27 | 0 | 376 |
| PSME/SYAL | 1 | 66 | 528 | 5 | 0 | 0 | 63 | 7 | 17 | 234 | 0 | 921 |
| PSME/CARU | 0 | 141 | 558 | 5 | 0 | 4 | 179 | 23 | 20 | 234 | 0 | 1164 |
| PSME/CAGE | 0 | 0 | 41 | 0 | 0 | 0 | 1 | 0 | 1 | 17 | 0 | 60 |
| PSME/SPBE | 0 | 0 | 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 8 |
| PSME/ARUV | 0 | 4 | 1 | 0 | 0 | 0 | 3 | 0 | 0 | 5 | 0 | 13 |
| PICEA/CLUN | 0 | 14 | 8 | 0 | 0 | 0 | 17 | 1 | 0 | 0 | 0 | 40 |
| PICEA/VACA | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 1 | 0 | 0 | 4 |
| PICEA/LIBO | 0 | 59 | 23 | 0 | 0 | 0 | 41 | 13 | 2 | 1 | 0 | 139 |
| ABGR/XETE | 4 | 218 | 521 | 370 | 5 | 14 | 509 | 65 | 21 | 156 | 0 | 1883 |
| ABGR/CLUN | 157 | 481 | 1397 | 816 | 39 | 67 | 317 | 169 | 115 | 156 | 0 | 3715 |
| THPL/CLUN | 394 | 798 | 1471 | 1270 | 22 | 1176 | 561 | 286 | 177 | 106 | 38 | 6299 |
| THPL/OPHO | 0 | 4 | 3 | 4 | 11 | 53 | 0 | 10 | 20 | 0 | 0 | 105 |
| TSHE/CLUN | 968 | 1124 | 1660 | 1692 | 1667 | 991 | 870 | 314 | 332 | 68 | 37 | 9723 |
| ABLA/OPHO | 1 | 6 | 13 | 0 | 0 | 0 | 3 | 36 | 20 | 0 | 0 | 79 |
| ABLA/CLUN | 118 | 621 | 883 | 179 | 9 | 32 | 709 | 673 | 793 | 19 | 39 | 4075 |
| ABLA/GATR | 0 | 6 | 0 | 0 | 0 | 0 | 0 | 1 | 4 | 0 | 0 | 11 |
| ABLA/VACA | 0 | 1 | 0 | 0 | 0 | 0 | 17 | 0 | 0 | 0 | 0 | 18 |
| ABLA/CACA | 0 | 0 | 5 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 7 |
| ABLA/LIBO | 0 | 61 | 46 | 3 | 0 | 0 | 146 | 35 | 39 | 0 | 0 | 330 |
| ABLA/MEFE | 32 | 183 | 182 | 27 | 2 | 14 | 408 | 556 | 767 | 0 | 55 | 2226 |
| TSME/MEFE | 44 | 65 | 103 | 14 | 1 | 4 | 260 | 175 | 388 | 0 | 488 | 1542 |
| ABLA/XETE | 35 | 205 | 1031 | 108 | 2 | 4 | 1536 | 290 | 726 | 68 | 8 | 4013 |
| TSME/XETE | 21 | 32 | 139 | 40 | 4 | 2 | 144 | 51 | 146 | 0 | 245 | 824 |
| ABLA/VAGL | 0 | 19 | 21 | 0 | 0 | 0 | 25 | 0 | 2 | 2 | 0 | 69 |
| ABLA/VASC | 0 | 47 | 19 | 0 | 0 | 0 | 150 | 53 | 81 | 0 | 0 | 350 |
| ABLA-PIAL/VASC | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 0 | 0 | 3 |
| ABLA/LUHI | 0 | 9 | 17 | 0 | 0 | 0 | 146 | 146 | 319 | 0 | 15 | 652 |
| PIAL-ABLA | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 1 | 13 | 0 | 10 | 27 |
| LALY-ABLA | 0 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 |
| OTHER | 3 | 91 | 568 | 30 | 4 | 20 | 391 | 159 | 220 | 58 | 0 | 1544 |
| Total | 1805 | 4645 | 11522 | 4683 | 1774 | 2441 | 6952 | 3092 | 4248 | 1989 | 935 | 44086 |

[1] Habitat codes defined in appendix A.

## Tree Size and Rate of Maturity

The variables ln(D) and $D^2$ represent the relative maturity of the tree. The logarithm of basal area increment is linearly related to the logarithm of d.b.h. with a relatively homogeneous variance (fig. 2). This allometric transformation results in some bias in predicted basal area increment, but the bias can be removed with a theoretical or empirical bias adjustment.

The coefficient of ln(D) is positive and usually has a value close to 1. The coefficient of $D^2$ is relatively small and negative. With other factors held constant, predicted ln(bai) increases with increasing D until the tree attains a diameter of 50 to 70 cm. Then, due to the increasing influence of the $D^2$ term, the ln(bai) predictions begin to decline. When predicted ln(bai) is converted to diameter increment, and plotted against D, the graph takes the skewed unimodal form that is typical of increment curves (fig. 3). The magnitude of the $D^2$ coefficient has considerable bearing on the ultimate diameters attained by trees in long-term simulations. These coefficients were found to be significantly different for different locations.

## Site Effects

Habitat types, along with other site descriptors, are used instead of site index as a gauge of the relative productivity of forest sites. The habitat type system is a land classification based on plant associations in climax forest communities (Daubenmire and Daubenmire, 1968). The habitat type system has been extended by Pfister and others (1977) and Steele and others (1981) to encompass most forest conditions in the Inland Empire. Techniques were also developed for recognizing habitat types on cutover and regenerated sites and habitat type can be readily determined for almost any stand within the Inland Empire.

Habitat type provides a crude gauge of productivity, but there is a great deal of variation in productivity within a type and much overlap between types. Some of the variation within types is accounted for by topographic variables such as location, slope, aspect, and elevation. In application, a further assessment of site quality is provided by measured increment data.

It would be desirable to treat location as a continuum, but latitude is confounded with differences in soil parent material and the orographic effects of the Selway-Bitterroot divide that bisects the Inland Empire from the northwest to the southeast. We have been unable to find a continuous expression of location that outperforms the simple discrete classification afforded by National Forest boundaries.

Slope and aspect effects are included with a modification of Stage's (1976) transformation. This transformation is circular (it gives the same result for ASP=0 and ASP=360) and optima exist with respect to both slope and aspect. When the aspect is level (SL=0), the transformation has a net contribution of zero to the ln(bai) prediction. For most species, optimum growth occurs on moderate slopes (30 to 40 percent) with southerly aspects.

A quadratic transformation is used to express elevation effects. All other factors held constant, the largest increments are predicted for elevations in the mid-range of species occurrence (EL=900 to 1200 m).

The Prognosis Model is designed to project inventories from existing stands and measured diameter increments are used to further enhance the discrimination of site capability. Predictions are made for each observed increment and then model intercepts are adjusted such that the median residual from the increment sample is equal to zero on the log scale (Stage 1973, 1981).

## Factors That Are Changed by Thinning

Because inter-tree distance is not used, terms expressing density and relative size effects are needed to produce the expected responses to management. Crown ratio is an expression of tree vigor, CCF (Krajicek and others, 1961) represents stand density, and basal area in larger trees integrates stand density and relative tree size.

CCF is based on a simple linear relationship between crown width and d.b.h. in open-grown trees. By assuming a circular crown base, crown coverage can be computed as a quadratic function of d.b.h. Crown coverage is expressed as percent of a unit area covered by an open-grown crown and stand density is determined by summing crown coverage across all trees in the sample for a stand. Using data from normal yield tables for even-aged upland oaks and Sitka spruce, Krajicek and others (1961) concluded that CCF was more or less constant for a wide range of age and site index.

Experience with uneven-aged stands containing large regeneration components led to the conclusion that small-tree crown coverage is overestimated by CCF. These stands typically have large CCF's (>300) but increment samples extracted from the sparse overwood are more typical of samples from open-grown stands. By assuming an allometric relationship between tree d.b.h. and crown coverage, the impact of small trees on CCF was substantially reduced and sensitivity of ln(bai) to density was somewhat enhanced. The allometric crown coverage models have exponents ranging from 1.5 to 1.8 and are more or less coincident with the quadratic crown coverage models for d.b.h. greater than 25 cm (fig. 4).

Stage (1973) used percentile in the distribution of tree basal area (PCT) as an indicator of relative dominance. PCT reflects competitive status and does an excellent job of explaining variation in increments in undisturbed stands. It results, however, in a counter-intuitive thinning response. When trees are removed from below, the smaller residual trees have substantially reduced PCT's. Because the regression coefficient for PCT is positive, the increment predictions following thinning are smaller than they would have been if the stand were not thinned. Basal area in larger trees (BL) conveys essentially the same information about competitive status. But BL has a negative coefficient and since BL is either the same or smaller following thinning, predicted increments are usually larger.

When a stand is thinned, stand density and the distribution of trees among size classes are changed. Over time, these changes may lead to elongation of crowns as trees are subjected to less competition. Trees with large crowns and trees in dominant crown positions are expected to attain larger basal area increments than trees with small crowns that are in subordinate crown positions. As stand density increases, all other factors held constant, a reduction in increments for all trees is expected (fig. 3). Similarly, when the stand is thinned, individual tree increments are expected to increase.

## MODEL EVALUATION

To test the performance of the model, residuals were plotted against each of the independent variables. There were no discernible patterns of association, and no significant ($P = 0.05$) linear relationships between the residuals and the predictor variables. In a second test, residuals were plotted against all possible interactions between the four tree-specific variables (D, CR, BL, and CCF). For Douglas-fir, all combinations that included D and CR were statistically significant, but the best (CR, D, and CCF) explained only 0.2% of the residual variation. The significance of this interaction is clearly attributable to large numbers of observations, and its omission is of no practical importance.

An independent dataset was used to evaluate the extrapolative behavior of the model. This dataset was a byproduct of a height increment study in managed regeneration stands. The measurement procedures used in this study were consistent with the procedures used in the timber management inventory. In comparison to the inventory data used to fit the model, the regeneration stands were relatively even-aged and predominantly from better sites, and the trees were younger and generally better spaced (Table 2). There were a total of 2,894 observations representing all of the species included in the timber management inventory except for mountain hemlock (Table 3).

Predictions were made for each of the observations from the managed regeneration stands. Residuals were computed and fitted against predicted ln(bai) and observed ln(D). Table 4 summarizes observed bias and percent of variation in residuals attributable to predicted ln(bai) and observed ln(D).

The ability of the models to predict for managed stands was evaluated with an F-test where the numerator was the variance of managed stand residuals, corrected for bias, and the denominator was the mean squared residual from the inventory data to which the models were fit (Table 5). This test is essentially the same as Freeze's (1960) $\chi^2$ where required accuracy is defined as the mean squared residual from the original regression. The hypothesis tested is that the two sets of residuals are from the same population. If the hypothesis is not rejected, the models are judged to do an adequate job of predicting for the managed regeneration data.

Table 2.--Comparison of tree and stand characteristics between the timber management inventory data used for model fitting and the data from young managed stands used for model evaluation

|  | Timber management inventory (n=11522) |  |  |  | Young managed stands (n=791) |  |  |  |
|---|---|---|---|---|---|---|---|---|
| Variable | Mean | Minimum | Maximum | St. dev. | Mean | Minimum | Maximum | St. Dev. |
| Diameter breast height (cm) | 35.4 | 7.6 | 139.8 | 18.8 | 24.4 | 7.6 | 85.1 | 13.7 |
| Crown ratio | 0.48 | 0.1 | 0.9 | 0.17 | 0.54 | 0.1 | 0.9 | 0.16 |
| Basal area in larger trees ($m^2$/ha) | 10.6 | 0.0 | 60.6 | 9.2 | 5.8 | 0.0 | 37.6 | 5.4 |
| Height (m) | 22.9 | 2.7 | 58.8 | 8.2 | 19.6 | 6.7 | 49.1 | 7.4 |
| Basal area increment ($cm^2$) | 131.5 | 2.7 | 956.6 | 102.6 | 158.9 | 5.6 | 688.1 | 95.8 |
| Diameter increment (cm) | 2.74 | 0.25 | 15.75 | 1.92 | 4.6 | 0.3 | 15.7 | 1.9 |
| Quadratic mean d.b.h. (cm) | 12.6 | 0.9 | 93.5 | 7.8 | 18.2 | 3.0 | 68.8 | 8.0 |
| Elevation (100m) | 13.6 | 5.2 | 24.4 | 3.2 | 10.2 | 6.7 | 13.7 | 1.8 |
| Basal area ($m^2$/ha) | 25.0 | 0.2 | 118.7 | 11.2 | 14.3 | 0.5 | 40.4 | 7.9 |
| Crown competition factor | 117.8 | 3.0 | 452.0 | 52.2 | 78.4 | 3.0 | 221.0 | 40.0 |
| Trees per hectare | 3957.0 | 2.5 | 81423.4 | 4518.2 | 815.4 | 2.5 | 6451.9 | 114.4 |

Table 3.--Number of observations by species for the diameter increment data from managed regenetation stand that were used for model evaluation

| Species | Number of observations | Species | Number of observations |
|---|---|---|---|
| Western white pine | 239 | Western redcedar | 240 |
| Western larch | 461 | Lodgepole pine | 168 |
| Douglas-fir | 791 | Engelmann spruce | 9 |
| Grand fir | 708 | Subalpine fir | 4 |
| Western hemlock | 124 | Ponderosa pine | 151 |

Table 4.--Statistics from model evaluation based on data from managed regeneration stands. Due to insufficient observations, data for Engelmann spruce and subalpine fir were excluded.

| | | Variation in residuals explained by | |
|---|---|---|---|
| Species | Bias (obs-pred) | Predicted ln(bai) | Observed ln(D) |
| | (%) | (%) | (%) |
| Western white pine | -6.9 | 2.8 | 8.3 |
| Western larch | -10.1 | 0.9 | 0.0 |
| Douglas-fir | -1.9 | 0.7 | 5.1 |
| Grand fir | 1.3 | 6.7 | 6.7 |
| Western hemlock | 3.6 | 2.6 | 6.0 |
| Western redcedar | 3.8 | 2.6 | 3.7 |
| Lodgepole pine | 0.1 | 1.2 | 3.7 |
| Ponderosa pine | -0.2 | 0.2 | 1.6 |
| All species | -1.7 | 0.3 | 2.7 |

Table 5.--Evaluation of model performance. Models were judged acceptable if the variance of residuals about zero for the test dataset was less than the mean squared residual from regression (F <1.0)

| | Mean square residuals | | Degrees of freedom | | |
|---|---|---|---|---|---|
| Species | Inventory data | Test data | Inventory data | Test data | F |
| Western white pine | 0.263 | 0.465 | 1,787 | 239 | 1.768* |
| Western larch | 0.305 | 0.410 | 4,619 | 461 | 1.344* |
| Douglas-fir | 0.337 | 0.264 | 11,496 | 791 | 0.784 |
| Grand fir | 0.315 | 0.254 | 4,658 | 708 | 0.806 |
| Western hemlock | 0.290 | 0.218 | 1,758 | 124 | 0.750 |
| Western redcedar | 0.326 | 0.264 | 2,420 | 240 | 0.810 |
| Lodgepole pine | 0.243 | 0.204 | 6,925 | 168 | 0.840 |
| Ponderosa pine | 0.257 | 0.221 | 1,966 | 150 | 0.860 |
| All species | 0.300 | 0.293 | 35,629 | 2881 | 0.977 |

* Values of F that are significant at 95% level.

With the exception of western white pine and western larch, the models made acceptable increment predictions for the managed regeneration stands. On the average, the models substantially overpredicted increments for larch and white pine. With white pine, there was also a significant negative trend of residuals (observed minus predicted) with increasing d.b.h. For these species we can conclude only that the two independent samples of increment are different. Otherwise, if the model is assumed to misstate the influence of management on larch and white pine, we must conclude that management has a deleterious effect on increment. During the period for which increments were observed, both species were subjected to exceptional stress from disease and insects (primarily white pine blister rust and larch casebearer). It is quite likely that the effects of these agents were not proportionally distributed among the two data sets.

## CONCLUSIONS

The slope of the basal area increment curve conforms to growth theory, and responses to changing site and stand characteristics are as expected. Model evaluation based on examination of residuals revealed no abnormalities, and although there were problems evident for two species, the model performed acceptably when predictions were made for an independent data set. Based on these comparisons, the behavior of the model is judged to be reasonable.

Evaluation of all Prognosis Model components is continuing. Currently, projected growth trends are being compared to observations of stand development as evidenced in a collection of long-term permanent sample plots. These tests should provide additional insight as to the behavior of the basal area increment model and will perhaps clarify the discrepancies observed here for white pine and larch.

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Prepared for presentation at "Forest Growth Modeling and Simulation," a meeting sponsored by IUFRO S4.01, Mensuration, Growth and Yield, on October 4-8, 1982, in Vienna, Austria. Date of preparation: September 27, 1982.

Appendix A.--Names for habitat types represented by the Inland Empire basal area increment models[1]

| Abbreviation | Habitat type name |
|---|---|
| SCREE | Scree |
| PIPO/AGSP | *Pinus ponderosa/Agropyron spicatum* |
| PIPO/PUTR | *Pinus ponderosa/Purshia tridentata* |
| PIPO/SYAL | *Pinus ponderosa/Symphoricarpos albus* |
| PSME/AGSP | *Pseudotsuga menziesii/Agropyron spicatum* |
| PSME/FEID | *Pseudotsuga menziesii/Festuca idahoesis* |
| PSME/VACA | *Pseudotsuga menziesii/Vaccinium caespitosum* |
| PSME/PHMA | *Pseudotsuga menziesii/Physocarpus malvaceus* |
| PSME/VAGL | *Pseudotsuga menziesii/Vaccinium globulare* |
| PSME/LIBO | *Pseudotsuga menziesii/Linnaea borealis* |
| PSME/SYAL | *Pseudotsuga menziesii/Symphoricarpos albus* |
| PSME/CARU | *Pseudotsuga menziesii/Calamagrostis rubescens* |
| PSME/CAGE | *Pseudotsuga menziesii/Carex geyeri* |
| PSME/SPBE | *Pseudotsuga menziesii/Spirea betulifolia* |
| PSME/ARUV | *Pseudotsuga menziesii/Arctostaphylos uva-ursi* |
| PICEA/CLUN | *Picea/Clintonia uniflorum* |
| PICEA/VACA | *Picea/Vaccinium caespitosum* |
| PICEA/LIBO | *Picea/Linnaea borealis* |
| ABGR/XETE | *Abies grandis/Xerophyllum tenax* |
| ABGR/CLUN | *Abies grandis/Clintonia uniflorum* |
| THPL/CLUN | *Thuja plicata/Clintonia uniflorum* |
| THPL/OPHO | *Thuja plicata/Oplopanax horridum* |
| TSHE/CLUN | *Tsuga heterophylla/Clintonia uniflorum* |
| ABLA/OPHO | *Abies lasiocarpa/Oplopanax horridum* |
| ABLA/CLUN | *Abies lasiocarpa/Clintonia uniflorum* |
| ABLA/GATR | *Abies lasiocarpa/Galium triflorum* |
| ABLA/VACA | *Abies lasiocarpa/Vaccinium caespitosum* |
| ABLA/CACA | *Abies lasiocarpa/Calamagrostis canadensis* |
| ABLA/LIBO | *Abies lasiocarpa/Linnaea borealis* |
| ABLA/MEFE | *Abies lasiocarpa/Menziesia ferruginea* |
| TSME/MEFE | *Tsuga mertensiana/Menziesia ferruginea* |
| ABLA/XETE | *Abies lasiocarpa/Xerophyllum tenax* |
| TSME/XETE | *Tsuga mertensiana/Xerophyllum tenax* |
| ABLA/VAGL | *Abies lasiocarpa/Vaccinium globulare* |
| ABLA/VASC | *Abies lasiocarpa/Vaccinium scoparium* |
| ABLA-PIAL/VASC | *Abies lasiocarpa-Pinus aulbicaulis/Vaccinium scoparium* |
| ABLA/LUHI | *Abies lasiocarpa/Luzula hitchcockii* |
| PIAL-ABLA | *Pinus albicaulis-Abies lasiocarpa* |
| LALY-ABLA | *Larix lyallii-Abies lasiocarpa* |
| OTHER | |

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[1] From Pfister and others 1977.

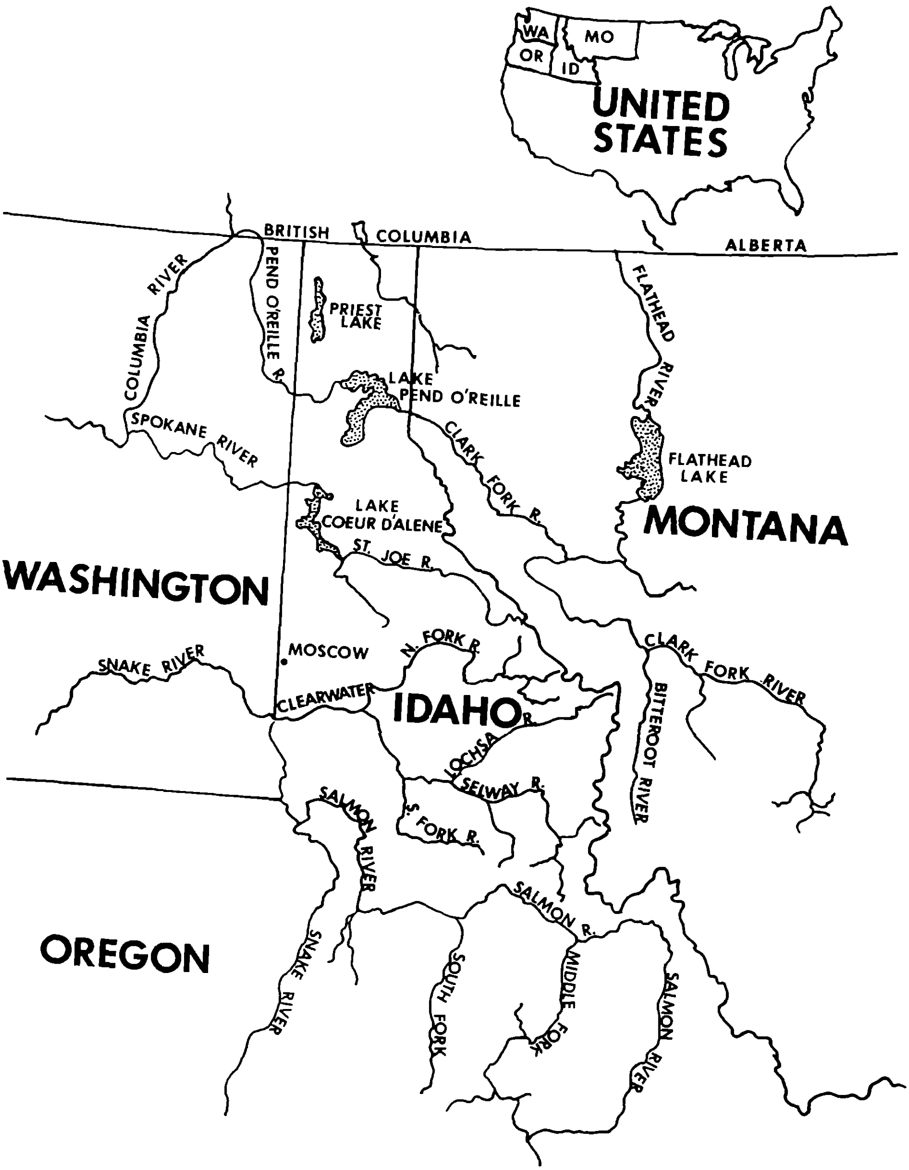

Figure 1.--The Inland Empire is located in the northwestern United States and includes portions of the States of Idaho, Montana, and Washington. The area is bounded by the Columbia River to the west, the Salmon and Snake rivers to the south, and the Flathead and Clark Fork rivers to the east. This area is in the transition zone between continental and marine climatic influences.

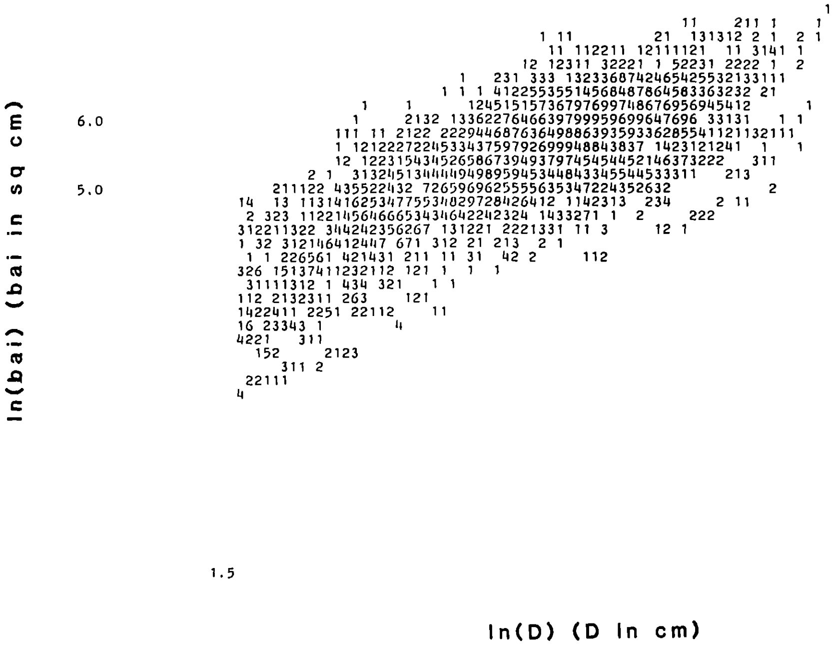

Figure 2.--If an allometric relationship exists between basal area increment and d.b.h., the patterns of observations should be linear and have homogeneous variance when plotted on the log-log scale. This random sample of Douglas-fir observations conforms well to expectations.

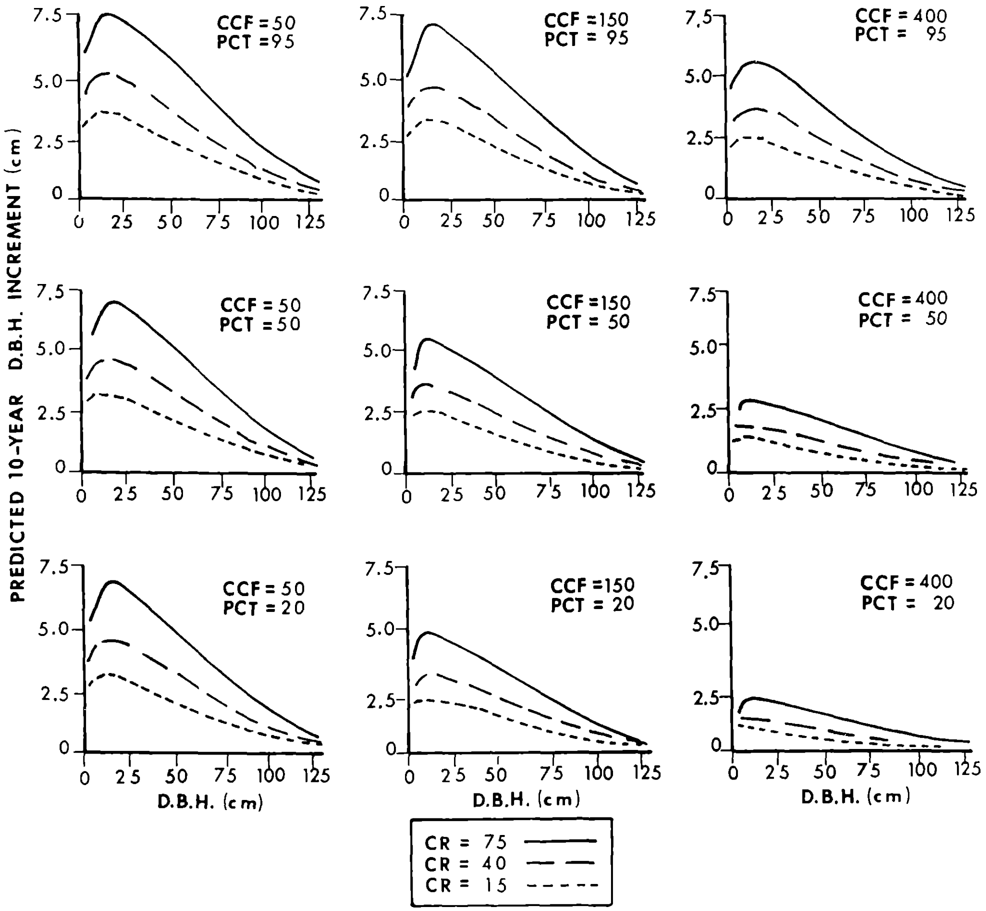

Figure 3.--The response of diameter increment relative to d.b.h. has the skewed, unimodal form that is characteristic of increment curves. For a given d.b.h., the largest increments are obtained on dominant trees with large crowns growing in open stands. Increment predictions are reduced when trees are subordinated, crowns are shortened, or stand density increases. The curves shown are for Douglas-fir.

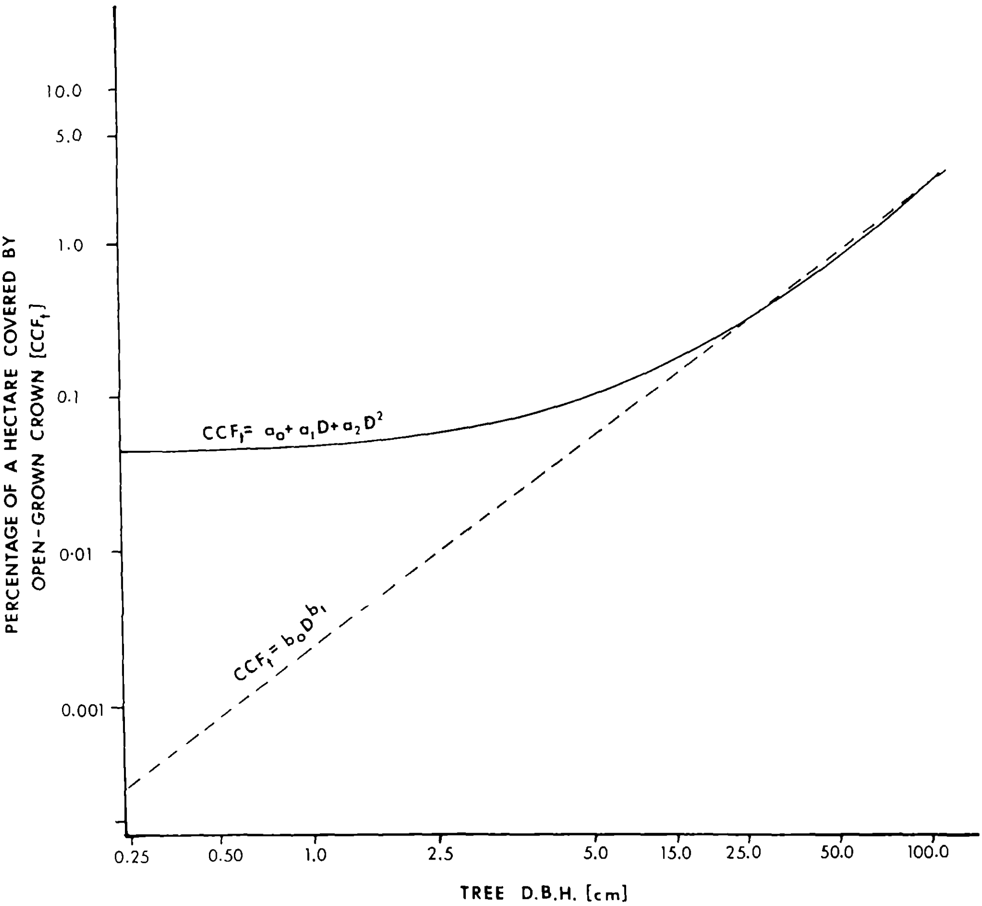

Figure 4.--Alternative crown coverage models for Douglas-fir. The quadratic function results if a linear relationship between crown width and d.b.h. is assumed. The power function results if an allometric relationship is assumed.

Zeitschrift/Journal: Mitteilungen der forstlichen Bundes-Versuchsanstalt Wien

Jahr/Year: 1983

Band/Volume: 147_1983

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